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An integrated review of architectural design and robotic planning for collective robotic construction

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Abstract

Most studies on Collective Robotic Construction (CRC) delineate the architectural designing and robotic route planning stages of the whole building process. A structure is built and forwarded to planners or compilers that generate assembly directions for the available robots. This has resulted in the construction of physically intricate buildings, although it complicates the planning procedure, rendering it unavailable to the architects. This study demonstrates how an Agent-Based Modelling System (ABMS) integrates CRC's building design and robotic development phases, highlighting the architect's role beyond merely designing static buildings. The whole construction pipeline is disrupted, resulting in more designer management, adjustments for limitations in the building process, broader comprehension of the procedures, and the possibility for design reconfiguring when utilizing CRC technologies. This is illustrated by introducing an ABMS for constructing a planar building utilizing a previously established CRC mechanism.

Keywords

Architectural Design, Robotic Planning, Collective Robotic Construction, Review

1. Introduction to Robic Construction

As knowledge of the building's financial, ecological, and social ramifications rises, interest in building automation is expanding [1]. This encompasses a thorough examination and application of diverse technological advances throughout construction manipulation, including the growth of computer-aided planning and engineering techniques, the utilization of automated systems for building operations, and the integration of robotics in various stages of building [2]. In automated robotics, which is distinguished by multiple robot sizes, kinds, and system facilities, Collective Robotic Construction (CRC) is a novel method [3]. The hallmark of CRC is the transition to employing a mobile robotics group instead of a solitary robot for construction management. The robots of CRC technologies are often compact, allowing them to remain within the structures they construct, facilitating activities such as checks, upkeep, reconfiguration, and ultimately demise during the building's life cycle. Current CRC technologies encompass a collection of terrestrial robots for installing stacking stones, quadrotor aircraft for constructing cubic buildings, and groups of homogeneous robots possessing diverse skills for producing buildings utilizing filament materials [4]. Despite the existence of these and other exemplary robust CRC structures, many study inquiries remain unresolved due to (i) the developing nature of the CRC field, (ii) the intricate challenge of coordinating mobile devices within the presently complex realm of Architectural Engineering, and Construction (AEC) [5], and (iii) the potential necessity to reevaluate every phase of the life of a structure, encompassing its design, building, and operations.

The intricacy of architectural design is increasingly evident when evaluating CRC about current methods of building automation, such as on-site and off-site prefabricated product facilities and specialized on-site robots [6]. Initially, the mobility of the robots in the CRC renders their workspace potentially boundless, facilitating the construction of more extensive architectural projects. Secondly, robots can occupy the structures they make, enabling their participation in both the assembly and the adaption or demolition of the construction. This necessitates that the robots react to their surroundings and make instantaneous judgments that can impact the architecture of the broader architectural framework as they construct or occupy it. Given that the essence of CRC entails the cooperation of several machines, comprehending these relationships and their impact on the assembly procedure is essential for designing buildings. The building design procedure evolves from focusing on a static workspace utilized by a solitary robot to a theoretically boundless workplace inhabited by several robots with identical or varying capacities.

2. Related Works

Research on CRC is classified based on the designing method, contingent upon whether the structure layout is established before the initiation of the building process [7]. This divergence pertains to whether the planning process follows a top-down strategy, in which the concept is established before building, or a bottom-up approach, where the design develops and changes during the assembly by the robotics [8].

Studies on CRC utilizing bottom-up building design methodologies are leading to the development of computational simulation programs that show designs throughout their generation [9]. In these systems, robots exhibit behaviors that allow them to make judgments according to the activities of other robotics and their surroundings when constructing a building. Given the challenges in predicting the finished buildings and assembly procedures, it is essential to provide tools for visualizing, validating, and assessing architectural ideas as they evolve during the building phase [10]. In the actual world, design iteration incurs more significant costs and waste than conducting the building process through simulations. These technologies allow the investigation of novel interpretations of building stages, such as one where building design and robotic scheduling converge [11]. Research illustrates how designing buildings with CRC structures includes concepts of structural safety [12].

As processing power continues to improve, the utilization of Agent-Based Modeling Systems (ABMS) [13], a method for simulating the actions and relationships of autonomous agents, is rapidly gaining traction in fields outside of its original computing domain. The study of the relationships between entities in space and time can be aided by agent-based models, which are virtual simulations. Individual agents, typically humans in epidemiology, are given specific properties in these stochastic models. The agents' actions and interactions with one another and their surroundings are predetermined by programming. The results of these interactions, known as emergent effects, could vary from one agent to another. Like systems dynamics modeling, agent-based modeling deviates from conventional regression-based approaches by facilitating the investigation of complex systems exhibiting non-independence of persons and feedback loops in causal processes. In addition to representing observed facts, it can also represent hypothetical situations or experiments that would be impractical or morally questionable to carry out in the actual world. The AEC sector exemplifies this phenomenon. The appeal of ABMS originates from its capability to concisely and effectively simulate intricate, non-linear structures and its adaptability to various scenarios.

The investigation of ABMS in construction first focused on digital forms, but it is now progressing towards sophisticated models that provide material, technical, and production restrictions [14]. ABMS facilitates the integration of many requirements for design into the planning procedure by integrating data into the agents' behaviors. The application of an ABMS in architectural development has been conducted for many structures and architectural components, such as Zollinger lamella constructions, wood shells, multistory constructions, and structure faces [5]. Although some of these initiatives use robotic prefabricated products inside the corresponding ABM, none employ CRC and hence do not account for it in the framework.

While ABMS has often been developed to be entirely autonomous in many fields, interactivity is increasingly being integrated into ABMS [16]. This interaction is a significant advantage of the technique. Attaining viable design results necessitates the modification of ABMS parameters to reconcile design objectives. The research examines both conventional and alternative layouts for handheld computers to facilitate interaction. This study seeks to explore the following inquiries about building design in CRC:

(i) How can the interior layout of structures, influenced by how groups of mobile machines assemble them, be examined using ABMS?

(ii) How does establishing an ABMS for CRC influence the use of models during the building process, allowing the system to fulfill functions beyond mere early-stage layout?

(iii) How can instruments for CRC be devised to facilitate architect participation at various stages of the building procedure?

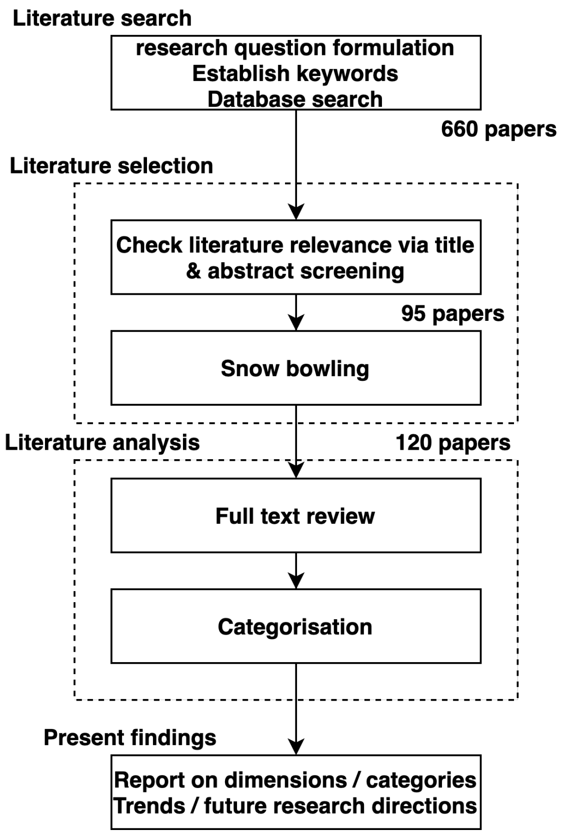

Fig. 1. Overview of the research

3. Research Overview

The study utilized a research review technique to examine the architectural design in CRC, akin to publications that assess the influence of technology advancements in building and design. The research approach utilized in this work comprised the following stages: (i) literature searches, (ii) literature choosing, (iii) analyzing the literature, and (iv) presenting of findings. This technique is visually shown in Fig. 1.

3.1. Literature search

The initial stage in any research review is to search for a complete body of research thoroughly. Finding literature in this study was divided into three phases: (i) creating a research inquiry, (ii) delineation of phrases, and (iii) execution of a database query. The creation of the research issue was the preliminary phase that established the foundation for the evaluation procedure. Initially, it delineates the literature to be examined and outlines the methodology for its analysis. The primary research inquiry in this study is: How is building design used to study CRC? Particular attention was directed to the processes employed in building design and the influence of the chosen method on the architect's role within the whole physical design procedure. Several phrases were derived from the study question to conduct a literature analysis. Given that CRC is an evolving study domain, many keywords were chosen to encompass the breadth of studies on the subject.

Each line or collection of phrases seeks to encapsulate the essential elements of CRC: (i) an automated system including numerous robots, (ii) the robots are portable, and (iii) the automation system is used in an architecture building context. The initial two phrases adequately encapsulate this, while the keyword groups were enhanced with further requirements utilizing Boolean expressions to guarantee the relevance of the gathered material to CRC. The OR operation was employed when two terms fulfilled one of the principal components of CRC. In contrast, the AND operation amalgamated phrases about distinct facets of CRC.

Phrases pertinent were supplemented with an extra criterion to enhance the probability that the findings pertain to building construction. This is seen by the use of the AND Boolean with ("assemblage" OR "building") in conjunction with the phrases. The terms "assemblage" and "building" possess alternative interpretations, resulting in this research's accumulation of irrelevant data. The examination of the filtering of these findings will take place in the part about literature selections. The term "Design" was deliberately excluded due to its prevalent usage in computer technology, a significant source of study.

The chosen phrase sets were employed to gather articles from an internet database. Following an initial evaluation of many records, including Web of Sciences, Google Scholar, and Cumin-Computer Aided Design (CAD), Scopus was selected for library retrieval due to its extensive collection of multidisciplinary research in building and construction. Scopus identifies the literature in Cumin-CAD, a specialized repository for computer-aided architecture design. Scopus was recognized as an archive that included studies about the specified subject of building style in CRC. The Scopus search yielded 660 articles from 2000 to 2023, further decreasing to 530 by restricting the language to English and the article type to meeting sessions and peer-reviewed papers.

3.2. Literature selection

The gathered literature was further improved by assessing the relevancy of the articles by a comprehensive review of their abstracts. This screening mostly entailed the exclusion of material about ARMS that was not contextualized within CRC but instead gathered owing to the vagueness of the phrases "assemblage" or "building." These words are employed to delineate the processes involved in developing and fabricating mobile robot equipment and formulating the computer algorithms underpinning ARMS.

Further articles were excluded for two more reasons. The primary problem was that certain publications enumerated many application fields for the studies, rendering them non-specific to architecture building. The second explanation is that the use of ARMS in building, in certain instances, pertains not to designing building inquiries but to the automating of specific tasks. An illustration of this is the oversight of building advancement. Following the evaluation of titles and descriptions, 95 articles were retained.

A snowballing method was employed to manually incorporate more material, like in other assessments, to guarantee the literature corpus was comprehensive. Snowballing is a method of reviewing chosen material to identify other pertinent literature among the sources related to the subject matter. The snowballing method was applied to the three presented studies on CRC to guarantee that the previously cited library on the topic was included in the bibliographic searches done for this article. The snowballing process yielded 30 more publications not captured in the first publication searches, culminating in an aggregate of 120 articles that were then reviewed in the second phase of the evaluation approach.

3.3. Literature analysis

The primary distinction from the previously stated assessments on technical advancements in building and architecture is that this review did a restricted bibliometric evaluation. This examination aims to concentrate on a particular feature of CRC, so a comprehensive bibliometric evaluation falls outside the purview of this work. An assessment of the chosen research according to the year of publication was performed, shown in Fig. 2.

The material review section of the approach in this study entailed a comprehensive examination of the literature to address the suggested study topic. This entailed reviewing each article to comprehend the approach to building design within the published work. This was executed concurrently with the classification of the literature to facilitate the understanding of diverse building design methodologies. This methodology utilized the grounded theoretical method, using recurrent literature studies to substantiate the evolving classification. The building's design statements in prior assessments formed the foundation for the initial material categorization, which was then modified and refined during the review procedure. The final classification was converted into measurements and particular subcategories to meet and relate to significant

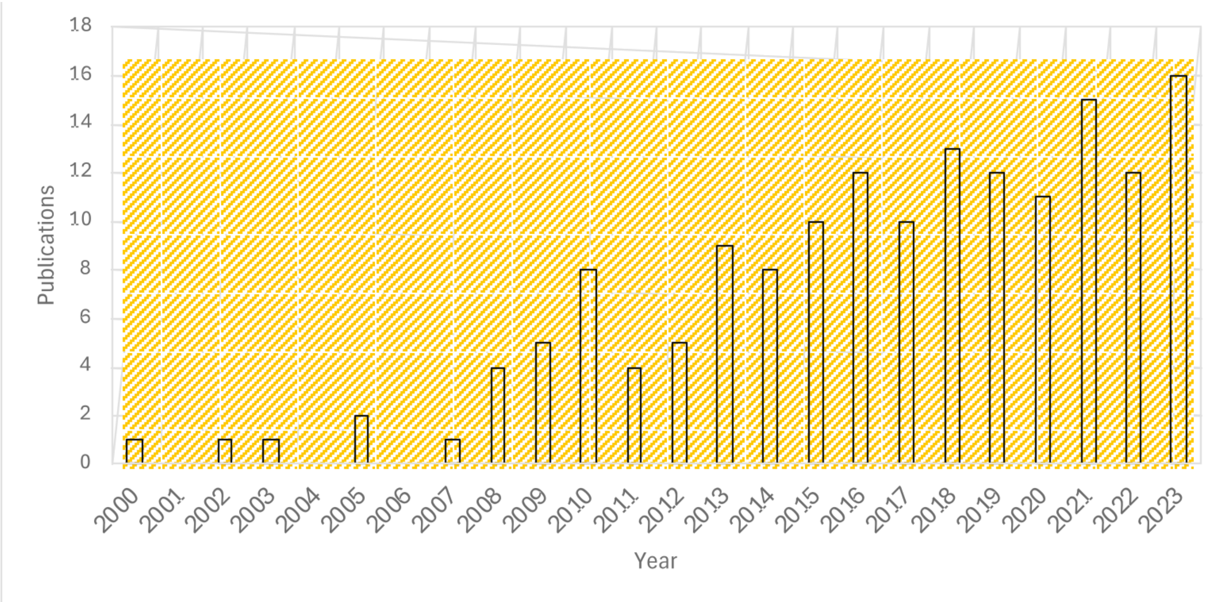

Fig. 2. Publication analysis

inquiries regarding building construction in CRC. The specified measurements and their classifications are illustrated in Fig. 3.

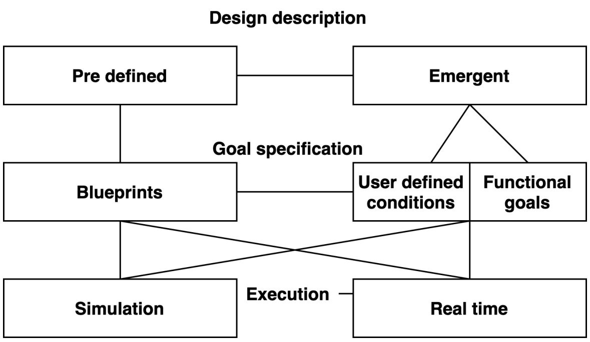

Fig. 3. ARMS classification analysis

3.4. Presentation of findings

The findings of the literature study, together with the categorization clarification, are delineated in the paper.

4. **Agent-based Model**

An agent-based design methodology for CRC was created to achieve the main goals of this study, facilitating the concurrent designing and robotic management of buildings. This section outlines the theoretical basis for developing an ABMS for use in CRC.

4.1. Agent

As shown in initial research, the determination of the algorithm's agent directly affects its application. This effort seeks to develop buildings like those in the prior paper. In addition to design research, the structure's aim includes formulating a pathway for the developed structure. The agent is a mobile robot integrated into the CRC systems. Although it is feasible to designate an agent as a construction component in an ABMS for CRC, integrating the construction assembly process proves to be more complex inside such a framework. The subsections elaborate on the methodology by which the agent depicts the mobile robot.

4.2. Environment and interaction typology

The setting serves as the context in which the robots engage. In the context of CRC, this refers to either a 2D or 3D Euclidean framework delineating the region or volume within which autonomous vehicles or agents operate. Numerous CRC instances entail manipulating items, with study as one illustration; hence, a 2D environment is adequate. The Euclidean domain delineates agents' interaction type or connectivity within the context, enabling them to engage within their vicinity. A neighborhood is defined by the neighboring agents with whom an agent can communicate.

Neighbors are defined by their material closeness or, in certain instances, by the social requirements of the CRC structure, such as the necessity for cooperation among particular agents. The primary characteristic of the setting is the provision for data on the constructed framework, detailing the position of both assembled construction items and those pending assembling. The context must include supplementary data from the physical surroundings necessary for the construction procedure.

4.3. Behaviours

Behaviors are regulations that govern the condition of the agents at every iteration of the framework. They synchronize reactions to (i) the present condition of the agent, (i1) the condition of other agents within the framework, and (i) the condition of the surroundings. This technique delineates the behaviors as robots' activities in the physical realm, hence elucidating the manufacturing restrictions intrinsic to the CRC systems. The particular behaviors vary based on the modeled CRC structure, and it is the architect's job to delineate these. Examples of these behaviors include procuring materials for installation, navigating the surroundings, interacting with another robot, or constructing materials into a building. Behaviors often possess characteristics that enable builders to modify them throughout the execution of the ABMS. Architects can modify behaviors to achieve varied goals.

4.4. Agent system

Every element of an ABMS characterizes the agent system. Explanation of two further critical components of the agent framework is required. An agent system comprises many categories of agents. It is crucial to highlight that not all CRC setups have a uniform collection of mobile robots. The agent network comprises agents with different meanings in a CRC network with several robot kinds.

At the agent system threshold, the second critical overall design choice pertains to selecting either a force-based or position-based method. Determining the agent's speed is essential to the robotic route planning procedure. A vector denoting the cumulative forces in force-based agent structures influences the agent's speed. At each iteration of the approach, the agent's new location results from the alteration in speed affecting its location. In position-based agent structures, the agent's location alters with every iteration due to the influence of translation vectors. In the previous method, an additional requisite property of the agent is its speed, which is continuously updated throughout the model's execution. Regulating the speed enables more precise calibration of the agents' movements. This degree of specificity is only sometimes necessary.

4.5. Model updation, implementation, and interaction

In reality, three alternatives exist to delineate the link between an ABMS and the assembly procedure. The initial point is that the ABMS operates with asynchronous changes relative to the robots' assembly operation. The second point is that ABMS operates with partly synchronized modifying, where the modeling updates about specific events in the real world, such as the motion and positioning of an individual building component. The ultimate possibility is that the ABMS operates with synchronous updates to the actual assembly processes. The ABMS changes directly influence the building phases that the framework can evaluate.

The ABMS operates asynchronously while continuously recording the robotic route intentions. The actual machine can implement the pre-programmed path plans independently from the algorithm's execution at a later phase. The model retains path plans for the scheduled event in partly synchronous modification. In those models, planning and development in simulation occur repeatedly alongside execution. It is feasible to update the surroundings following each iteration of operating a physical system. In synchronous modifying, the model operates concurrently with the execution. It is essential to continually update the ABMS ecosystem to align with the physical infrastructure.

4.6. Validation

The conversion of this theoretical framework into an official structure was employed to verify this methodology. The formal concept was implemented in building a building to demonstrate how it can be utilized in an accurate CRC assembly procedure.

5. Discussion

5.1 Interactivity

The designer's role evolves from conventional practice in the suggested ABMS method. The architect must establish the ABMS by creating the behaviors, configuring the initial circumstances for the system's operation, and managing the factors that affect the whole structure. Instant feedback in the graphic representation of the CRC method transpires when adjusting the diverse settings for the ABMS. The designer not only organizes what is needed to create a building but also modifies the assembly process of the robotic devices involved in its construction.

5.2 Design Workflow

Beyond the realm of CRC, ABMS in building design mainly concentrates on the first design phases. The rationale is that the expense of implementing design modifications escalates considerably while the capacity to effect change diminishes during the building's planning phase. Avoiding alterations to the design can become complex when domain-specific information beyond the design itself necessitates reevaluation of components in stages of the construction. The established hypothesis posits that ABMS can integrate domain-specific expertise, such as environmental analysis or production limitations, into early-stage design processes, thereby enhancing the building design procedure's overall efficiency and cost-effectiveness without requiring extensive modifications in design phases. The study demonstrates that including specifics of the assembly method in ABMS influences a structure's design and assembly. Future studies integrate diverse domain information to develop models that more accurately reflect reality and assist in addressing further inquiries in structural design.

5.3 Optimization of planning

Employing the suggested technique, agents choose actions that do not consistently yield the most optimum solution. The prototype clearly shows that the number of robotic movements required to manufacture a single wood strut might differ. Extended construction durations correlate with increased energy usage and elevated overall building expenses. While re-executing the model to get outcomes with fewer robotic steps mitigates this issue, interactivity might delay the creation and assembly processes. Additional studies should explore methods for enhancing ABMS to achieve more effective robotic scheduling. Reward learning is a promising approach for developing behaviors in mobile devices and optimizing agent actions to meet the design goals. Integrating these efforts, reinforcement learning techniques aimed at cultivating goal-directed behaviors can be utilized to minimize the duration of robotic programs. This necessitates additional study of the association between the number of stages in the schedule and the overall trip distance since not every phase corresponds to the same journey and the time traveled by a kinematic cycle.

5.4 Validation and Design Effectiveness

The successful construction of the model has commenced the validation of the technique. Further studies should focus on applying this ABMS methodology to various CRCs, incorporating diverse robotic and material configurations, to verify the concept further. It is essential to acknowledge that mastering novel techniques gets closer, and technologies require time. While the methodology employed in this study is prevalent in the architectural industry, creating ABMS from the ground up entails an extensive learning process. In contrast to traditional design methods where agents symbolize abstract things, the behavior design for agents in the suggested method is grounded in the features of actual robots.

6. **Conclusion**

This study presents an ABMS methodology for designing buildings constructed by teams of several mobile robots, building upon the first presentation of this concept in prior research. This research emphasizes a method that facilitates concurrent design and robotic routing of buildings. The study elaborates on the conceptual framework for designing the ABMS, encompassing planning and developing activities. It details the formulation of an official model utilizing this method for current CRC systems. The objective is to establish a foundation for future investigators in the field to investigate, enhance, and share features with the proposed method based on the objectives of the ABMS architecture from which it originated.

The suggested methodology diverges from existing design strategies in CRC. Rather than a blueprint being predetermined and developed by an architect for building sequences and robotic planning of routes, the building's layout materializes concurrently with the assembly procedure. The immediate visual input from the ABMS integrates the designer into the building procedure, enabling real-time modifications as the procedure progresses. This methodology allows a designer to suggest architectural reorganization, which disrupts prevailing design methodologies in CRC and challenges traditional design practices.

The study demonstrates implementing the suggested ABMS technique at full scale by building a formal description and using it in the initial construction. This illustrates the abstraction of a physical CRC system into an ABMS, highlighting how essential features and actions of physical robots are translated into digital actors and behaviors. The prototype demonstrates how the communication capabilities of the ABMS facilitate a shift in the architect's role from only determining structural elements to orchestrating the movements and behaviors of the robotic creatures. This interaction enables the management of limitations in the construction of CRC structures since the architect modifies plans based on real-time updates of the digital model. The designer can revert to a general role, as seen by the emergence of alternative computational processes for building robotics. The CNC technology allows for the customization and shaping of prefabricated structure components in accordance with digital 3D models during manufacturing. In order to increase output and check the quality of manufactured parts, several robots have found their way into the production process. CRC and ABMS helps architects to build a sustainable buildings by using a precise materials and real-time adjustments and optimizing the efficiency of the construction. This research demonstrates the excellent application of ABMS in building design and autonomous navigation inside CRC. This underscores the need to formulate methodologies for designing buildings in CRC since the approach selection might result in varying concerns during the building phases. To realize the objective of small mobile computers occupying a self-assembled framework, enabling them to modify, upkeep, or dismantle it, a re-evaluation of the layout concerning CRC is necessary. In future, research should focus multi robot coordination, material handling, human robot collaboration and improving safety and efficiency in the industry standards.

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