Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich, Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Beyond Babel: Towering With Minimal Communication

Tsung-Wei CHENG, Kevin HARSONO[*], Yu-Xi LIU[a], Ching-Yen CHEN, Shen-Guan SHIH, Oliver TESSMAN[a]

[*] Department of Architecture, National Taiwan University of Science and Technology
No. 43 Keelung Road, Section 4, Da'an District, Taipei 10607, Taiwan
d11113803@mail.ntust.edu.tw

[a] Department of Architecture, Technische Universität Darmstadt

Abstract

This research aims to improve the efficiency and sustainability of constructing dry-stacking building blocks using SL block by developing a parallel construction method. Inspired by M.C. Escher's woodcut prints of the Tower of Babel and Filippo Brunelleschi's helical herringbone patterned brick structure in the Duomo di Firenze, the study introduces tower structures designed for concurrent assembly by independent working units. SL blocks, octo-cubes for dry-stacking, form interlocking structures requiring minimal communication. The assembly process involves placing components in specific sequences, with additional support if needed. The challenge lies in enabling simultaneous construction by independent units. A computational framework using attributed grammar defines interlocking relationships, generating patterns for towering structures. An algorithm automates candidate block calculations for parallel assembly, ensuring collision avoidance and structural stability. Physical models were used to study proposed methods, testing various tower constructions for feasibility and limitations.

Keywords: SL Block, Parallel Assemblies, Attribute Grammar. Autonomous Construction

1. Introduction

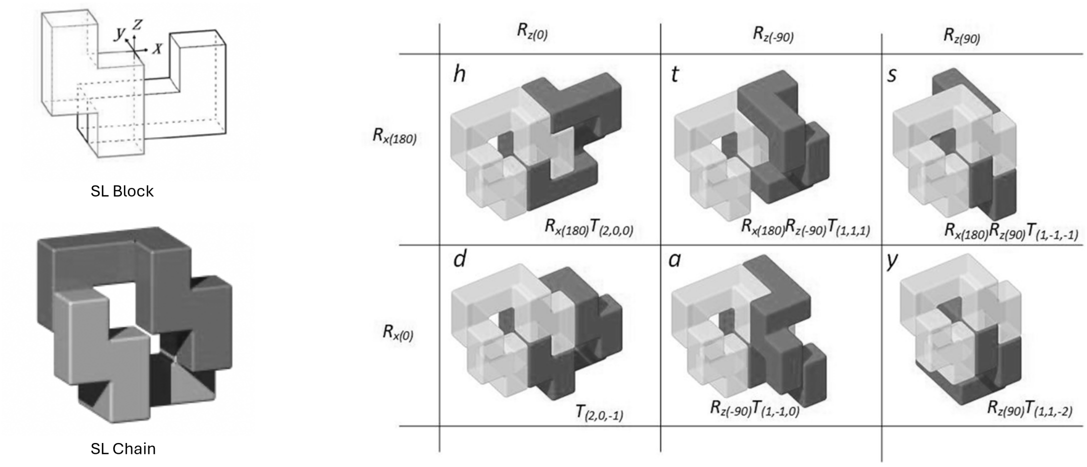
In traditional construction methods, the complexities inherent in the process often lead to significant challenges during the construction phase. As noted by Yarnold et al. [1], these challenges stem from the intricate coordination required among various stakeholders, resulting in delays, errors, and inefficiencies. Communication breakdowns, misinterpretations of instructions, and coordination issues are common pitfalls that can plague construction projects, ultimately hindering their progress and increasing costs. Addressing these communication challenges has long been a concern in the construction industry. Traditional methods often involve the combination of diverse building parts, leading to complications and delays in the construction process. Moreover, as highlighted by Xia et al. [2], the abundance of information and the complexity of construction projects can exacerbate communication issues, underscoring the need for streamlined communication channels with contractors and construction teams.

In this context, innovative solutions like SL Blocks offer promising opportunities to streamline construction processes and minimize the need for extensive communication. Inspired by the modularity and efficiency of SL Blocks, this research aims to explore an innovative method for constructing complex structures with minimal communication overhead. By leveraging the modular nature of SL Blocks, which enable parallel construction and autonomous assembly, construction projects can significantly reduce the reliance on constant communication between construction units. This approach not only simplifies coordination but also enhances efficiency and reduces the risk of errors during the construction process.

This paper aims to investigate the potential of parallel construction with SL Blocks and its role in minimizing communication in construction projects. The objectives include providing an abstract-level explanation of parallel construction with SL Blocks, presenting a case study illustrating the practical implications of this concept, and contributing to the understanding of how SL Blocks can streamline construction processes.

Through this research, The importance of minimal communication in construction projects is highlighted and demonstrates how innovative solutions like SL Blocks can address communication challenges, ultimately leading to more efficient and cost-effective construction practices.

1.1. SL Blocks and Grammar Representation



(a) SL Block and SL Chain

(b) Conjugation rule of SL Chain

Figure 1: SL Block with the respective rule of assemblies and its transformation matrix. Source: [3]

SL Block is an octo-cube combining S and L shapes, as proposed by Shih [3]. Two SL blocks conjugated in the Z-axis can be considered as one SL Chain, as depicted in Figure 1a. SL blocks can be utilized to construct extendable self-interlocking structures, enabling designers to assemble large and stable constructions using a substantial number of SL blocks without the need for any adhesive materials. This makes SL block assemblies one solution for sustainable construction, promoting reusable building components [4].

Over the years, researchers have conducted extensive studies on SL Blocks. Shih [3], [5], [6], [7] laid the foundation by proposing the shape and assembly rules of SL Blocks. Building upon this work, Wibranek et al. [8] developed an algorithm for assembling SL Blocks using a robotic arm and explored the application of Reinforcement Learning for sequential assembly, offering an innovative approach to architectural design. Additionally, Liu et al. [9] introduced autonomous assembly techniques using a hierarchical system, further expanding the scope of SL Block research.

Through the combination of strings and phrases, a language can be structured, with grammar serving to analyze and decipher sentences within that language. Similarly, expanding upon the previously mentioned representation of SL Chains, we can define compositions akin to phrases and integrate them into larger assemblies. These SL Chains adhere to six predefined rules, each denoted by letters representing specific transformations applied [6]. When combined with labels such as *h, t, s, d, a, y*, these rules delineate the six primary connections of the SL Chain. Such rules facilitate assemblies not only in vertical but also in horizontal configurations. However, among these rules, only *h* and *a* maintain the height of the bottom surface when an extra SL Chain is added. The corresponding transformations and rules are illustrated on Figure 1b.

Assemblies of SL Blocks can be represented using grammar through rule-based generation, involving computational tools and a predetermined set of rules to produce architectural designs [7]. These rules, akin to grammars in computer programming languages, offer a structured framework for SL Block assemblies, enabling designers to systematically create designs that adhere to predefined standards. A grammar serves as a systematic set of principles, acting as an architect's toolkit for articulating the syntax and structure of a design language. By incorporating labels with transformations, a more sophisticated level of SL Chain combination can be structured through lexical sequences. Subsequently, the configurations of SL Chains can become significantly more intricate by introducing mathematical expressions. For example, exponents can denote the repeated use of labels and transformations in concatenation, without allowing for commutative and associative properties. Figure 2 illustrates the possibility of SL Chain configuration with rule associates with it.

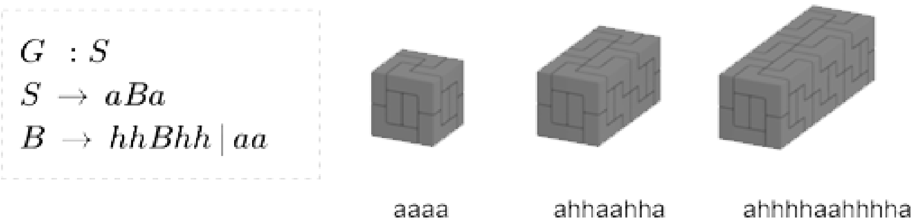


Figure 2: Possibility of SL Chain ”S” configuration.

In this study, attribute grammar (AG) is utilised to address semantic issues that traditional context-free grammars (CFGs) might encounter. This attribute grammar, denoted as G, consists of a triple comprising a CFG (G), an attribute (A), and AG (production rules). Specifically, Token $\langle s, TS(s)\rangle$ and Token $\langle a, ID(a)\rangle$ are employed to denote terminal symbols with transformation actions and the semantics of SL Block placement actions, respectively. For example, the production rule $S \rightarrow a\ I\ a\ I\ a\ I\ a\ I$ signifies moving the pointer under the ”a” transformation and placing the SL Block ”I” three times. Consequently, the appropriate representation of the grammar with syntax and semantics is:

$$\begin{aligned} G &: \langle S\rangle \\ \langle S\rangle &::= a\ a\ a\ a \\ \{\langle S\rangle .val &::= TS(a)\ ID(I)\ TS(a)\ ID(I)\ TS(a)\ ID(I)\ TS(a)\ ID(I)\} \end{aligned} \tag{1}$$

where can be simplified into:

$$\begin{aligned} \langle S\rangle &::= 4\ a \\ \{\langle S\rangle &::= (TS(a)\ ID(I))^{N(4)}\} \end{aligned} \tag{2}$$

Based on the definition of SL Block provided earlier, the assembly of SL Blocks can be facilitated by an interpreter that can construct the blocks in conjunction with a phrase from the sentence A, shown in Figure 2. Each component within the assembly can be assigned new transformation and label tokens, which can then be coordinated with larger aggregation actions.

1.2. Swarm Construction

Swarm construction involves utilizing large numbers of simple robots to build structures without central guidance and minimum information, inspired by the collective behaviour of social insects like termites.

These robots work autonomously, cooperating to construct projects according to a plan, similar to how termites build massive structures. In the context of construction, swarm construction involves coordinating a large number of relatively simple agents or robots to collaboratively build structures. These agents typically communicate and coordinate their actions locally, often without centralized control, to collectively achieve construction goals. How and Loh [10] propose a construction method based on swarm behaviour, which empowers the robot to operate autonomously and execute its assigned tasks independently. Through collective action, swarm robotics can produce intricate geometries. When compared to single robotic construction, employing a collective of smaller and more mobile robots concurrently results in a swifter and more efficient construction process.

2. SL Block Parallel Construction

The concept of parallel construction draws inspiration from the collaborative building processes observed in termite mounds, where termites exhibit decentralized and self-organizing behavior, constructing intricate structures efficiently without central oversight. Robotic construction studies have leveraged this natural phenomenon, employing multi-agent environments to enhance efficiency. Similarly, architecture, with its diverse elements governed by rigorous rules, can benefit from efficient assembly practices. In this research, parallel assembly focuses on distributing local and global workloads effectively and determining assembly sequences. Nodes on a hierarchical tree navigate composition relationships, and assessing the efficiency of composing components at different levels simultaneously is crucial. Considering these factors, incorporating parallel assembly is essential for streamlining the arrangement of SL Blocks with hierarchical characteristics.

2.1. Autonomous Construction

Autonomous construction is a collaborative process in which several robots operate independently to create structures or complete construction-related tasks. Inspired by natural systems like termite colonies, these robots self-organize and accomplish construction projects using local interactions and simple rules [11]. For the robot to be able to process the task given, Finite State Machines (FSMs) are utilized. FSMs offer a structured approach to controlling a robot's behaviour, which operates by transitioning between a finite number of states based on inputs or conditions. In construction, FSMs define states like material handling, and component assembly. In collective construction by robotic swarms, FSMs coordinate multiple robot's actions, assigning roles and simple tasks to each depending on the environment changes [12].

2.2. Duplication

The SL block assembly can duplicate assembly methods from previous layers. Specifically, the current arrangement enables robots to scan and follow conjugacy patterns from preceding layers to determine suitable block orientation. In Figure 3, the shape rule is defined in (3). The initial layer, depicted in grey blocks, necessitates the completion of blocks from the lowest position and label. Following the creation of a concave by the ”d” label and subsequent turns by the ”t” label, the stack of green blocks must align with the void that corresponds to the ”t” conjugated pair. In Figure 3b, blue block pairs are placed in accordance with the ”d” and ”h” labels, interlocking with the greens. Subsequently, the capping process completes the conjugated pair based on the preceding steps, resulting in the placement of the dark greens and blue blocks.

The duplication characteristic of the SL block provides the aggregation method from the local information of former layers reducing the amount of information. Besides, this singularity of the SL block

(a) (b) (c) (d)

Figure 3: The duplication figures based on the rule $\langle B \rangle$.

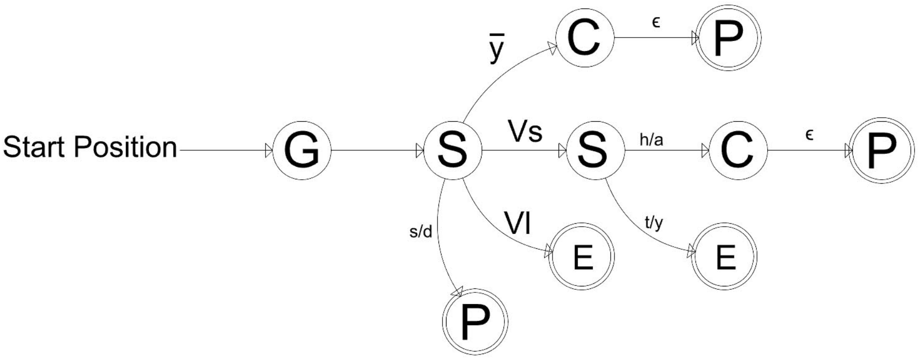
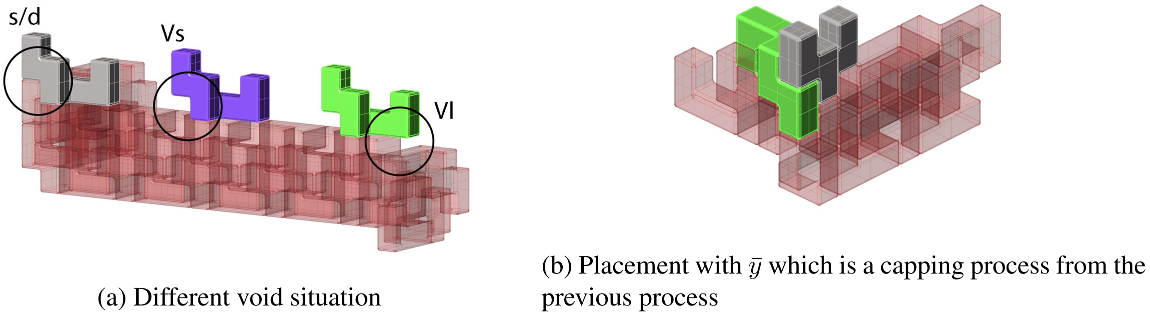


Figure 4: The finite state machine diagram shows the process of decision-making for a robot.

assembly can be addressed with a finite state machine. The inputs are the current location of the assembly hint, the block configuring without any void between the previous layer, and the interlocking sequence based on the degree of freedom; for example, in 3d, the green block placed at the concave can fill the step created from the ”d”. Also, the ”d” and ”h” are interlocked mutually, they both need to be placed together. Since, if we placed either one of them, the ”d” and ”h” occur a void at the bottom. Hence, ideally, the robots scan and gain limited information from the patterns to determine the start point and manners of the SL block location.

$$\begin{aligned} G &: \langle B \rangle \\ &\quad \langle B \rangle ::= \langle S \rangle \; 3 \, \langle T \rangle \; d \\ &\quad \langle S \rangle ::= d \; h \\ &\quad \langle T \rangle ::= d \; t \; h \end{aligned} \tag{3}$$

Figure 4 illustrates the states and actions for a robot to place the SL blocks after setting the start position from the SL block assembly pattern. The single circles depict the state of the robot’s actions, while the double circles represent the final state that either error state ”E” or placing block state ”P”. Moreover, the ”G” represents the grabbing of a block on the robot, the ”S” means the action of scanning the conjugacy pattern from the next placement, and the ”C” shows the combination of the current block assembly position from the conjugacy pattern with the current block on the robot. When the final state is at ”E”, the robot will not place the block, instead, it changes another start position. However, if it goes to ”P”,



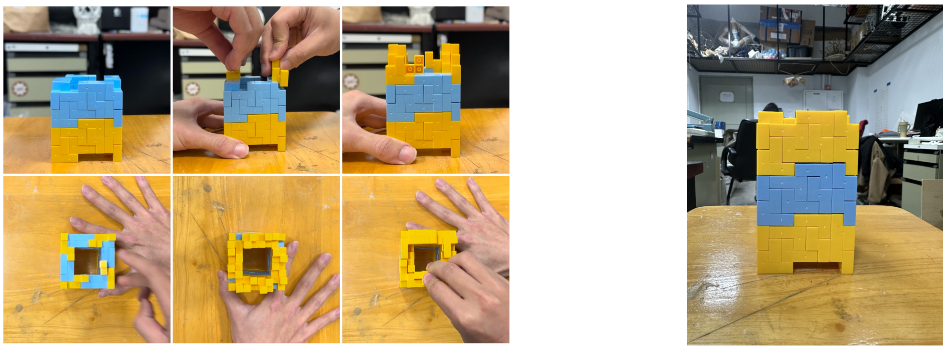
(a) Different void situation

(b) Placement with $\bar{y}$ which is a capping process from the previous process

Figure 5: Block placement situation The situation.

the robot will place the blocks it carries. The arrows show the conditions navigating to different states. During the scanning state ”S”, the robot knows if the placement leads to voids at either ”S” or ”L” parts, see figure 5a. Additionally, the translation ”y” is different from the others, which needs to assemble with the capping process in the previous layer, see Figure 5b.

Figure 6a illustrates the initial experimentation of duplicating SL Block assemblies, based on the shape rule defined in (3). In this experiment, the blue SL Chain serves as the first layer to be replicated by the robot. Following the FSMs diagram depicted in Figure 4, the robot strategically places blocks based on the evolving pattern. The outcome of this duplication process is presented in Figure 6b.



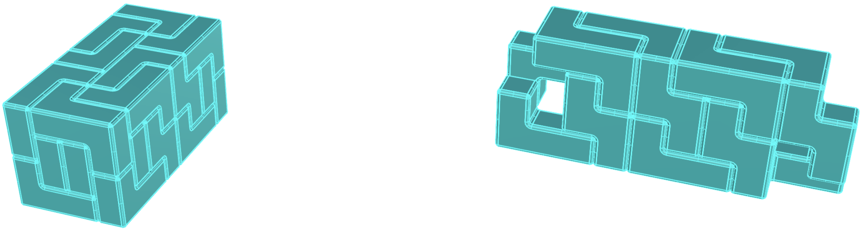
(a) (b)

Figure 6: Duplication experiment for creating SL Chain.

2.3. Stage Stabilisation

Planning for a collision-free path complexity can be enhanced by meticulously configuring the blocks into their correct positions. Tian et al. [13] employed a heuristic method, constructing a neural network to efficiently assemble complex shapes. In this section, two critical aspects is explored: sequence planning and physical feasibility, based on the degree of freedom (DOF). The DOF determines the approach to placing the blocks, with a closed chain having the potential to reduce the DOF, thereby leading to structural stabilization. This action primarily concerns the capping process, which completes the conjugated pair into an SL chain from the duplication process, except for $\bar{y}$. This capping process will secure the stability of the assemblies. The orthogonal directions specified in this paper include the x, y, and z axes, as well as their inverses.

In essence, the tolerance of each transformation for every chain is intricately linked to their Degree of Freedom (DOF). Consequently, the DOF not only influences the number of transformation actions required during assemblies but also serves as a determinant of stability and the likelihood of displacement. A class with fewer DOFs inherently embodies greater stability and a diminished probability of displacement. Moreover, the configuration of SL Blockchains, whether closed or open, also impacts the DOF. For instance, a closed chain (depicted in Figure 7a) yields a stable composition owing to its 0 DOF. Conversely, the start and end chains in an open chain scenario (illustrated in Figure 7b) may result in higher DOF, consequently diminishing stability. Notably, in an open chain setup, either the start or end chain must contain at least one DOF to accommodate the overall structure.

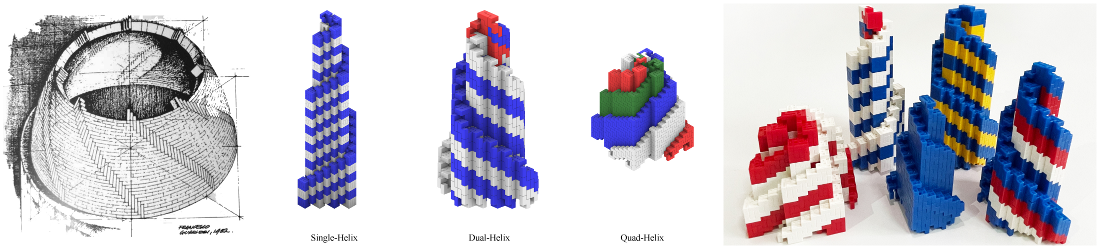


(a) Closed SL Chain (b) Open SL Chain

Figure 7: Stability of SL Chain based on DOF.

3. Case Study

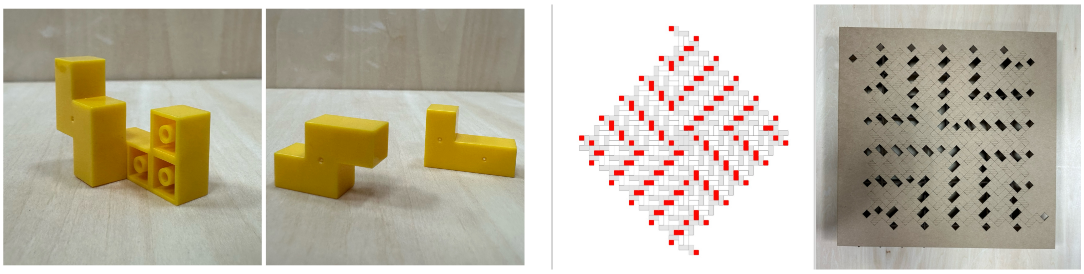
To delve into the potential of parallel construction with SL Blocks and showcase autonomous assembly, this section introduces double helix tower shapes inspired by M.C. Escher's Tower of Babel artwork and Brunelleschi's dome principle. These structures exemplify SL blocks seamlessly forming continuous spirals with varying lengths along the z-axis, resulting in captivating conical shapes with multiple layers. The first step involves conducting a computer simulation to define the grammar and semantics of the tower. The envisioned tower's form is intricately derived from the interweaving of *n*-numbered conical helix shapes, reminiscent of the architectural marvel observed in Filippo Brunelleschi's dome brick structure at the Duomo di Firenze, as illustrated in Figure 8a, as originally drawn by F. Gurrieri, 1982. Resulting from the simulation and adherence to predefined rules, Figure 8b visually illustrates the Babel Tower constructed from SL Blocks. Through the application of rules *h, y, a,* and *d*, a helical herringbone emerges, evoking the elegance of Brunelleschi's design. The figure also showcases the generation of single, double, and quad conical helices. Additionally, Figure 8c exhibits the experiment using small SL Blocks with a size of 5mm to assemble the tower.



(a) (b) (c)

Figure 8: Dual helix construction.

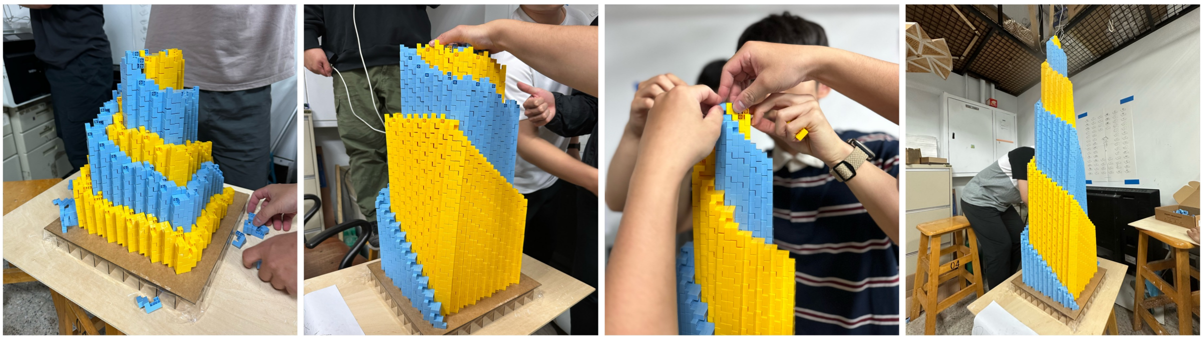
To simulate the parallel assemblies of SL Chains, we utilized real-scale SL Blocks. Figure 9a displays the SL Blocks used in this case study, comprising both S-shaped and L-shaped blocks. The design of the tower is depicted in the construction drawing (Figure 9b), serving as the base pattern for the robots to assemble. In order to achieve the tower construction, each ”robot” was assigned to know 4 rules: *h, y, a, d*, which can be repeated infinitely. The robots followed the pattern of the previous SL Block arrangement and attempted to determine the next placement based on local information.



(a) SL Blocks (b) Construction drawing and base layer

Figure 9: SL Block and Base layer pattern.

In this experimental setup, students are participate and tasked with embodying the roles of robots to undertake the construction of the Babel Tower. The construction endeavor is meticulously divided into four sides, with each ”robot” entrusted with the responsibility of a distinct side. Figure 10 illustrates the progress of parallel construction. Each ”robot” operates autonomously, relying solely on local information without any form of communication with others. The finite state illustrated on figure 4 is systematically applied to orchestrate the assembly of the tower. The pre-condition for duplication assemblies, which the robot adheres to, is based on the guidelines outlined in Figure 5a and Figure 5b.



(a) Babel tower construction progress.

(b) Screenshot from time-lapse video.

Figure 10: Parallel construction of Babel Tower.

Due to the inherent nature of the shape and rules guiding the construction process, the potential exists for the tower to be expanded or grown to an infinite height. However, for this experiment, our goal was to construct a tower reaching a height of 1,5 meters, as shown in Figure 10a. This required approximately 8200 units of SL blocks. Each participant had full control over their designated environment throughout the experiment, as depicted in Figure 10b, without causing disruption to others.

By employing parallel construction concept, participants were not dependent on each other's progress. This means that if one participant did not finish on time, others could continue their assemblies without waiting for completion by others. Nevertheless, using helix assembly methods introduced a potential drawback: variations in participants' speeds could cause delays since the SL Chain assembly is continuous. Specifically, if one participant failed to complete their assigned steps promptly, it could hinder others from starting or continuing their assembly process. However, despite this challenge, the use of SL Block assemblies offered significant advantages. By adhering to simple yet effective rules, participants could construct far more complex structures efficiently.

4. Conclusion

This research demonstrates the potential of parallel construction with SL Blocks to revolutionize construction processes and improve efficiency in erecting complex structures. Drawing inspiration from natural systems such as termite colonies and utilizing advanced computational frameworks like attributed grammar and finite state machines, a novel approach to autonomous construction is proposed. Through case studies of the Babel Tower, this research shows how SL Blocks can be assembled in parallel, mimicking the collaborative behavior found in nature. This method not only simplifies complexity and reduces information overhead but also offers opportunities for sustainable and cost-effective construction practices.In the long run, the use of SL Blocks as building material can reduce material costs since there is only one type of component. Furthermore, employing SL Blocks promotes reusability, as they can be assembled into dry stack structures.

However, it's important to note that this research primarily focuses on the theoretical concept of parallel assembly of SL Blocks, encompassing autonomous construction, duplication methods, and the stabilization of SL Chains to facilitate parallel construction. Future research endeavors could involve utilizing robots to assemble SL Blocks, further advancing the materialisation, practical implementation, and scalability of this innovative construction technique.

Acknowledgments

The study described in this paper is result of collaboration project supported by the Ministry Of Science and Technology, Taiwan, R.O.C. and German Academic Exchange Service, German, under project number 113-2927-I-011-503.

References

[1] J. Yarnold, S. Banihashemi, C. Lemckert, and H. Golizadeh, "Building and construction quality: Systematic literature review, thematic and gap analysis," *International Journal of Building Pathology and Adaptation*, vol. 41, no. 5, pp. 942–964, Nov. 24, 2023, ISSN: 2398-4708. DOI: `10.1108/IJBPA-05-2021-0072`. [Online]. Available: `https://www.emerald.com/insight/content/doi/10.1108/IJBPA-05-2021-0072/full/html` (visited on 12/12/2023).

[2] B. Xia and A. P. Chan, "Measuring complexity for building projects: A delphi study," *Engineering, Construction and Architectural Management*, vol. 19, no. 1, pp. 7–24, Jan. 6, 2012, ISSN: 0969-9988. DOI: `10.1108/09699981211192544`. [Online]. Available: `https://www.emerald.com/insight/content/doi/10.1108/09699981211192544/full/html` (visited on 12/12/2023).

[3] S.-G. Shih, "Advances in architectural geometry 2015 - on the hierarchical construction of SL blocks: A generative system that builds self-interlocking structures," in *Advance in Architetcural Geometry 2016*, vdf Hochschulverlag AG an der ETH Zürich, 2016, pp. 124–136. DOI: `10.3218/3778-4_10`. [Online]. Available: `https://vdf.ch/advances-in-architectural-geometry-2016-e-book.html` (visited on 12/12/2023).

[4] M. Esmaeili Charkhab, Y. Liu, B. Belousov, J. Peters, and O. Tessmann, "Designing for robotic (dis-)assembly," in *Advances in Architectural Geometry 2023*, K. Dörfler, J. Knippers, A. Menges, S. Parascho, H. Pottmann, and T. Wortmann, Eds., De Gruyter, Sep. 18, 2023, pp. 275–288, ISBN: 978-3-11-116268-3. DOI: `10.1515/9783111162683-021`. [Online]. Available: `https://www.degruyter.com/document/doi/10.1515/9783111162683-021/html` (visited on 12/13/2023).

[5] S.-G. Shih, "The art and mathematics of self-interlocking SL blocks," in *Bridges 2018 Conference*, Sweden, 2018, pp. 107–114.

[6] S.-G. Shih, C.-H. Yen, and L.-W. Chou, "Extensible structures of interlinking SL strands," in *Bridge 2019 Conference Proceedings*, 2019, pp. 415–418.

[7] S.-G. Shih, "Grammar of SL block construction," in *Bridge 2020 Conference Proceedings*, 2020, pp. 399–402. [Online]. Available: `https://m.archive.bridgesmathart.org/2020/bridges2020-399.pdf`.

[8] B. Wibranek, Y. Liu, N. Funk, B. Belousov, J. Peters, and O. Tessmann, "Reinforcement learning for sequential assembly of SL- blocks," presented at the The 39th eCAADe Conference, 2021.

[9] Y. Liu, B. Belousov, N. Funk, G. Chalvatzaki, J. Peters, and O. Tessmann, "Auto(mated)nomous assembly," in *Trends on Construction in the Digital Era*, A. Gomes Correia, M. Azenha, P. J. S. Cruz, P. Novais, and P. Pereira, Eds., vol. 306, Series Title: Lecture Notes in Civil Engineering, Cham: Springer International Publishing, 2023, pp. 167–181, ISBN: 978-3-031-20240-7 978-3-031-20241-4. DOI: `10.1007/978-3-031-20241-4_12`. [Online]. Available: `https://link.springer.com/10.1007/978-3-031-20241-4_12` (visited on 12/13/2023).

[10] Y. Hou and P. Loh, "TOWARDS SWARM CONSTRUCTION," in *Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2021*, vol. 1, Hong Kong, 2021, pp. 673–682.

[11] M. Dorigo, G. Theraulaz, and V. Trianni, "Swarm robotics: Past, present, and future [point of view]," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1152–1165, Jul. 2021, ISSN: 0018-9219, 1558-2256. DOI: `10.1109/JPROC.2021.3072740`. [Online]. Available: `https://ieeexplore.ieee.org/document/9460560/` (visited on 03/15/2024).

[12] Z. Zhang, Y. Li, and C. Li, "Modelling of collective construction in a minimalist robotic swarm," in *Advances in Computer Science, Environment, Ecoinformatics, and Education*, S. Lin and X. Huang, Eds., vol. 216, Series Title: Communications in Computer and Information Science, Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 385–391, ISBN: 978-3-642-23344-9 978-3-642-23345-6. DOI: `10.1007/978-3-642-23345-6_71`. [Online]. Available: `http://link.springer.com/10.1007/978-3-642-23345-6_71` (visited on 03/21/2024).

[13] Y. Tian *et al.*, "Asap: Automated sequence planning for complex robotic assembly with physical feasibility," *arXiv preprint arXiv:2309.16909*, 2023.