Intelligent Stone Masonry Robot for Sustainable Construction: Opportunities and Challenges

Qianqing Wang[1], Jingwen Wang[2], Bryan G. Pantoja-Rosero[3], Stefana Parascho[2], Katrin Beyer[1]

[1]Earthquake Engineering and Structural Dynamics Laboratory (EESD), EPFL, 1015 Lausanne, Switzerland
[2]Lab for Creative Computation (CRCL), EPFL, 1015 Lausanne, Switzerland
[3]Digital Intelligence for Structures and Construction Laboratory (DISC), Nanyang Technological University, Singapore

Abstract

Masonry construction, the assembly of discrete units into load-bearing structures, offers distinctive advantages for sustainable building: local material sourcing, adaptability to diverse resources, and reduced embodied carbon when using minimally processed materials. This review traces the evolution of robotic masonry from early bricklaying machines of the 1980s to emerging systems capable of assembling irregular natural stones. We identify three persistent challenges that have limited the adoption of bricklaying robots: sensing and feedback for error compensation, computational planning for design-to-fabrication translation, and economic viability given high setup costs. We then present robotic stone masonry construction as a sustainability-driven frontier, detailing recent advances in geometric planning, manipulation of irregular units, and multi-sensor feedback control that have achieved sub-4 cm placement tolerance. The review argues that the next phase of masonry robotics lies in extending automation beyond uniform manufactured units toward low-carbon, locally-sourced materials, a shift requiring integrated sensing, planning, and design capabilities.

Keywords –

Construction robotics; Robotic masonry; Stone assembly; Sustainable construction

1 Introduction

The construction industry faces an urgent need to reduce the carbon footprint. Masonry construction offers a distinctive response to the challenge. Unlike monolithic construction methods, masonry assembles discrete rigid units into load-bearing structures. This modularity confers high adaptability: the primary material can be sourced locally, enabling construction with reused waste materials [1] or natural resources such as unprocessed stone, earth, or bamboo with minimal processing [2], thereby reducing embodied carbon relative to manufactured alternatives.

The research on automating masonry construction can be dated back to the mid-1980s when Warszawski [3] provided one of the earliest systematic assessments of where robotics might be applied in building construction, identifying masonry as a high-priority domain alongside painting, plastering, and tiling. Due to its highly repetitive nature, masonry is one of the most compelling candidates for robotic automation. Yet despite four decades of research, robotic masonry remains rare on construction sites — a gap that reflects not only technical limitations but also economic, regulatory, and social barriers.

This narrative review traces the evolution of masonry robots from early bricklaying machines to emerging systems capable of assembling irregular natural materials. Studies were identified through Scopus using using the following query: TITLE-ABS-KEY ((masonry OR brick* OR stone* OR block*) AND (robot* OR automation) AND (construction OR building OR structure* OR wall*)). The selection prioritizes works before 2000 that established fundamental methods in bricklaying robots, and recent advances that illustrate the current frontier of stone masonry robots. Section 2 surveys the development of bricklaying robots and identifies three persistent challenges: sensing and feedback, computational planning, and economic viability. Section 3 examines robotic stone masonry as a sustainability-driven frontier that extends automation beyond uniform manufactured units. Section 4 concludes with open challenges and future directions.

2 Bricklaying Robots: Evolution and Challenges

The first wave of masonry robot development emerged in the mid-1980s. Slocum et al. [4] at MIT initiated a construction automation research program that produced Blockbot (illustrated in Figure 1), a manipulator-based system designed specifically for assembling cement block walls [5]. Blockbot demonstrated that a robotic arm could grip, transport, and place concrete masonry units with adequate positional accuracy. Similar efforts produced dedicated masonry machines that typically operated in fixed work cells, handled one unit type, and treated the bricklaying task as a purely geometric placement problem [6–9].

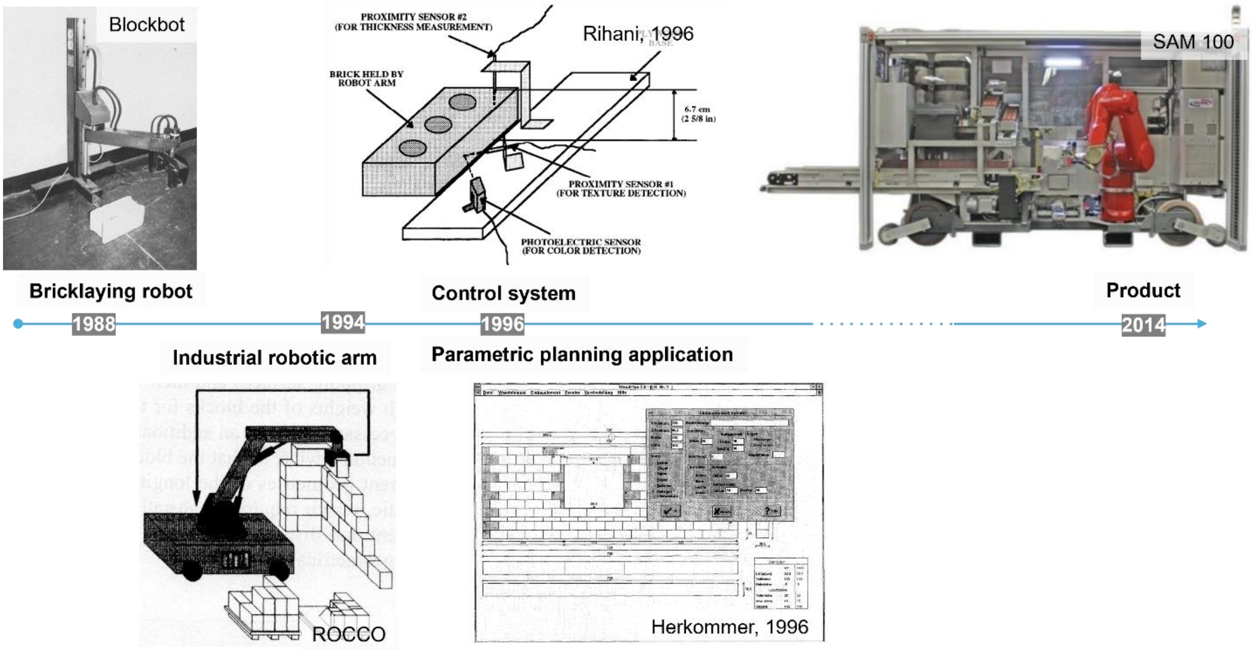

Figure 1 The emergence of bricklaying robot, the supporting system for control and planning, and one of the available products in today's market.

Shortly after, a second approach emerged. Rather than building specific machines only for bricklaying, researchers began adapting general-purpose industrial robot arms for construction assembly tasks. The most significant effort in this direction was the European ROCCO project (RObot assembly system for Computer-integrated COnstruction), which developed a large-range manipulator specifically for on-site masonry assembly [10, 11]. To increase the mobility of the industrial arm, mobile robot platforms combining a manipulator arm with a self-propelled base were developed, capable of navigating the construction site; accompanying control systems allowed the platform to localize itself relative to the building plan and to reposition as courses progressed [12, 13].

This generation of masonry robots demonstrated the mechanical feasibility of automating brick placement, while revealing the substantial gap between placing a single brick and building a wall.

The first challenge is that the as-built state of a masonry assembly inevitably diverges from the as-designed model due to unit dimensional variability, placement errors, and mortar deformation. The robot must detect and compensate for these divergences to avoid error accumulation. Rihani and Bernold [14] took an initial step toward closed-loop operation by integrating sensors for brick color detection and size measurement into a robotic masonry work cell. The ROCCO project incorporated fault tolerance into block assembly [10] and later adaptive control with fuzzy supervision to manage the imprecision of large hydraulic actuators [15].

The second challenge is the planning support that translates architectural design into block coordinates. Abdul-Sater and Delchambre [16] developed a computer-aided high-level planning system for masonry construction, while Herkommer and Bley [17] addressed the CAD/CAM pipeline for brickwork prefabrication.

The third challenge, which might pose the largest gap between research and practice, is economic viability. Warszawski and Rosenfeld [18] concluded that robotized construction becomes cost-effective only at high annual utilization (1,500–2,000 hours) and relatively high labor costs; at lower wages, automation increases total cost. Indirect activities — setup, repositioning, material transfer — can consume as much time as direct bricklaying, eroding the productivity gains that justify capital investment. The SAM100 illustrates this tension: while the system can place over 3,000 bricks per day under ideal conditions, case studies report setup times of several days and limitations on constructing long, straight walls, limiting realized gains on complex facades [19].

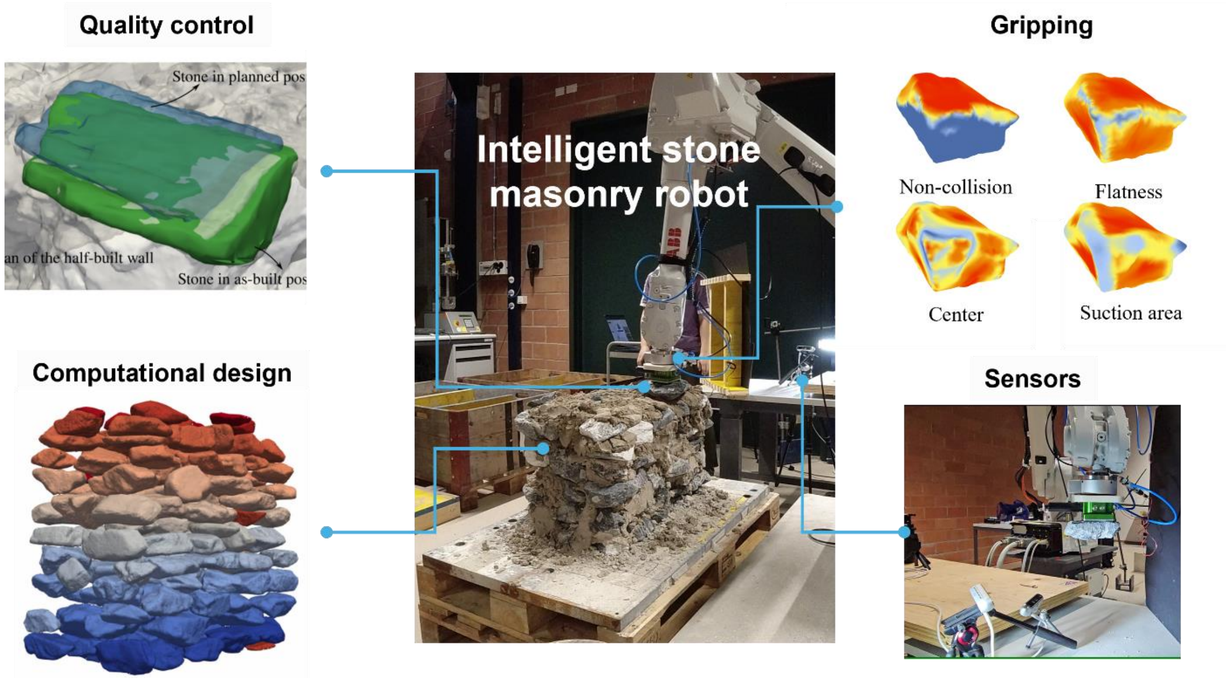

Figure 2 The intelligent stone masonry robot and the supporting system.

Despite these barriers to wide adoption of bricklaying robots, the rapid advancement of robotic sensing and planning provides new flexibility to extend masonry automation beyond standardized bricks toward irregular, locally-sourced, and low-carbon materials.

3 Stone Masonry Robots

Natural stone is among the most sustainable construction materials. Life cycle analysis of construction using concrete rubble has shown up to a 50% reduction in embodied carbon compared to brick masonry, as minimal energy is required for material processing [20]. This advantage also applies to construction with natural stones. However, the geometric irregularity of stones has long placed it beyond the reach of automated construction. Skilled masons navigate this irregularity through tacit knowledge accumulated over years of practice, knowledge passed through generations. Translating this craft intelligence into robotic capability poses challenges on multiple fronts.

Stone masonry is traditionally built from intuition without quantitative guidelines specifying how to select stones or how to place each unit. The skill depends highly on local resources; a mason with know-how in dry-stack construction may be unfamiliar with mortar techniques. Mathematical formulations that translate these ambiguous rules into coordinates for robot instruction are necessary, and ideally adaptable to a wide range of stone types. Planning algorithms that target for dry-stack stone masonry focus on maximizing the packing density while ensuring the stability of the structure [21, 22], while stacking with mortar-joint, local stability of single placement is of less concern, and algorithms can focus on maximizing the global resistance of the structure [23]. A common feature of these algorithms is that they all target for construction without scaffolding, creating a very different setting for the mathematical programming problem compared to bin packing. Initial experiments demonstrated that optimizing stone layout purely as a bin-packing problem — maximizing fill ratio — does not produce masonry typologies close to traditional craft work [24]. Encoding craft heuristics such as offsetting vertical joints and creating horizontal layers proves essential [25, 26]. Maximizing global behavior by changing microstructure is a challenging question for two reasons. The first is that the influence of microstructure of masonry on global behavior is still unclear. Therefore, such algorithms always depend on a physics simulation that can predict the performance of a plan, which is always the bottleneck in terms of computation time [23]. The second is that the space for searching the optimal solution is too vast, that expanded exponentially with the number of stones and the size of the structure.

Geometric planning for stone masonry extends beyond determining the coordinates of each unit. Manipulating stones in a stable and robust manner along the entire assembly trajectory requires appropriate gripping systems, such as suction-based or 2-finger gripper [22, 27]. Multi-metric optimization models can determine the most stable pick-up facet of a stone, while trajectory planning methods avoid collision with the as-built structure [27].

Quality control, already problematic in brick assembly [10], becomes more acute in stone construction due to irregular geometry, mortar deformation, and positional instability. Multi-sensor systems address this tolerance challenge: a camera system obtains the as-picked stone pose to update the planned trajectory in real time, while a scanning procedure after each layer captures the as-built structure and dynamically informs the layout of subsequent stones [27-29]. These methods have achieved a consistent tolerance of less than 4 cm between as-built and as-designed positions across approximately 10 layers of stones, as shown in Figure 3. Similar geometry updating strategy is employed in the framework of [22], where as-built geometry is obtained through laser-scanning instead of a camera system. The tolerance is the construction experiment is 0.1 m for building with rubble of volume of 0.3 m^3.

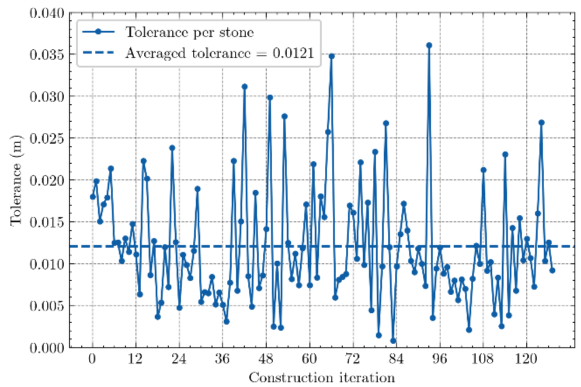

Figure 3 The evolution of stone placement tolerance as construction progresses in the stone masonry robot construction experiment in [27].

The autonomous excavator developed in [30] operates at 12–21 min per stone placement, which trails experienced excavator operators (11 min per stone). However, when it comes to building stonemasonry where the unit are manageable by masons, with an approximate speed of 1 minute per stone, they outperform stone masonry robot which requires up to 5 minutes to place one stone. However, this direct speed comparison understates the robot's economic advantages considering manual masonry faces a shrinking skilled workforce. Furthermore, the robot enables specific construction requirements such as complex nonplanar geometries, full digital twin documentation for lifecycle accountability, and construction in extreme environment such as lunar construction. Nevertheless, accelerating the current robot can position the system not merely as a niche solution for complex architectural applications but as a cost-competitive alternative for broad construction adoption.

Several limitations remain. Current systems operate in controlled laboratory settings; transferring to unstructured construction sites introduces challenges in localization, environmental variability, and human-robot coexistence. We note that our method requires adequate illumination primarily during the scanning phase for initial stone localization and pose estimation; the subsequent robotic construction process itself does not depend on continuous lighting conditions. Should on-site ambient lighting prove insufficient, the scanning subsystem can be readily substituted with LiDAR-based or structured-light depth sensing, which operate independently of natural light variability. Concerning workspace scale, two complementary pathways exist to address the limitations of our fixed, laboratory-scale setup: first, the robotic system can be mounted on a mobile platform (e.g., an autonomous ground vehicle or tracked carrier) to enable reconfiguration across large site footprints; second, for scenarios where on-site spatial or temporal constraints are prohibitive, the stone assembly workflow can be migrated to a prefabrication facility where modules are robotically assembled under controlled conditions and subsequently transported to the site for final installation.

The structural performance of robotically assembled stone walls, such as compressive strength, shear resistance, durability, has not yet been systematically compared with traditional manual construction. Although a uniaxial compression test of a robot-built wall has been carried out and the results show that the compressive strength is comparable to mason-built walls [27], this is far from enough to fill up the validation gap that impedes code acceptance of such stone masonry typology. Numerical simulations in [31] show that robot-built walls have slightly smaller initial stiffness and shear strength compared to mason-built walls, which highlight the necessity for structural validation of this new construction typology.

4 Conclusion

This review has traced the origin of masonry robots and revisited the emergence and evolution of bricklaying automation. By identifying technical bottlenecks and barriers for bricklaying robots, we argue that recent developments in robotics and computational design, combined with the urgent need for sustainable construction, create new opportunities for masonry robots that extend beyond bricklaying.

As a case study of how masonry robot development can respond to sustainability needs, we have presented recent work in robotic construction using unprocessed stones. By leveraging advances in computer vision, robotic planning, and computational design, these experiments demonstrate that an intelligent robot can assemble irregular stones autonomously with tolerance under control.

Two concrete findings emerge from this trajectory:

Stone masonry offers a sustainability-driven application where automation provides unique value — enabling construction with low-carbon, locally-sourced materials that would be impractical to assemble manually at scale.

The field is converging toward sensor-informed, design-integrated systems where feedback loops between as-built sensing and computational planning replace the open-loop execution of early bricklaying machines.

Several challenges remain open, including on-site adaptability, structural certification, and human-robot collaboration. These challenges span technical, regulatory, and social dimensions. The next phase of robotic masonry will likely be defined not by any single technical advance but by the integration of multiple capabilities into reliable, economically viable, and architecturally meaningful construction systems.

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