Earthen Construction: Integrating Robotics, Biomimetic Design, and Vernacular Knowledge

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Abstract. Earthen construction, rooted in vernacular traditions, offers numerous sustainability-related advantages. However, it faces challenges in contemporary adoption due to the intensity and complexity of manual labor. This research addresses the adaptation of automated construction methods to the non-standardized nature of earthen construction. It proposes the development of frameworks where robotic automation systems - including, but not limited to, humanoid platforms - informed by bionic principles and vernacular knowledge, enable the construction of earth-sheltered buildings and living roofs. The central hypothesis posits that while heterogeneous robotic systems can optimize for scale and force, the anthropomorphic morphology of humanoid platforms offers unique advantages in interacting with tools and techniques originally developed for human labor. As a result, the proposed methodology analyses vernacular precedents and biomimetic processes and suggests a research pipeline which evaluates a spectrum of robotic platforms and adaptive design strategies and simulation tools.

Keywords: Robotic Construction, Earthen Construction, Vernacular Architecture, Bionic Design, Robotic Fabrication

1 Introduction

Earth-Sheltered Constructions, with their “deep roots” in vernacular traditions, have demonstrated resilience and sustainability throughout history (Correia et al., 2014). Despite their undeniable environmental and energetic advantages (Nguyen et al., 2019), their contemporary adoption is significantly limited by the intensity and detail that manual labor requires. The complexity associated with the variability and lack of homogeneity of local natural materials, and the non-standardization of traditional techniques, represents a substantial obstacle to their integration into contemporary, larger-scale construction processes.

This research proposes to address the problem of adapting automated construction methods to the intrinsically diverse and non-uniform nature of this type of building. The central objective is to develop and evaluate frameworks in which robotic automation systems—with a particular focus on humanoid and heterogeneous platforms—guided by biomimetic principles (Yuan et al., 2017) and vernacular knowledge, can enable the construction of buildings with earthen envelopes. Our central hypothesis lies in the premise that diverse robotic systems can optimize for force and scale. Additionally, the anthropomorphic morphology of humanoid robots allows for a more intuitive interaction with tools and techniques designed for human action, while their growing sensorimotor capabilities enhance the effective manipulation of vernacular materials (Roychoudhury et al., 2023).

This approach aligns directly with the growing global industrial investment in the field of humanoid robotics (Tong et al., 2024) and, more broadly, with automation in construction (Regona et al., 2022), driven by significant advancements in actuation systems and artificial intelligence control. Its relevance lies in the development of adaptive construction solutions applicable to multiple scenarios. These include promoting sustainable community housing, creating emergency shelters in disaster scenarios, and buildings in extreme climates.

More ambitiously, the research could extend to construction in extraterrestrial habitats, where the use of In-Situ Resource Utilization (ISRU) is a fundamental requirement. In this sense, this research investigates the concept of 'meta-responsive' systems. These systems are characterized by human-robot collaboration (Liang et al., 2021) and robotic autonomy that dynamically adapt to diverse environmental and socioeconomic contexts, as well as to the inherent variability of construction materials and labor demands. Such adaptability is crucial for the successful application of robotics in unstructured environments, such as those found in construction with earthen envelopes.

2 Methodology

To address the complexity of automated construction in unstructured environments, this research proposes a multifaceted methodology that combines theoretical case studies, biomimetic inspiration, and a technological evaluation of both physical platforms (hardware) and control systems (software). The conceptual design framework is informed by two primary sources of knowledge. First, vernacular architecture precedents from diverse geographies are analyzed, including the subterranean dwellings of China and the Middle East, and the inhabited caves of Europe. However, the study delves deeper into the paradigmatic case of the Musgum mudhuts of Cameroon, deconstructing their structural logic, material efficiency, and passive climate strategies.

Second, biomimetic processes are observed (Andréen & Goidea, 2022), studying constructive solutions where other living beings have solved analogous challenges of resource optimization and environmental resilience. Paradigmatic examples include the form and material processing of the Rufous Hornero's nest (*Furnarius rufus*), the thermo-structural optimization observable in termite mounds (*Macrotermes*), and the geothermal insulation strategies of mammal burrows.

The feasibility of physical implementation is assessed through a systematic comparative analysis of robotic platforms, covering a spectrum that includes industrial robots, autonomous mobile systems, and, with special detail, humanoid robots. Concurrently, the construction process is explored in a digital simulation ecosystem. The proposed pipeline, inspired by existing methodologies, such as the combination of machine learning with simulations in Unity for bricklaying by drones (Mutis et al., 2024) focuses on the specific challenge of this project. It adapts these technologies to simulate the assembly of compressed earth blocks (CEB) by humanoid robots, replicating the catenary geometry and beehive type of the Musgum domes. To this end, the methodology proposes the integration of specific software for the adaptation and structural validation of the generated models.

3 Results

The results of this research are organized into three interconnected domains of analysis that, together, establish a path from theoretical principles to the feasibility of their practical application: (1) design principles extracted from biomimetic and vernacular studies; (2) a comparative evaluation of software environments for simulation and control; and (3) a critical analysis of the state-of-the-art of robotic platforms that serve as potential execution agents.

3.1 Domain 1: Biomimetic Design and Vernacular Studies

The analysis of natural and vernacular precedents revealed a set of highly efficient material and energy construction strategies, which were deconstructed to inform the speculative robotic construction workflow.

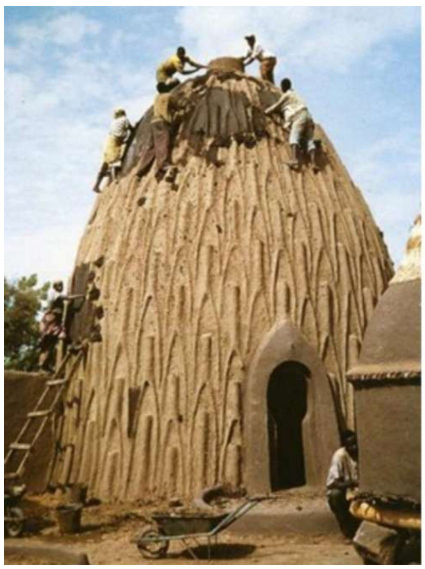
The first category of principles focuses on logistics and material processing, inspired by the Rufous Hornero bird (Furnarius rufus). It does not merely transport mud; it actively processes it, mixing it with organic binders and vegetable fibers to optimize its mechanical properties. This complex behavior, detailed by Hansell (2000), served as an inspirational model for robotic work. Research in additive manufacturing with cementitious and clay-based materials already explores how robots can actively control fiber orientation during extrusion, drastically increasing the final composite's tensile strength (Buswell et al., 2018). Analogously, a robotic system for earthen construction can be conceptualized to perform a "harvest-mix-deposit" cycle, where the robot not only processes the material but can also dose additives, using sensors to verify the mixture's consistency before application.

The second area, structural optimization and environmental control, found a paradigm of passive climate control in the termite mounds of the genus Macrotermes. Their external morphology, with complex networks of channels and chimneys, generates convection ventilation to regulate internal temperature and humidity, a phenomenon whose effectiveness was quantified by Turner (2001). This study served as the basis for generative design algorithms, where construction robots can later optimize a structure's shape in real-time to maximize natural ventilation.

The third line of investigation addresses terrain adaptation and the use of thermal mass, observing both the behavior of mammals and solutions from vernacular architecture. The fundamental strategy is the use of the soil's thermal inertia to create stable interior environments (Boyer & Grondzik, 1987). Notable examples of "subtractive" architecture include the Yaodong subterranean dwellings in China, carved into loess plateaus (Knapp, 1989), and the underground cities of Cappadocia, Turkey, which offered protection and thermal comfort to entire communities (Ousterhout, 2005). Similarly, the architecture of Matmata, Tunisia, cataloged by Rudofsky (1964), demonstrates an advanced excavation strategy around central courtyards, which function as lungs for ventilation and lighting. These precedents suggest a phased robotic construction approach: an initial excavation phase with a large autonomous robot, followed by the modeling of interior spaces by humanoid robots with greater dexterity.

As a culmination of these principles, the Musgum mudhuts of Cameroon represent a paradigmatic example of "additive" optimization. Analyzed by Mainstone (2001), their efficiency lies not only in the inverted catenary shape, which puts the structure to work almost exclusively in compression. An equally crucial aspect is their construction method: the huts are erected through the successive application of clay layers. Each thin layer has time to dry and gain strength before the next is applied, resulting in a laminated composite of high cohesion and resistance to deformation (Figure 1, left).

Inspired by this dual optimization—geometric and material—robots can be programmed not only to follow the catenary geometry but also to replicate the additive construction process, ensuring maximum structural efficiency, as the design case (Figure1, right) of a catenary dome made of compressed earth blocks (CEB) following similar geometry and material.



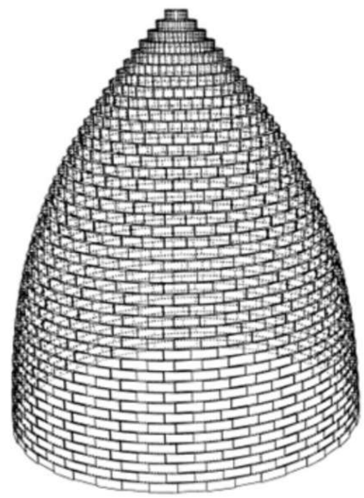


Figure 1. (left) Cases Obos, of the Musgum ethnic tribe. The profile of the structure is that of a catenary arc and with a relief pattern as a scaffolding. Source: www.eartharchitecture.org/?p=599. (right) Design case study of a catenary dome, made of CBE (source: authors).

3.2 Domain 2: Comparative Analysis of Simulation Software

As part of the research to define the speculative workflow, it was crucial to evaluate software tools capable of modeling the complex physics of robot-environment interaction and the behavior of non-uniform materials. A single-software approach proved insufficient, leading to the conclusion that a pipeline of complementary tools is the most effective approach, as also suggested by literature reviews such as Collins et al. (2021). These software tools support different stages of the project, from early conceptualization (form optimization and environmental analysis) to data generation and vision training in synthetic environments, followed by robot-control validation and final structural verification. The tools are chosen based on the specific needs of each phase, helping to refine and validate designs through simulation before real-world implementation. The following table summarizes different software categories and their strategic function in the proposed pipeline. It provides a comparative analysis, focusing on their advantages, limitations, and strategic roles. In Phase 0, parametric design plugins like Kangaroo and Ladybug optimize form and validate environmental performance but lack integration with robotic control. Game engines, such as Unreal Engine and Unity, are key in Phase 1 for real-time data generation and computer vision validation, but offer low physical fidelity. High-fidelity simulators like NVIDIA Isaac Sim play a crucial role in Phase 2 for validating robot-material interaction and control algorithms, although they demand high computational power. In Phase 3, structural analysis software like Abaqus and LS-DYNA ensure the structural integrity of designs using finite element analysis, though they are offline tools with no real-time capabilities.

Table 1. Comparative Analysis of Simulation Environments and their Function in the Research Pipeline (Phase 0 to 3)

Software Category (Examples)	Focus and Key Advantages	Limitations and Inherent Trade-offs	Strategic Role in Pipeline
Parametric Design Plugins *(Rhino/Grasshopper: Kangaroo, Ladybug)*	**Kangaroo:** Interactive physics-based form-finding; optimization of structural geometries (catenaries). **Ladybug:** Validated environmental and climate analysis (solar radiation, thermal comfort).	Not robotic simulators (no kinematics or robot control). Analyses are specific (physics vs. environmental) and not integrated into a unified physics engine.	**Phase 0: Form Optimization and Environmental Validation.** **Kangaroo:** Used in the conceptual phase to generate the structurally efficient geometry. **Ladybug:** Used to validate the design's passive and climatic performance.
Game Engines *(Unreal Engine, Unity)*	**Real-time Visualization and Interaction** •Photorealistic rendering for synthetic data. •Vast library of assets and plugins.	**Low Physical Fidelity** •Physics simulation optimized for speed, not scientific rigor. •Unsuitable for deformable materials.	**Phase 1: Data Generation and Perception Validation.** Used to train and validate the robot's computer vision algorithms.

High-Fidelity Simulators *(NVIDIA Isaac Sim)*	**GPU-Accelerated Physical Accuracy** • Robust physics (PhysX 5) for granular materials (**NVIDIA, 2023**). • Native support for ROS/ROS2.	**High Computational Demand** • Requires powerful NVIDIA hardware. • Steep learning curve.	**Phase 2: Control and Interaction Validation.** Primary tool for simulating robot-material interaction and validating control algorithms.
Structural Analysis Software *(Abaqus, LS-DYNA)*	**Maximum Structural Accuracy (Offline)** • Finite Element Analysis (FEA), the gold standard for structural validation.	**Not Real-Time** • Designed for analysis, not for robotic control or sensor simulation.	**Phase 3: Final Structural Validation.** Used offline to verify the integrity and load-bearing capacity of the generated architectural artifacts.

3.3 Domain 3: Comparison of Robotic Platforms and State of the Art

The physical feasibility of the project depends on the capabilities of robotic platforms. Although the analysis concludes that the most promising short-term approach is a collaborative multi-robot system (Burden et al., 2022), the hypothesis of focusing on humanoid robots is strategically justified by the recent explosion of investment and development in this sector. Until a few years ago, humanoids were mostly academic research prototypes. Today, we are witnessing an industrial race led by tech giants (Tesla, Samsung, Xiaomi) and well-funded startups (Figure AI, Sanctuary AI, Apptronik), which promise to scale production and drastically reduce costs (Tong et al., 2024). This transition from niche to mass market makes research on their application in construction not just speculative, but predictive, anticipating their future availability and economic viability.

Despite this focus, a pragmatic approach recognizes that automation in construction will most likely be heterogeneous. Companies like Monumental AI already demonstrate the effectiveness of specialized (non-humanoid) robots for repetitive tasks like masonry, achieving high precision and speed. Their approach, however, is optimized for a single type of task and material (standardized bricks). The challenge this research addresses is the manipulation of non-uniform materials (like CEBs) in complex geometries (like catenaries), where the dexterity and adaptability of a humanoid can offer advantages.

Managing this complexity on the job site highlights the importance of a robust operating system. The vision of companies like Atrium, which is developing an "Operating System for Software-Defined Construction", is crucial. Their goal is to create a unified framework that can manage and coordinate different types of robots (humanoids, cranes, autonomous vehicles) and integrate data from sensors and BIM models in real-time. It is within this software ecosystem that the specialization of each robot can be maximized.

Figure 2. Diverse humanoid robotic platforms in action, including Tesla Optimus, Figure01, and Apptronik Apollo. These advanced systems are actively being developed to master complex manipulation and interaction tasks, often leveraging learning paradigms such as imitation learning and reinforcement learning, which are critical for their application in unstructured environments like construction sites. (Source: authors' compilation from public video data).

In this context, the analysis of individual platforms serves to map their potential functions within a future collaborative job site. The following table summarizes the characteristics of the main platforms analyzed.

Table 2. Characteristics of the Main Platforms Analyzed, based on the State of the Art in mid-2025.

Platform	Developer	Primary Focus / Distinctive Capability	Current Status (June 2025)	Implications for Construction
Atlas	Boston Dynamics	Dynamic locomotion,	All-electric version presented;	Ideal for brute-force tasks and navigation

		strength, and balance on complex terrain.	advanced research platform.	on unstructured job sites.
Optimus	Tesla	Manual dexterity, large-scale AI integration, production scalability.	Gen 2 prototypes tested in assembly line tasks.	Potential for fine manipulation and assembly, if cost competitive.
Figure 01/02	Figure AI	Advanced manual dexterity, rapid learning for industrial tasks.	Pilot program with BMW underway but surrounded by controversy.	Focused on replacing manual labor; its real effectiveness is yet to be demonstrated.
4NE-1	Neura Robotics	Cognitive perception, haptic and force feedback, safety in interaction.	Focused on "sense and manipulate" applications (quality control).	Crucial for quality control of natural materials.
H1	Unitree	Agility, speed, and relatively low cost.	Commercialized as an agile RD platform.	Excellent for on-site logistics and visual inspection.
AEON	Hexagon AB	Industrial precision, robustness, 24/7 operation, and spatial awareness.	Pilot programs with industry leaders; commercial launch expected.	Represents the new generation of industrial humanoids (measurement, assembly).

4 Discussion

By leveraging the adaptability of robotic systems and AI control, informed by biological and traditional construction strategies, this work explores a potential shift towards construction processes, more symbiotic with diverse terrestrial biomes. The proposed methodology, which begins with the analysis of precedents like the Musgum mud huts and termite mounds, establishes a conceptual framework for developing robotic construction workflows. The technological analysis confirmed that while no single hardware or software solution exists, an integrated pipeline—using parametric design tools for form optimization, high-fidelity simulators for physical interaction validation, and structural analysis software to ensure safety—is a viable and effective methodological approach.

The strategic bet on humanoid robots, contextualized by their growing industrial prominence and the vision of unified operating systems for construction, such as that proposed by Atrium, positions this research at the forefront of innovation. It is recognized that the most pragmatic short-term approach will be heterogeneous, combining the strength of specialized machines with the adaptive dexterity of humanoids.

Figure 3. Hypothetical scenarios depicting constructions executed by collaborative humanoid robots capable of developing mostly compressive, self-supporting structures based on ancestral techniques and technologies using minimally processed, locally sourced, low-environmental-impact materials. Photomontage software and stable diffusion technologies were employed. (source: authors).

In conclusion, this work presents a rigorous speculative framework that opens new paths for autonomous construction, aligned with the principles of Industry 4.0. Its applicability extends from local and ecological housing solutions to the challenges of construction in extreme environments, on Earth and beyond, contributing significantly to the evolution of architecture in symbiosis with its human-robot inhabitants and the surrounding contextual life.

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