Impact printed structures : design systems and construction strategies

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IMPACT PRINTED STRUCTURES

DESIGN SYSTEMS AND CONSTRUCTION STRATEGIES

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Introduction

The construction industry contributes significantly to environmental degradation through pollution, waste generation, and climbing greenhouse gas emissions, prompting the exploration of alternative materials with lighter environmental impact. The use of earth as a building material has been common in construction for centuries, offering advantages like high thermal inertia, moisture regulation, fire resistance, and acoustic insulation, which are ideally suited for construction. However, most traditional earth-building methods are formwork-dependent and labour-intensive, resulting in slow build rates and high costs. These shortcomings present a significant opportunity to leverage novel digital construction techniques for non-standard but sustainable materials such as raw earth.

To address these challenges, this research presents the design and construction potentials of a novel robotic earth-building technique called ‘impact printing’ (IP). The robotic building process resembles a ‘shooting’ process from a close range, where discrete malleable parts of the material are deposited at controlled high velocities and frequencies by a custom mechanism, resulting in monolithic material structures. Like traditional adobe or cob construction, the IP process utilises a custom material mix in a plastic state that gradually gains mechanical strength as it dries. A custom low-carbon earth-based material is developed for the IP process using minimal hydraulic binders. This development aims to enhance and control the curing rate and boost the compressive strength of the structure. The high-payload IP mechanism is mounted on a bridge-like superstructure controlled by a 3-axis gantry. This configuration facilitates a free unrestricted movement of the mechanism in Cartesian space, achieved through the synchronous control of two external axes within a multi-axis robotic gantry system.

The paper outlines a set of computational tools and construction strategies necessary to effectively use the IP process. The use of these methods is demonstrated through the design and fabrication of customised building components, such as columns and walls featuring architectural elements like doors and windows. In summary, the research presents the IP process as a viable solution for sustainable digital construction, facilitating the industrialisation of earth-based construction and fostering innovative design opportunities.


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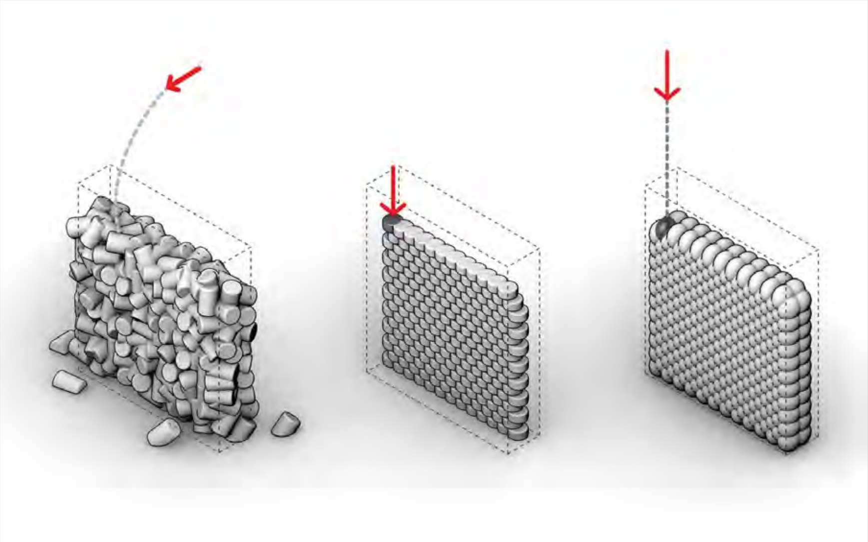
Impact printed structures

The construction sector holds a global reputation for its negative environmental impact and wasteful practices, primarily from the extraction and processing of building materials (Çetin *et al.*, 2021). The construction sector faces further criticism for its consistently low annual productivity, largely attributed to the conservative nature of the sector and the slow adoption of digital technologies (McKinsey, 2017).

Adopting additive manufacturing (AM) techniques in the construction industry is geared towards digitising construction sites and enhancing material and production efficiency, with concrete being the most commonly used material. However, the material mixes used for 3D concrete printing (3DCP) leave a higher carbon footprint and have reduced durability compared with standard reinforced concrete construction (Flatt and Wangler, 2022). In parallel with 3DCP developments, the past decade has seen a growing interest in processing sustainable materials with digital manufacturing techniques, including raw earth. Raw earth has been used as a building material for centuries because of its abundant availability and, thus, is cheaper at cost. In addition, earth has been used for construction with local knowledge and requires minimal manufacturing energy. But the reliance on manual labour and the necessity of formwork in most earth-building methods contribute to a slow and costly construction process. Even traditional earth buildings tend to be slow and over-priced.

Contemporary research has concentrated on modernising traditional building techniques to improve efficiency and economic feasibility. Notable examples include Gramazio Kohler Research's digitisation of cob construction in the Clay Rotunda (Gramazio Kohler Research, 2021), Technical University of Braunschweig's implementation of the robotic rammed earth process (TU Braunschweig, 2022), the endeavours of organisations like World's Advanced Saving Project (WASP), the Institute for Advanced Architecture of Catalonia (IAAC), and Emerging Object in integrating extruded earth methods (WASP, 2021; Dubor *et al.*, 2019; San Fratello *et al.*, 2020), and Mudd Architects' adaptation of the wattle and daub technique in the Mud Shell project (Mudd Architects, 2019).

When adapting extrusion 3D printing for earth-based materials, the process tends to be slower and necessitates a high percentage of mineral-based stabilisers such as lime or cement, which offsets some of the environmental advantages. As a result, there exists a trade-off between construction efficiency and environmental impact. Hence, there is a need to explore alternative digital techniques and AM methods, specifically for dense earth materials, that offer improved efficiency, reduced reliance on additives, and cost-effectiveness.



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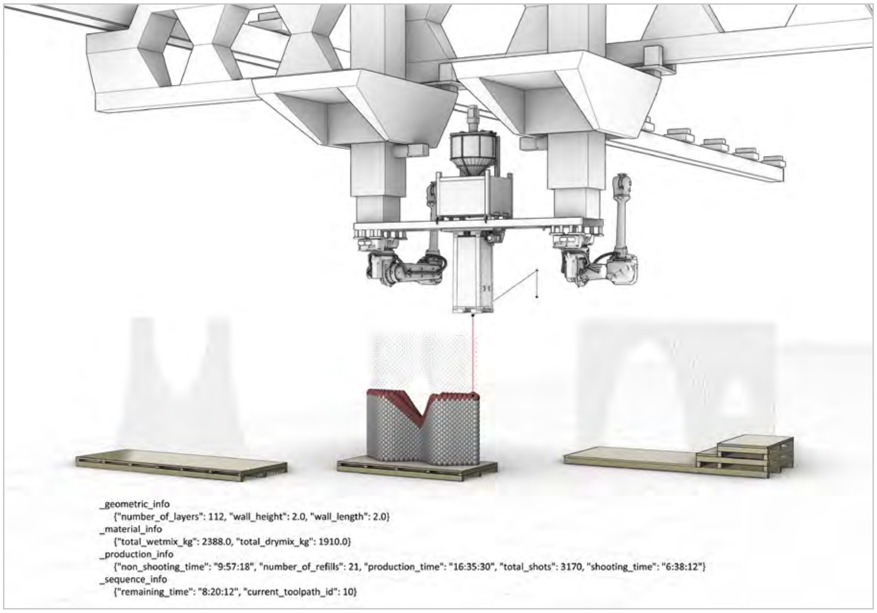
A novel robotic earth-building method

IP is a novel AM process that deposits discrete portions of malleable material at high velocities to improve interlayer bonding and compaction without formwork. This paper presents the progression and upscaling of IP for one-storey volumetric structures (Ming *et al.*, 2022), building on the precedent research of Remote Material Deposition (RMD) (Dörfler *et al.*, 2014) and the Clay Rotunda project. RMD introduced a 'throwing' method with extended reachability but limited control and longer cycle times. In contrast, Clay Rotunda employed a 'pressing' technique for precise deposition control but limited by operational constraints and slowness, mainly caused by the time taken by the robot to move between the prefabricated earthen parts and their intended positions. Additionally, both methods involved using cylindrical earthen parts for deposition, which had to be prefabricated off site, thus adding transportation costs to the production process. These constraints pose challenges for scaling up these processes for commercial applications.

Synthesising the two previously mentioned technologies, IP uses a short-range remote deposition process of 'shooting' at high velocities and frequencies. The process holds the potential for efficient volumetric build-up due to the compaction achieved on impact. While the approach has successfully produced continuous construction of

1. Full-scale prototypes of *Impact Printed Structures*, fabricated at the Robotic Fabrication Lab at ETH Zürich, using a custom end-effector mounted on two gantries programmed for synchronous operation. © Michael Lyrenmann, ETH Zürich.

2. Illustration showing high-level concepts of precedent and current techniques at Gramazio Kohler Research used to fabricate with discrete malleable earth parts: (a) 'throwing' technique used during Remote Material Deposition in 2014, (b) 'pressing' technique used during Clay Rotunda in 2021, and (c) 'shooting' technique currently investigated during *Impact Printed Structures*. © Kunaljit Chadha, ETH Zürich.



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3. Screen capture of the design and planning environment displaying the construction date in the bottom left corner and highlighting the construction sequence presently followed in the fabrication setup. © Kunaljit Chadha, ETH Zürich.

vertical structures up to 1.5m high, further testing is required to fully validate the potential of the IP process for volumetric and customisable construction.

IP was developed as an AM method that can be adapted for off-site pre-fabrication, on-site pre-fabrication, and in-situ monolithic construction. The presented work is an outcome of ongoing research on the design and construction potentials of the IP process in a pre-fabrication context. The subsequent phase will involve transitioning to on-site testing in a less structured environment, utilising the autonomous excavator created by the Robotic Systems Lab at ETH Zürich (Jud *et al.*, 2021). Thus, the custom IP mechanism was developed and integrated to be compatible with high-payload gantry systems and autonomous construction machines.

In the presented work, the IP mechanism consisting of extrusion, portioning, and shooting sub-systems arranged in a vertical stack is mounted on a bridge-like structure to distribute the payload between two external axes. The IP mechanism can be manoeuvred freely in Cartesian space with a fixed orientation by synchronous control of two external axes of a multi-axis robotic gantry system in the Robotic Fabrication Lab (RFL) at ETH Zürich. Currently, the tool can extrude parts weighing between 0.75kg and 0.8kg at an average cycle time of 7.5 seconds.

The software architecture consists of four communicating modules: a CAD design and planning environment, a tool-controller PLC, a robot controller, and a high-level controller with a Linux PC to synchronise all processes. To design and visualise architectural structures, a custom design library is developed using the RhinoCommon library, with Rhino serving as the CAD planning environment. Individual toolpaths containing building sequences are sent directly to the high-level controller using COMPAS FAB (Casas *et al.*, 2023) with necessary position and timing information. The high-level controller then communicates at high frequencies with both the robot controller and the tool-controller PLC to synchronise the dispatching of the parts at planned target positions.

The IP method uses a batch-mixing process for material processing, where premixed material is manually fed to a screw-based extrusion system. In this context, the critical factor regarding the material state is the yield stress, representing a material's ability to endure stress before permanent deformation (Coussot, 2014). In contrast to extrusion-based methods, IP allows for plastic deformation upon impact, meaning that the material, in its malleable state, must endure both forces due to impact and cumulative weight. Hence, through empirical testing, the initial yield stress of the material for the IP process is calibrated between 26 and 28kPa. In traditional methods, like cob construction, the material contains fine particles (<63µm) with clay at 15 to 20% of the total mix. To adapt a comparable mix for the IP process, adjustments are made to increase the content of fine particles, enhancing the internal cohesion of the material. This modified material mix was developed in collaboration with the Chair of Sustainable Construction at ETH, utilising locally sourced materials rich in fine particles such as clay and silt. By employing a material mix with reduced water content and incorporating as little as 2.5wt% of commercial hydraulic lime, the objective is to expedite early strength development for the IP process.

Design challenges of building with earth

Earth construction inherently presents many design and construction challenges due to the malleable and variable nature of the material. Earth structures typically take a long time to dry, and there is a tendency for uneven shrinkage, leading to issues like building tolerances, cracking, and structural failures under varying environmental conditions. This unpredictability hinders the design process and limits the range of design possibilities in both traditional and automated methods. Additional challenges involve maintaining structural stability during construction and preventing cold joints. Structural failures such as plastic deformation, layer delamination, and global buckling must be considered and mitigated during construction. Beyond the construction phase, regular repairs and maintenance are key topics in constructing durable structures out of earth. These challenges present an excellent opportunity to address the issues by re-evaluating the materials used and exploring new and inventive construction methods.

The unique IP process poses additional distinct challenges as compared to other AM techniques. For extrusion-based 3D printing, plastic failures due to self-weight are mitigated by modifying and increasing the early strength development of the material. In contrast, with IP, the load cases experienced during construction include both self-weight and impact forces. Consequently, IP necessitates suitable computational design methods and construction strategies that align with the production method and the unique load cases during construction. Preliminary tests have suggested that the combination of the higher yield stress at which parts are deposited, and the high-velocity deposition of the IP process enables higher stable volumetric build-up compared with other AM methods, particularly conventional extrusion-based printing. The printing efficiency in terms of volume per time has to be further investigated and optimised.

To demonstrate the potential of IP as a building method, a series of prototypes are built that focus on designing and fabricating customised load-bearing building components, such as columns and walls featuring architectural features like doors and windows. The design and fabrication processes were implemented and evaluated within the context of a semester-long course offered in the Master of Advanced Studies in Digital Fabrication (MAS DFAB) programme at ETH Zürich.

Computational design system

When designing with the IP process, a primary challenge lies in breaking down the intended volumetric construction into discrete components that must be deposited in specific sequences. Unlike traditional brick stacking, these discrete parts are malleable in state and take on an elliptical shape due to the compaction process before deposition. Their deformation is additionally influenced by factors like the material's yield stress, deposition velocity, and the positioning of neighbouring parts; thus, the spacing between the parts must be precisely planned to avoid undesirable and uncontrolled vertical build-up. It is also crucial to computationally handle the spacing of the parts in subsequent layers to prevent them from dislodging or bouncing off previous layers as a consequence of the impact of the deposition process.

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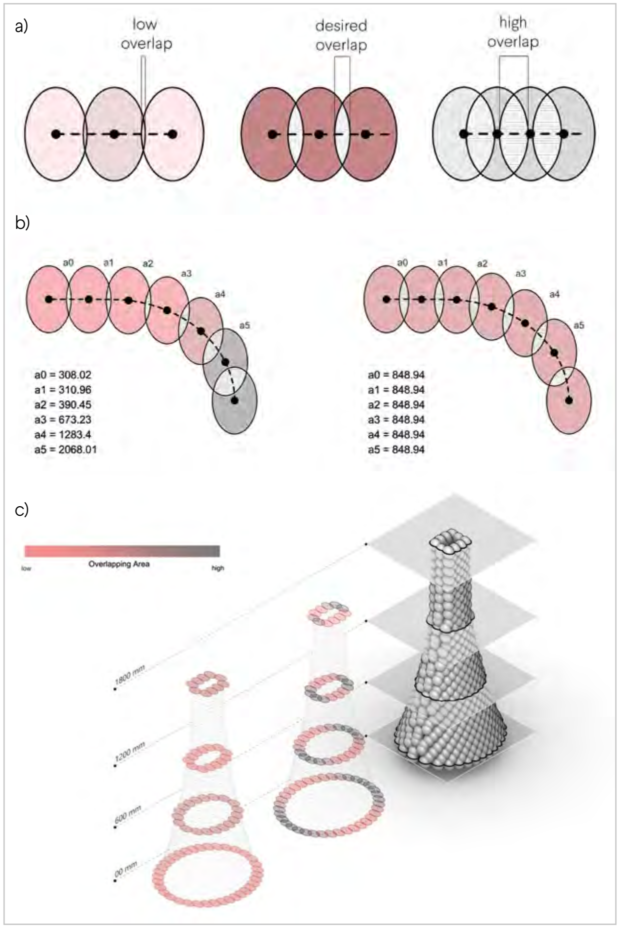
4. Results of successful design and fabrication of novel wall and tapered column structure combinations incorporating timber elements. The earth and timber combination achieves a levelled surface suitable for potential use in flooring or roofing applications. © Michael Lyrenmann, ETH Zürich.



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5. (a) Spacing logic to visualise overlapping areas between successive parts, (b) a comparison of part distribution along a curved toolpath between spacing by distance and iterative spacing, and (c) planar sections demonstrating the effective application of iterative spacing for a tapered column with varying toolpath lengths across different layers. © Kunaljit Chadha, ETH Zürich.

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An object-oriented library and a set of computational tools are developed to generate valid impact printed designs. These tools consider the constraints from the fabrication setup, specifically collision, and manage the generation of discrete parts and building sequences. The developed computational tools also allow the previewing of construction sequences and outputs of construction data for planning production logistics.

To deal with the complexities of the IP process, computational methods are devised to achieve uniform part distribution along the deposition toolpath for diverse geometric conditions, including variable curvature and thickness. An algorithm initially distributes parts equidistantly along the toolpath, then iteratively refines the spacing until a consistent overlap area is achieved. This method enables the design of IP structures featuring higher degrees of curvature and variable toolpath lengths to enable formal variants like tapered columns. Addressing the spacing of parts in subsequent layers, a diagrid sequencing strategy is developed to ensure an alternating deposition pattern in these layers. This strategy ensures the consistent deposition of each part within the voids between parts on previous layers, thereby preventing any dislodging.

The fabrication of impact printed structures presents challenges due to the time-sensitive nature of material curing. This necessitates careful coordination between all fabrication process parameters, including material mixing, feeding timing, and machine capacity. Hence, planning tools are needed to integrate these process constraints into design and production planning. To facilitate this, a computational planning tool generates building sequences and outputs construction data. At present, the fabrication setup uses an automated batch-mixing approach, which needs timely refilling. Therefore, the intended structure is divided into individual toolpaths, each containing 50 parts, aligning with the prevailing material capacity of the extruder. The construction data provides quantitative insights into production, including parameters such as the total number of parts, material quantities for mixing, and predicted deposition time for each sequence. This tool enables users to make informed decisions while planning material mixing schedules, allowing for the parallelisation of tasks to minimise machine downtime.

In contrast to layer-based 3D printing, where the extrusion nozzle is in contact with the printed structure, raising the possibility of collisions while embedding external elements, the non-contact process of IP allows for discrete and non-planar sequencing for construction. This approach allows for the integration of functional architectural elements into structures during the construction process. Successful tests have been conducted, depositing material from heights ranging between 0.2 and 2.0m above the intended parts. To explore this potential further, a series of prototypes feature geometrically non-standard architectural openings that effectively function as doors and windows. Embedded timber frames are placed and pushed into position during the IP sequences to achieve

6. Image of a three-layered structure with an integrated arch opening during construction, illustrating even distribution of parts along a curved toolpath. © Nijat Mahamaliyev, ETH Zürich.

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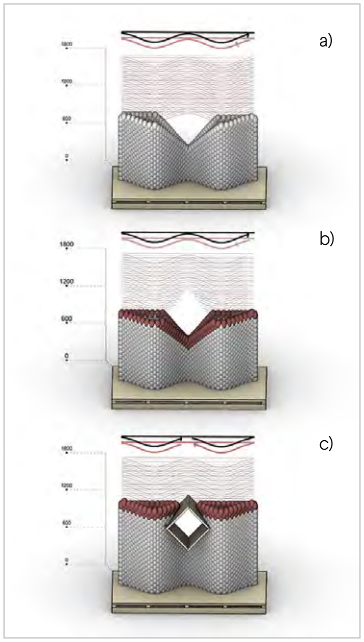

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integrated elements. The vertical tool offset distance is adjusted to prevent the tool from colliding with the frame. With the possibility of building with a non-planar sequence, strategies are developed to selectively deposit a fresh layer of material underneath the embedded frame, preventing the occurrence of dry joints in the structure.

Additionally, within the computational framework, each part is assigned a unique identifying number (UID) and stored to log the success of deposition. Together with the online communication with the fabrication setup, the UIDs allow for dynamic regeneration of the construction sequencing at the last successful shot location in cases of fabrication error.

Construction strategies

Overall stability is an important consideration in the IP process, during both the building and curing phases. With deposition velocities as high as 9.5-10.0m/s, the resulting impact force can be estimated to be more than a hundred times the self-weight of a single part. Therefore, it becomes imperative to implement temporary stabilisation measures to withstand live loads during construction, preventing potential snags like global buckling and overturning failures. Furthermore, building components, such as timber frames, integrated into the construction process must be temporarily stabilised and kept steady until the material has cured to avoid uncontrolled displacement.

To address these concerns, three distinct strategies, to ensure the stability of the structure and prevent deformation and structural failures during construction due to the impact force of material deposition and the weight of the material, are developed and tested. These strategies comprise: a) edge constraints, where supports constrain the edges of the structure to ensure consistent build-up, b) removable infills using loose aggregates as temporary internal supports for creating overhanging sections, and c) adjustable props to provide temporary stabilisation for embedded elements forming openings, which are removed once the construction material has sufficiently cured.

Shrinkage is a long-drawn-out issue with earthen construction, as it involves using a material mix that requires adding water to form a workable compound for construction. This leads to uneven deformations in the structure and cracking during curing, arising from ambient conditions and local stress concentrations. Two distinct construction strategies are developed to address the challenge of shrinkage within the IP process. The first approach focuses on controlling cracking and involves deliberately designing gaps or high-stress concentrations in strategic locations of the structure to induce the formation of cracks that can be manually repaired. This approach minimises the probability of unexpected cracks and enhances the overall reliability of the construction process. The second approach is native to the IP process, and tackles the cracking caused by the impact forces upon externally embedded building

7. Results from the successful prototyping of a double-layered wall with a diamond-shaped opening displaying the use of non-planar sequencing. © Michael Lyrenmann, ETH Zürich.

8. This involves (a) non-planar sequencing to direct the placement of the frame, (b) adding an extra layer to ensure a fresh material is deposited beneath the embedded timber frame for the opening, and (c) a customised order of deposition, starting from the outside and moving inwards to stabilise the frame. © Kunaljit Chadha, ETH Zürich.

9. Temporary props stabilising the frame during the IP process. Right: Employing a formative process to ensure the evenness of the upper surface of the columns prior to the installation of the roofing element. © Kunaljit Chadha, ETH Zürich.

components. The approach focuses on mitigating the cracks by embedding rigid timber elements within the structure during construction. These elements are strategically placed along the length of the toolpath to ensure an even distribution of impact forces, thereby addressing the problem of cracking induced by the impact force of the parts.

Conclusion and outlook

In sum, the IP process adds to the enduring tradition of building with earthen materials. It presents a low-cost, waste-free building method that incorporates high levels of design control while using local materials with low environmental impact. The presented work underscores the pivotal role of computational design and building strategies in employing IP to create new architectural forms characterised by compacted, free-form volumes. Moreover, the successful demonstration of integrating other building components within the IP process not only expands the range of potential applications in the field of architecture but could facilitate the industrialisation of hybrid earthen construction systems for commercial purposes.

The rough surface of structures built through IP, characterised by its high-speed but low-resolution building process, suggests an interesting prospect for secondary surface finishing strategies. Furthermore, the material employed in IP stays workable for an extended duration and can enable secondary refinement and detailing and integration with other systems. The future implementation of the IP tool on the HEAP excavator will provide an opportunity to evaluate the reliability of the computational methods and construction strategies on site in an unstructured environment. The possibility of orienting the tool and shooting from different angles because of the multiple degrees of freedom of the excavator can further help to explore designing and fabricating structures in uneven terrain.

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