Rising from rubble

Leveraging existing construction tools for upcycling concrete waste into slender walls

Maxence Grangeot[1, 2][0000-0001-9141-5786], Qianqing Wang[3][0000-0002-6750-4612], Katrin Beyer[3][0000-0002-6883-5157], Corentin Fivet[1][0000-0003-4558-9835] and Stefana Parascho[2][0000-0001-8929-1825]

[1] EPFL SXL, 1700 Fribourg, Switzerland
[2] EPFL CRCL, 1015 Lausanne, Switzerland
[3] EPFL EESD, 1015 Lausanne, Switzerland
`maxence.grangeot@epfl.ch`

Abstract.
In this paper, we present a new method for upcycling concrete rubble waste into slender walls through the lightweight digital augmentation of mainstream construction machines. By using such method, the environmental impact of concrete construction and demolition is alleviated while leveraging accessible tools. In our proposed method, pieces of rubble are scanned from photos, robotically drilled to insert a lifting anchor, and assembled along their larger surface plane with a digitally augmented overhead crane. The highlight of this method is the orientation of irregular concrete debris through gravity, thus only requiring a lifting and a drilling tool for 3D orientation. Our method benefits a 2D stacking algorithm which accounts for the logistical constraints of construction sites. We document the construction process with augmented tools and implement them for the design and construction of two full-scale wall demonstrators. We also detail prospects of scalability for prefabrication, for onsite applications and potential use cases.

Keywords: concrete rubble, upcycling, wall.

1 Introduction and research goal

Although concrete is known to be one of the most environmentally damaging construction materials [1], it remains as popular as ever. All over the world, new concrete buildings continue to be built, and demolition debris from the old ones generate the most waste besides excavated soils [2]. Circular strategies exist to reclaim concrete, such as crushing it into recycled aggregates or saw-cutting elements to reuse them. However, these strategies are environmentally insufficient or logistically constraining [3]. Reusing concrete rubble generated by conventional demolition techniques without additional material processing remains complex and underexplored [4], partly due to the high variability and irregularity of their geometry. By harnessing the geometrical variability of the stock through digital processes, new scalable strategies are possible for upcycling concrete rubble in novel load-bearing applications [5]. Our research seeks to upcycle large flat concrete rubble units, as seen in Fig. 1, into slender walls while making the most out of market-ready tools to aim for scalability.

Fig. 1. Pile of concrete rubble and segmented debris oriented along their largest surface plane

2 Background

Using concrete debris from demolition in the design of new structures has been explored in academia for trusses [6], walls [7,8] and retaining walls [9]. However, their implementation in industry remains difficult as they have no built demonstrators or they rely on expensive machinery such as automated excavator or a carving robots.

Toward harnessing the geometrical complexity of as-found materials, other research projects use 3D scanning through LiDAR [10], structured light [11] or photogrammetry [12] to build walls and columns out of irregular stones. However, the 3D manipulation of non-standard materials is computationally intensive and requires high expertise, thus preventing their scalable adoption in the construction industry. To bridge digital processing to construction by leveraging existing tools of construction sites, other studies show the potential of augmenting cranes [13] or manual tools [14], while historical practices provide hints to orient irregular stones simply through lifting [4].

3 Methods

Due to the flat property of most large concrete debris, we consider rubble pieces as 2D geometries and define their flat orientation as largest surface plane. To assist the design and construction planning of the walls, we implemented a 2D scanning and stacking method. Aiming for scalability and accessibility, this project uses tools commonly used on construction sites, such as cranes and hammer drills, augmenting them for accessible digital processing. Instead of orienting heavy concrete fragments of non-standard geometries in 3D with expensive and payload-constrained robots, we achieve their desired orientation using any hoisting machinery. By lifting rubble units from precisely drilled lifting points computed from their desired orientation and their centre of mass, they are oriented simply by gravity. The concrete debris are drilled with a robotically-augmented hammer drill, lifted with a digitally-augmented overhead crane, stacked along their largest surface plane, and connected with mortar or reclaimed rebar, to construct single-leaf masonry walls. We construct two full-scale demonstrators as case studies to identify the construction time and robustness of our upcycling process.

3.1 Design tools

In order to sustainably construct walls for buildings, their embodied energy and footprint size need to be minimized by optimizing their slenderness and quantity of material. Unlike traditional masonry, we aim to stack large flat rubble pieces along their largest surface plane into single-leaf masonry walls. However, this strategy requires care for stability throughout the construction. To avoid large storage areas and cumbersome logistics, we only consider the concrete fragments of the topmost layer of a pile for scanning and stacking. Each rubble unit is placed flat on a pallet and photographed from an augmented overhead crane. The contour 2D outline geometry of each concrete piece is obtained through canny edge detection [15] from the top-view images (Fig. 2), while thickness is acquired through a distance sensor of the augmented overhead crane. To maximize the success rate of edge detection, we increase the image contrast using a black backdrop placed underneath the rubble unit and its pallet.

Fig. 2. Rubble pieces 2D contour geometry obtained from edge detection from top images.

To identify the optimal placement for each candidate rubble unit, we implemented a raster-based stacking algorithm [16] to obtain a tightly packed arrangement within given boundaries. Computing the object-oriented minimum bounding box of 2D outlines provides the orientation of straight edges if any, informing stacking stability and aesthetic design intents. Oriented in 4 orthogonal directions, the best out of 5 random candidates is selected using a hierarchical method that prioritizes large lateral force capacity, uniform course height, interlocking, and small void area. The details are given in an external article [16]. The lateral force capacity is represented by the maximal tilting angle of the wall in a tilting table simulation using kinematics analysis [17].

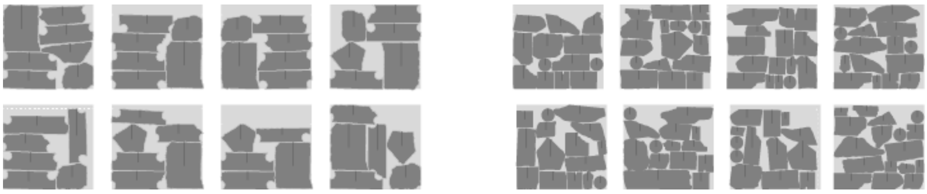

Fig. 3. First 8 ranked stacking options using a stock of (a) 15 and (b) 27 rubble pieces.

Aiming for robustness in case of stock or geometry alteration, the sequential algorithm allows for on-the-fly changes. Ranking wall stacking solutions by void area and wall height highlights optimum solutions (Fig. 3). Using the centroid of the 2D outline as the estimated centre of gravity and knowing its intended orientation in the wall, the locations of lifting points are identified as above the centre of gravity of each rubble unit and transmuted to the ground position of the rubble unit to be drilled and lifted.

3.2 Hardware tools

Augmenting heavy-lifting hoisting machinery.
For acquiring the geometry of concrete debris and their location, we use an overhead crane with a 10 tons lifting capacity. By augmenting it with three optical distance sensors, an industrial RGB camera, a compact computer, and an acquisition module, the augmented overhead crane can stream the following: the x and y position of the trolley based on a virtual static point, the vertical distance to the nearest surface below the trolley, and top-view images. This sensing unit shown in Fig.4 is clamped to the crane trolley to be easily dismantled and installed on another overhead crane or a tower crane. The distance sensor targeted at the ground allows to detect the thickness of each rubble unit by subtracting the distance to the floor and the pallet height. We also use the visible red beam of the vertical distance sensor as a digital pointing device, to calibrate all tools and coordinate systems between each other. A load cell between the swivel hook and lifting slings allows to record the weight of the rubble pieces for documentation but this data is not used in the fabrication planning. The data of the sensing unit is locally treated in LabView, a systems engineering software, and streamed to a ground computer.

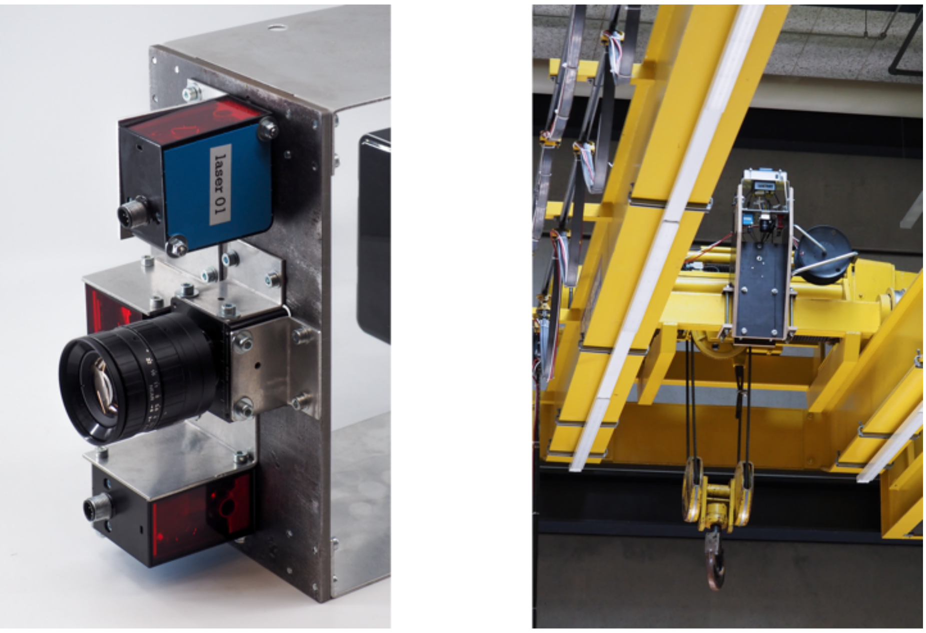

Fig. 4. (a) Sensing unit composed of 3 optical distance sensors, an industrial camera, a computer, and an acquisition module (b) Overhead crane trolley with clamped sensing unit.

The overhead crane is positioned by the human operator based on a cartesian target and live feedback while avoiding the swinging of loads and physical collisions. Manual operation of the overhead crane ensures safe and swift operation.

Robotically augmenting concrete hammer drills.

We achieve the desired orientation of irregular concrete fragments through gravity when lifted from specific anchor points. The lifting anchors of each rubble unit are drilled using an augmented hammer drill. Leveraging the fast-prototyping capabilities and 3m reach of an industrial robotic arm on a linear track, we convert a hammer drill to a robotic end-effector via a bespoke pneumatic shock absorber (Fig. 5, 6). The off-the-shelf concrete drill accepts a wide range of drilling bits for varying hole diameters and length. For deep holes that require long bits, a holder extends during predrill to minimize eccentricities. Extending the holder and turning on the drill is controlled automatically via the I/O signals of the robot controller. Robotic control is achieved using compas_RRC [18], while compas_FAB [19] is used for path planning and simulation.

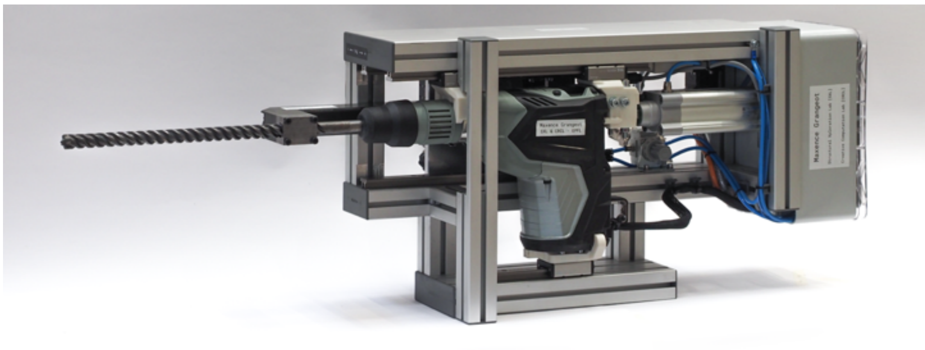

Fig. 5. Concrete hammer drill acting as a robotic end-effector, mounted on a pneumatic shock absorber for dampening vibrations and relieving stress on the robotic arm joints.

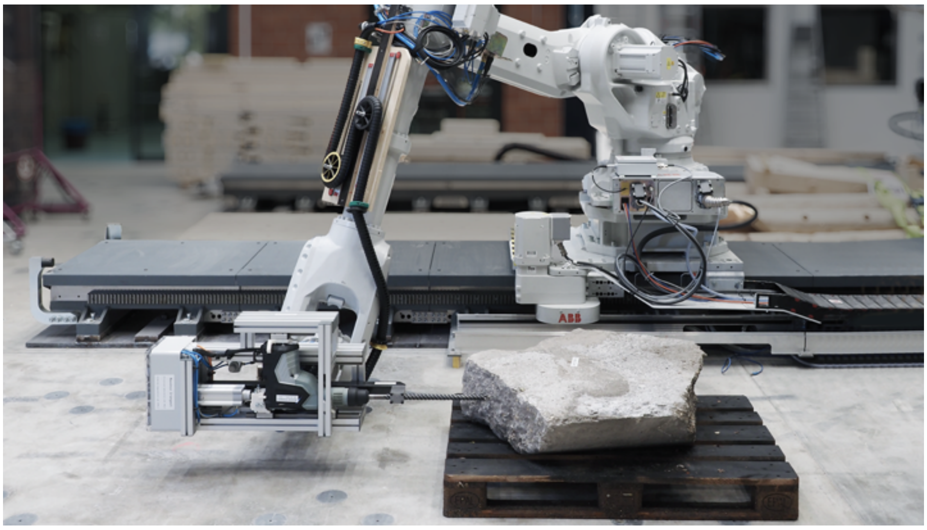

Fig. 6. The positions of the lifting points are precisely drilled on the middle axis of the side faces of flat rubble pieces. For heavy concrete fragments, two anchors ensure redundancy.

3.3 Machines and human collaboration

All augmented tools and the wall building support are referenced in 3D space relative to each other when located within a single fabrication facility (Fig. 7). Operating the drill below the augmented crane allows data to be shared by several tools. For instance, the camera of the crane is also used for referencing the position of the concrete debris for robotic drilling.

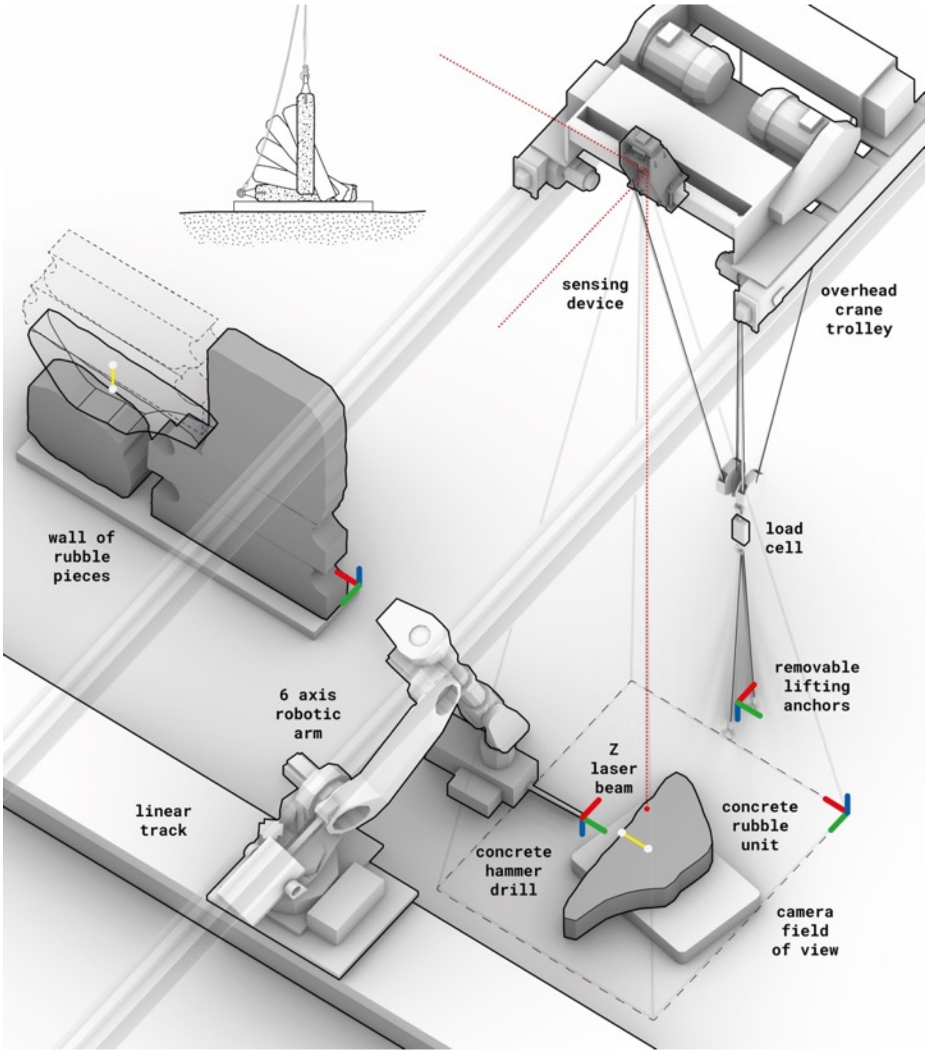

Fig. 7. Tool augmentations and relevant planes used for calibration and operation. The Z laser beam of the sensing unit of the overhead crane acts as a reference for calibrating the camera, the concrete hammer drill end-effector, the wall base, and the lifting hooks.

At the interface of all tools, a human operator acts as a critical agent of the upcycling process (Fig. 8). Like a mason, the human operator is needed for design decisions, safe operation and adjustments of concrete debris positioning for stability during assembly. This ability to react instantly and adapt efficiently is our rationale behind avoiding automation. A metal detector operated manually allows for the detection of potential drilling collision with rubble rebar and the adaption of drilling points in consequence. During assembly, we manually verify the position of the rubble pieces using measuring tape. The hardware limitations to 2D silhouettes narrow connection strategies to those that provide tolerances and stability when interfacing the debris: dry stack, cementitious mortar, concrete rubble wedges, and reclaimed rebar as alignment and support rods. The choice between such connections is dependent on requirements for airtightness, load-bearing capacity, and rubble geometry as it influences stability during assembly.

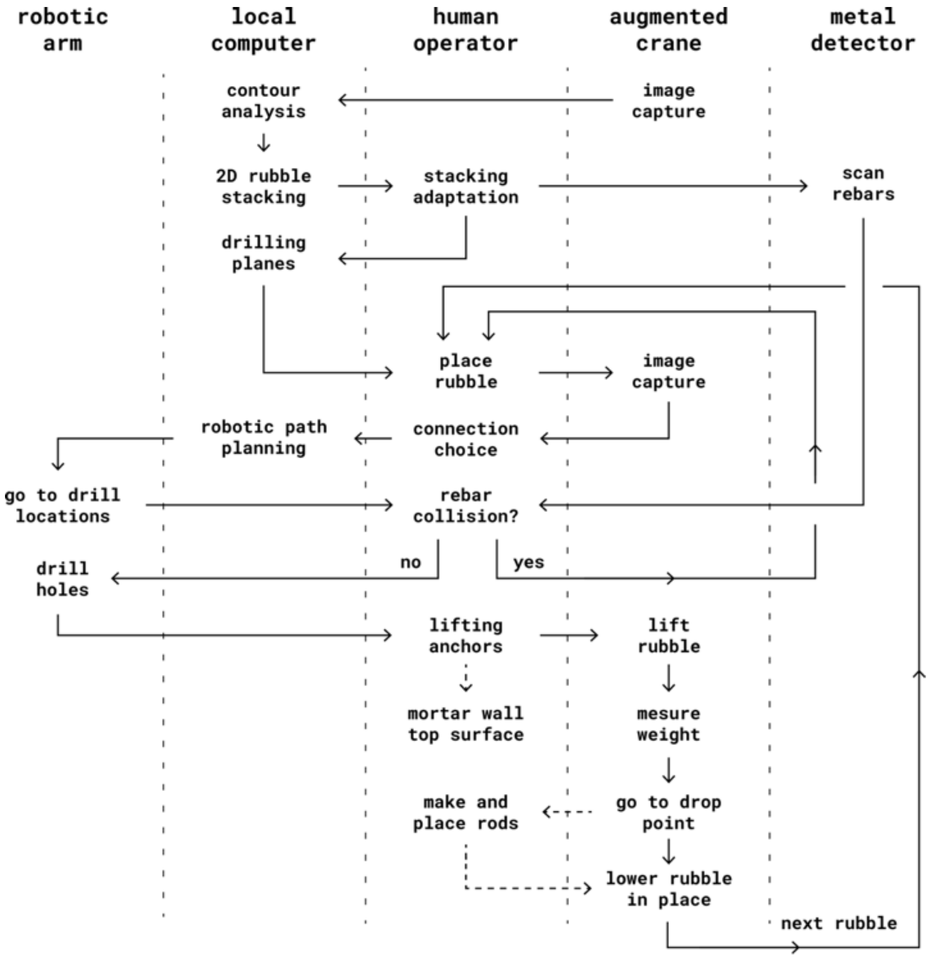

Fig. 8. Machines and human interactions within the upcycling construction process, starting from the image capture of debris. Dashed arrows are optional connection types.

4 Case studies

To assess the performances of our upcycling method and improve it, we design and build successively two full-scale slender single-leaf walls using equal boundary geometries (270 x 250cm) but different stock sizes and different connection types (Fig. 9).

Fig. 9. Walls built out of large off-the-pile concrete rubble units ranging from 80kg to 730kg.

For the first prototype, we scanned 12 large rubble pieces as the first extracted from a bin. We chose the stacking solutions containing the smallest void area (15%) (Fig. 3) and manually adjusted it, due to software limitations of raster resolution. Adjustments prevented physical collision of fragments and improved stability and aesthetics. To identify the most rapid processing method, we tested all 4 connection types independently and in combination. Mainly due to the numerous dowel holes and their 8.5min drilling time each, the construction of the wall is executed in 14 hours. We did not fill the voids, leading to a mortar use of 1% of the wall volume.

Learning from these results, we refined the upcycling process for the second prototype. We scanned more rubble units, 27 in total. The best stacking solution contained 21% of void, which we further reduced by adding one fragment to minimize infill material and related labour. We manually filled the remaining void with smaller debris and casted concrete using a localized formwork. This process provides airtightness but is more time consuming (40hours of construction) and increased mortar quantity to 15%.

Based on this refined prototype and processing method, its embodied energy is lower than stone masonry and recycled concrete. However, its structural capacity lies between these alternatives, while its 7:1 slenderness outperforms irregular stone masonry walls.

During lifting and rotation of rubble pieces from horizontal to vertical position, we observed no splitting at the lifting anchors. Concrete fragments thinner than 15cm are not drilled but lifted from the same point using a lifting clamp, reducing processing time and risk of splitting. For some fragments with lifting anchors, we reoriented the robotically-augmented drill to the normal of the drilling point during predrill to avoid the slippage of the drilling bit. We also solved this issue by jackhammering the surface at the lifting point to create a flat surface normal to the drilling direction.

5 Discussion

The tools of our upcycling process are augmented with mainstream components for accessibility and scalability, at the expense of auxiliary data. The absence of automatic detection of rebar layout and of side faces 3D geometry requires human intervention in non-design tasks which could otherwise be automated. Moreover, differences of rubble thickness are not considered in 2D stacking, neglecting pragmatic stability principles.

The tools augmented in this research project can be found in industrial prefabrication facilities, thus making our upcycling process suitable for prefabricating walls from concrete rubble, or in parts. Our stacking strategy, which also targets minimal storage area, increases the prospects of scalability for prefabrication and on-site construction.

Furthermore, our upcycling fabrication process can be easily adapted to construction sites using tower cranes and concrete drills. Most tower cranes are already equipped with position sensors, load cells, and occasionally with cameras. Concrete drills are frequently present during the construction of structures, yet they lack the positional capabilities of robotic arms. While other projects have shown the feasibility of operating robots on construction sites [20], the required drilling precision is achievable with guiding devices such as positional lasers. In future work, we will use the Z laser sensor of the sensing unit of the crane to guide human operators in manual drilling.

Compared to traditional masonry and concrete walls, our method, when applied to prefabrication, is expected to save embodied energy by minimizing mortar quantities, while maintaining the average amount of needed labour and construction time. Due to the experimental and academic nature of this study, and the variance of labour costs throughout the world, we do not provide a price comparison. However, concrete rubble from demolition is a cheap commodity in large quantity often given to recycling centres alongside compensation to avoid the high costs of landfilling.

6 Outlook

Concrete rubble from demolition remains a largely unexploited construction material due to its irregular geometry and is systematically downcycled as a result. In our upcycling method, large concrete rubble pieces are stacked along their largest surface plane into slender single-leaf walls of controlled dimensions using a 2D stacking algorithm considering logistic constraints, quantity of labour and material, and stability. We digitally augment tools of construction sites such as cranes and hammer drills to achieve orientation of irregular rubble pieces through gravity during lifting. The construction process, assessed with two full-scale demonstrators, involves human intervention to safely operate tools and make adjustments to ensure stability. Application-wise, our upcycling method is suitable for prefabrication and can be easily adapted for onsite construction. Compared to stone masonry walls, the resulting walls are faster to build, more space-efficient, have comparable structural performances and use less mortar. Consequently, we offer an approach that not only has a practical and economic path to meaningful adoption in industry, but also diverts the environmentally burdensome concrete waste stream away from consumptive practices of recycling and landfilling.

Acknowledgements

We warmly acknowledge the contribution of Eric Duong for proof-reading, Sika AG and Tinguely Recyclage SA for supplying materials, Lullin Engineering for robotic fabrication hardware and GIS EPFL for technical assistance.

References

1. Monteiro PJM, et al. Towards sustainable concrete. Nature Mater **16**, 698–699 (2017)
2. Giorgi S., et. al. Guidelines for Effective and Sustainable Recycling of Construction and Demolition Waste. In: Benetto E, Gericke K, Guiton M, editors. Designing Sustainable Technologies, Products and Policies: From Science to Innovation, 211–221 (2018)
3. Küpfer, C., Fivet, C., Panorama of approaches to reuse concrete pieces: identification and critical comparison. Journal of Physics: Conference Series, 2600(19) (2023)
4. Clifford, B. : The cannibal's cookbook: mining myths of Cyclopean constructions. Second edition. Novato, California: Oro Editions (2021)
5. Grangeot, M., Fivet, C., Parascho, S., From concrete waste to walls: An investigation of reclamation and digital technologies for new load-bearing structures Journal of Physics: Conference Series, 2600-192019 (2023)
6. Khalil Yaqoob Al Khayat, L. Fibers and Fragments - Weaving local resources into the Arabian Gulf's modern material culture. Massachusetts Institute of Technology. (2023)
7. Marshall, D., Mueller, C., Clifford, B., Kennedy, S., Computational arrangement of demolition debris. Detritus **11**,3–18 (2020)
8. Clifford, B., McGee, W., Muhonen, M.: Recovering Cannibalism in Architecture with a Return to Cyclopean Masonry. Nexus Network Journal **20** (3), 583–604 (2018)
9. Johns, R. L., Wermelinger, M., et. al. A framework for robotic excavation and dry stone construction using on-site materials. Science Robotics, **8** (84) (2023)
10. Settimi, A., Wang, Q., Andò, E et.al., Projector-based augmented stacking framework for irregularly shaped objects. Construction Robotics **7**, 159–175 (2023)
11. Furrer, F. et al. Autonomous robotic stone stacking with online next best object target pose planning. In International Conference on Robotics and Automation, 2350–2356 (2017)
12. Wibranek, B., Tessmann, O., Digital Rubble Compression-Only Structures with Irregular Rock and 3D Printed Connectors. Proceedings of IASS Annual Symposia, 1-8 (2019)
13. Joachim, L. et al. Evaluation of the quality of real-time mapping with crane cameras and visual slam algorithms. In The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, **43**, B2, 545–552 (2022)
14. Settimi, A., Gamerro, J., & Weinand, Y. Augmented-reality-assisted timber drilling with smart retrofitted tools. Automation in Construction, **139**, 104272 (2022)
15. Bradski, G. OpenCV Canny edge detection https://opencv.org/, last accessed 2024/02/07.
16. Wang, Q., et. al., An image convolution-based method for the irregular stone packing problem in masonry wall construction. European Journal of Operational Research, (2024)
17. Wang, Q., Dos Santos, K. R. M., & Beyer, K.. Micro Modeling of Irregular Stone Masonry Walls Using Mathematical Programming. Str. Analysis of Hist. Constr. **46**, 591–602 (2024)
18. Fleischmann, P., Casas, G., COMPAS RRC: Online Control for ABB Robots over a Simple-to-Use Python Interface., V 1.1.0 https://compas-rrc.github.io/compas_rrc (2021)
19. Rust, R., Gonzalo C., et al., COMPAS FAB: Robotic Fabrication Package for the COMPAS Framework., V 0.28.0, https://github.com/compas-dev/compas_fab/ (2018)
20. Bock, T., Linner, T., Site automation: automated/robotic on-site factories. New York, NY: Cambridge University Press (2016)