Walking Assembly: A Method for Craneless Tilt-Up Construction

Tyler Swingle[1](✉), Davide Zampini[3], and Brandon Clifford[1,2]

[1] Matter Design, 76 Elm Street, Suite 207, Boston, MA 02130, USA
`tyler@matterdesignstudio.com`
[2] MIT School of Architecture + Planning, 77 Massachusetts Avenue, 7-23,
Cambridge, MA 02139, USA
[3] CEMEX Research Group AG, Römerstrasse 13,
2555 Brügg b. Biel, Switzerland

Abstract. The mysterious knowledge surrounding the transportation and placement of megaliths used by ancient societies eludes contemporary building practices. The construction of massive elements in architecture, particularly tilt-up construction, is largely dominated by reliance on external structures and mechanisms such as cranes and tilting tables. This reliance has irreducible implications on costs and access to the potentials of massive construction. This paper taps into the potentials of innovative concrete technologies and ancient methods of transportation and assembly of megalithic architecture to inform contemporary practice by embedding intelligence into building elements to assemble without the aid of external lifting. The paper describes the development of massive concrete prototypes that walk and assemble with ease. It outlines the use of concrete densities and recursive solver computation in the design process to ensure the safe and stable movement of the massive elements. The computation surrounds two key geometries—the form of the element and the center of mass (COM). The forms of the elements are constrained by the need to rotate for transportation, to rest for stabilization, and to interlock for assembly. The solver leverages the potentials of varying densities of concrete to drive the geometric COM to a new target position, thus ensuring the calculated movements. This multi-variable calculation is verified with three built prototypes that test different assembly approaches. The resulting artifacts range from self-assembly to incredibly massive solid cast concrete elements that can walk and assemble effortlessly. The introduction of innovative concrete technologies was fundamental to enable versatility in geometrical design and achieve the target performance from the displacement of the COM. The success of these prototypes points to the possibility where computation, coupled with novel concrete technologies, can expand the reach of, for example, tilt-up wall construction and reconsider the potential of mass in rapid and responsive deployable systems.

Keywords: Megalithic architecture · Craneless construction · Concrete technology · Center of mass · Constant and variable curvature

C. Gengnagel et al. (Eds.): DMSB 2019, *Impact: Design With All Senses*, pp. 237–249, 2020.
https://doi.org/10.1007/978-3-030-29829-6_19

1 Introduction

Since its invention, concrete is the most used manufactured material in the world with "three tonnes of concrete (…) used annually per person" (Brito 2013). From this one material, three categories of architectural construction exist—site-cast, pre-cast, and tilt-up. Each of these methods relies upon external devices to transport material from the quarry or concrete plant to the ultimate site. This reliance on external mechanical devices expands the cost and carbon footprint of concrete construction, but it also limits the deployment to large budgets and regions that are accessible by large trucks and heavy cranes. Tilt-up wall construction is a site-based method whereby large concrete units are cast horizontally and tilted vertically into position. While this method has a great number of advantages, its constraints drive many design decisions. In his text 'Tilt-Wall—A Brief History', Jeffrey Blain Brown describes the building practice as having "more in common with parochial methods of cultural procedures such as barn raising" but as a "commercial manifestation of technique rather than any kind of communal activity" (Brown 2014). While efforts are being made to optimize the energy embedded in the brute force approach of crane construction (Peng 2018), these efforts assume to embed the intelligence of assembly into the mechanical devices as opposed to the building element themselves.

Inherent to concrete is mass, and much of the work surrounding intelligent futures for concrete have focused on reducing mass and deploying the material where needed. These examples include (Elrehim 2019), (Jewett 2018), and (Liew 2017). As beneficial as these efforts are, mass is not the only parameter and it can even be advantageous to have, such as improving the thermodynamic performance as show in the Hsu House (Cupkova and Azel 2015). Is it possible to maintain the material's massive property while reducing energy consumption?

This challenge of today is identical to moments of the past when ancient civilizations such as the Romans or Egyptians erected incredibly massive megalithic assemblies without the energy consumption of mechanical cranes (Dibner 1991). While much is still uncertain about the ancient Egyptian and Roman methods, archaeologists were able to prove that the colossal statues of the Moai Rapanui were carved with a highly calibrated relationship between the curvature of the form and the center of mass (COM) of the object. This enabled the Moai to march forward when tugged side to side (Hunt 2012).

Significant research is currently engaging the challenge to embed intelligence into the material itself by controlling the location of the COM. A paper describes the process of computing the variable density of an additive manufacturing process to solve for the moment of inertia, thus enabling many forms to serve as spinning tops (Bächer 2017). In her thesis, Inéz Ariza describes a method whereby a system can incrementally solve for stability throughout the construction process (Ariza 2016). The combination of these efforts projects the potential of building elements that are calibrated to perform physical actions that can assemble in a procedural manner such as with Penrose's self-assembly machine (Penrose 1959).

This paper describes a method to calibrate the location of the COM of a concrete building element in relationship to the object's curvature to ensure stability throughout the construction process. The calibration of the COM location relies on the ability to control the design and distribution of variable densities of concrete within the elements.

2 Balance Geometries

Two geometries are critical in controlling the balance, stability, and motion of an object. The first is the COM and the second is the center of curvature (COC). Each of these points are inherited from the form of the object. The relationship between the COM and the COC determines an object's stability. If the two points are coincidental, the object is free like a wheel and has many stable positions. If the COM is below the COC, the object has a unique stable position. In both instances, there is equilibrium between the gravity vector from the COM and the reciprocal vector from the ground at the contact point. If the vectors do not align, a righting moment generates a restoring force to move the system into equilibrium. Because stability is a result of a moment force imparted on the object between a gravity vector pulling down from the COM and an inverse vertical vector from the ground, the COC at the contact point with the ground can predict this behavior. Figure 1 demonstrates this relationship.

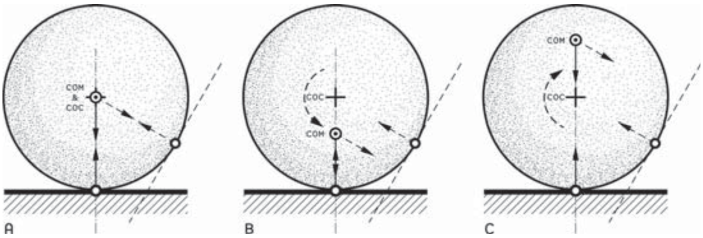

Fig. 1. (A) COM and COC are coincidental, resulting in a stable, but free motion. (B) COM is below the COC, resulting in a righting moment when rotated. (C) COM is above the COC resulting in an accelerating and unstable resting position.

2.1 Center of Mass

Archimedes' principle (of Syracuse c. 287–212 BC) defines the COM (or center of gravity) of an object with uniform density as coincidental with the volume centroid of the object. If an object is composed of multiple materials with varying densities, the summation of those respective parts results in a single point. The equation below solves for this collective COM. The ability to vary the density of a material allows for a range of center of mass locations, thus enabling the designer to control the motion of an object through mass distribution (see Sect. 4.3).

$$x_{cm} = \frac{\sum_i m_i x_i}{\sum_i m_i}$$

2.2 Center of Curvature

For objects with positive curvature, a contact point represents the collision of the object and the ground. In two-dimensional space, this point exists on the bounding curve of the rigid body. The curvature of that curve, at the contact point, can be represented by a circle. The centroid of that circle is the COC, and the radius of that circle is the radius of curvature. For more on the COC, see the chapter on 'Plane Curves' in Geometry and the Imagination (Hilbert and Cohn-Vossen 1952).

2.3 Constant and Variable Centers of Curvature

Geometries with constant curvature, such as circles and arcs, maintain a single point as the COC, regardless of where the contact point rests on the curve; however, objects with variable curvature, such as an ellipse or a calculus-generated curve result in a variable COC. As the contact point sweeps across the curve, the curvature of that object transforms, thus resulting in a mobile COC that can be represented by a curve in two-dimensional space. This curve is significant as it can inform the designer of regions where a COM can ensure geometric stability, or instability. Figure 2 demonstrates this principle.

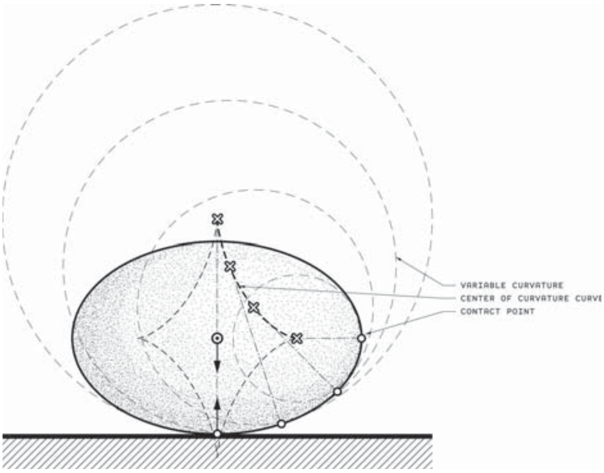

Fig. 2. Variable curvature diagram.

3 Variable Density Concrete

While the form of the object determines a center of geometry, this research employs innovative variable density concrete in order to displace the COM to the desired position in massive objects, and consequently allows for particular motions.

The concrete technology consists of mix designs that ranged in densities between one-third the density of conventional concrete (2400 kg/m^3) to double the density. The aforementioned material properties are achieved using proprietary chemical admixtures and special lightweight additions. The chemical admixtures have the function to entrain air as well as impart high fluidity (ease of casting), whereas the lightweight additions lower the material weight, but selected in such a manner to minimize strength reduction.

Each object was composed of concretes having two different densities, and it was important to cast both materials into a single element and respect the orientation and mass distribution to achieve the shift in center of mass required to perform the targeted motions of the object.

Thus, the production of the final object is a result of designing material intelligence through tailoring concrete with precisely calculated material properties and the adoption of creative casting methods to combine different densities that achieve the predicted motions.

4 Method

Formal circumstances control both the movement and the connection of building elements within the assembly. In both cases, the balancing form (see Sect. 2) contributes to defining and meeting said circumstances. The combination of these frameworks results in a multi-variable problem with a shared target location for the COM. A recursion solver uses a division plane to distribute the two densities and drives the COM to the target location so that each of these conditions are sufficed.

4.1 Motion Geometries

The riding surface allows elements to stand from a horizontal to vertical position, rest in a stable vertical position and walk by tilting, pivoting and rotating to mimic pedal locomotion of the Moai (Lipo 2013). It is described by a riding curve as shown in Fig. 3, with a region along the curve that is stable because the COC and the COM align. The riding surface is bracketed on either side by braking surfaces to ensure the object does not tip over. These surfaces provide a restoring force by increasing the curvature and therefore misaligning opposing vectors from the contact point and the COM (see Sect. 2). The restoring force absorbs and dissipates momentum generated from walking or standing, and the increase in curvature removes any impact and high g-force on the element during movement as outlined by a patent on Amusement-Railways that had a similar problem of transitioning motions (Green 1901).

tyler@matterdesignstudio.com

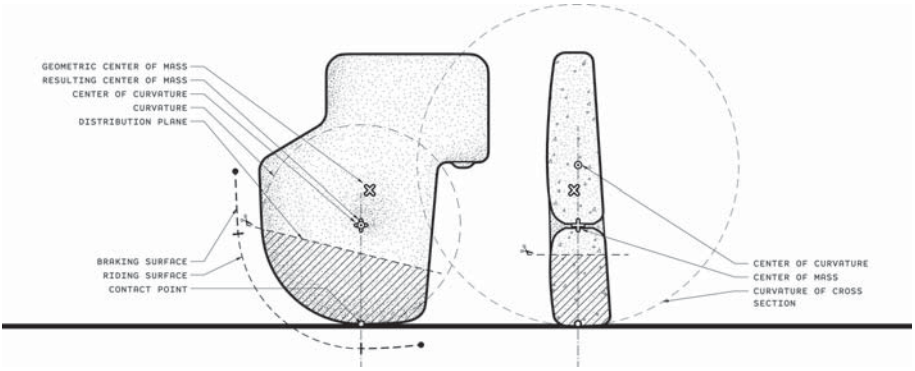

Fig. 3. Key of typical element.

4.2 Assembly Geometries

All prototypes rely on the rotation movement defined by the motion geometries to assemble elements. The assembly geometry of the elements considers the possible collisions of elements by the defined movement and locks elements together by resisting backwards rotation and spinning out of plane. When combined sequentially, the elements overlap, and the last element resists the previous elements from rotating out of the assembly. Dado joints with a draft angle are integrated with the overlapping connection to resist spinning in the vertical axis as seen in Fig. 4.

Fig. 4. Assembly geometry details.

4.3 Center of Mass Solver

The COM is relocated to a desired target point by means of a recursion solver to determine the distribution plane which divides the two densities of concrete. Two input values are inherited from the current COM and the target point. Those two values inform the vertical motion (*m*) and rotation (*r*) of the distribution plane. The first value (*v*) is the vertical distance between the current COM and the target COM. The second value (*a*) is the angle defined by a vector between the current COM and target COM, and a vertical line from the current COM. In each increment of the solver, the plane moves (*m*) and rotates (*r*) a fraction of both input values in order to decrease the overall distance between the target COM and the resulting COM. After each increment, the resulting COM of the new concrete distribution defines new, smaller input values for the next increment in the recursion solver as seen in Fig. 5.

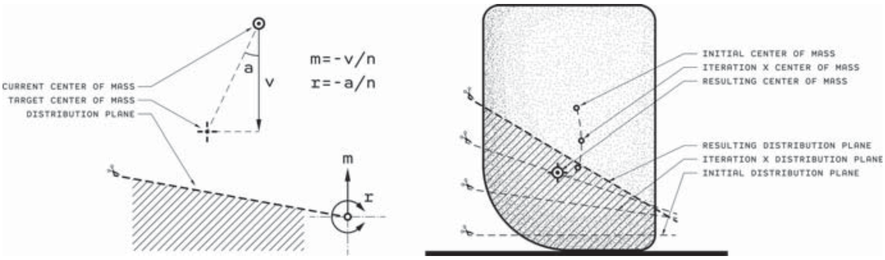

Fig. 5. Recursion solver diagram.

5 Prototypes

The three prototypes test the mobility and connectivity of the elements without a crane or heavy-lifting mechanism. Each prototype uses the solver to drive the COM and activate the multi-variable motion and assembly geometries. The prototypes are explorative of different scales, motions and methods of assembly, from self-assembly, to aided-assembly, and walking assembly.

5.1 Self-assembly Prototype

The goal of the self-assembly prototype is to assemble two elements from a horizontal starting position, a common tilt-up construction problem. The first challenge is standing elements without any external force. This is accomplished by driving the COM beyond the fulcrum of the formwork and below the COC when standing. The second challenge is to adjust the elements and their motion geometry to their horizontal positions to ensure contact with the ground. The motion geometries in the prototype are two-dimensional extrusions with a constant curvature and rely on the single stable position to conclude their motion. The final challenge is to make the two elements fit together with assembly geometries. The solver is used with both elements to drive the COM to the target location. Before self-assembling, the righting moment of both elements in the horizontal position is countered by an additional mass until released. Once released, the momentum of the object over-rotates the element beyond the stable resting position to collide with the second element (Fig. 6), thus releasing it to allow both elements to collide and align, thus self-assembling.

The self-assembly prototype verifies the controlled relocation of the COM within the combined constraints of the motion and assembly geometries. It also confirms the generation of a righting moment established by the geometric relationship between the COM and the COC. However, the aspiration to produce an entirely self-assembled architecture evidenced a number of challenges that are overcome in the following prototypes. These challenges include the ability to re-set a potentially misaligned collision, the ability to adjust tolerances, and the overall safety of this proposal at a larger scale.

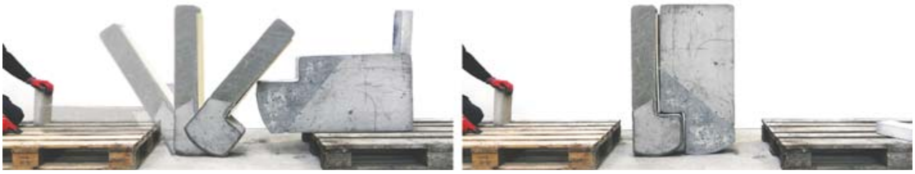

Fig. 6. Self-assembly prototype.

5.2 Aided-Assembly Prototype

The aided-assembly prototype (Fig. 7) explores the possibility of a larger assemblage by increasing the number of elements. It suspends the challenge of pure self-assembly in favor of reducing the force required to lift and align elements so a human can provide the force. In total, five elements assemble using different variations of overlapping connections. Like the self-assembly prototype, the motion geometry is a flat 2D extrusion without a braking surface; however, three elements have a riding surface along the short section and the remaining two elements have the riding surface along the long section.

While this modeling method of the motion geometry produces stable elements with controlled movement in two different axis, it makes small adjustments and overall movement of the elements difficult. Further, the flat overlapping connections do not provide enough surface tension to resist the elements from spinning out of plane during assembly. Although the elements assemble together with little or no external energy, they require transportation within the assembly site and require rigorous procedures for alignment because of the inability to make small adjustments.

Fig. 7. Aided-assembly prototype.

5.3 Walking Assembly Prototype

The walking assembly prototype expands the COM solver to engage a fully three-dimensional curvature continuous motion geometry as well as interlocking assembly geometry at a larger scale. The purpose of this prototype is to embody the intelligence of COM location in relation to the element's COC so it can spin, rotate and tilt safely, therefore making it transportable and adjustable on site. Further, all elements utilized braking surfaces with variable curvature in the cross section of the motion geometry for stability. The assembly geometries incorporate dado connections into the element overlap. The additional interlocking surfaces aid in the final alignment of the elements and account for the element's rotational draft during assembly.

Each of the smaller elements (Fig. 8) is roughly 1.2 m wide and 1.5 m tall, ranging in depth from 0.3 m to 0.5 m. They range in mass from 420 kg to 700 kg and can easily be positioned by a single person. A stair is incorporated into a series of smaller elements so that a person can climb and continue the assembly of a larger element twice the size (Fig. 9). This element is 1.75 m by 0.5 m by 3.0 m and weighs over 1,770 kg, but is just as agile as the smaller elements.

Finally, a weight is added to one of the elements to control multiple COM locations (Fig. 10). The movement of the COM from the weight produces two different instances of the COM and COC relationship. With the weight, the element has a free movement stability for easy movement; without the weight, the COM moves below the COC and stabilizes the element in one vertical position. This multiplicity aids in the assembly by quickly transitioning from a free stable position to a singular stable position.

Fig. 8. Walking assembly prototype elements.

Fig. 9. Walking assembly prototype.

Fig. 10. Removing counterweight to stand element.

6 Conclusion

This research successfully demonstrates the ability to control the location of the COM of an object in relation to its form via variable density concrete. This relationship allows designers to create massive concrete elements that can be assembled without the aid of external mechanisms, heavy equipment, or cranes. These findings point to two conclusions, surrounding the material and form, as well as applications of this technique.

6.1 Material and Form

Each prototype confirmed the predicted location of the COM in relationship to the form of the element. The walking assembly prototype further tested this relationship by locating a pick point at the COM to allow the element to be lifted from that location. When lifted from that location, the COM is verified through the free spin of the element. While the varying densities ensured the location of the COM, the division between densities did not always occur above the motion geometry. When walking the elements, the lighter, and therefore softer, concrete was less resistant to the pedal motion. Future research can account for the density of a more robust material throughout the entire riding surface.

6.2 Applications

Each prototype, though specifically the walking assembly prototype, demonstrated the potential to embed the intelligence of transportation and assembly into an element of architecture. While the walking assembly prototype demonstrates the potential to walk massive elements of construction, it does not resolve long-distance transportation. It does however allow for on-site mobility and the productive ability to adjust and align elements, thereby accounting for tolerance of on-site construction. This potential could be better incorporated; by mimicking pedal locomotion, the elements can easily and safely walk across site, but have difficulty finding the exact position for assemblage. The overlap connections confirm alignment but do not aid the alignment process, nor do they completely resist backwards rotation. The most successful connections occur when the assembly rotation of consecutive elements is not in the same plane as shown in Fig. 11. The self-assembly prototype points to the potential to embed the intelligence of the formwork of the element to serve in the raising of the element, but future research could also incorporate the transportation rational into the assembly logic.

Because these elements are easy to set, they are therefore also easy to dismantle, pointing to a potential to create masonry units that can be re-applied in future architectures without demolition. One unexpected finding was the ability to calibrate the lever-arm between the COM and COC to unshackle the dependency on size. Regardless of size, the relationship between those two geometric vertices allows humans to guide these gargantuan elements into place. If a brick is designed for a single mason's hand, and a concrete masonry unit (CMU) is designed for two hands, these prototypes demonstrate the ability to easily maneuver massive concrete masonry units (MCMU) that are independent of size and beyond the lifting power of a human. While these efforts are largely demonstrated at ground level, future research could incorporate the problem of intelligently lifting elements and assembling vertically.

Fig. 11. Perpendicular assembly detail.

tyler@matterdesignstudio.com

Acknowledgements. This research is funded by *CEMEX Research Group AG*. The recursion solver is generated through a custom definition that employs Anemone (theobject.co/anemone), a plugin developed by Object to resolve recursion in Grasshopper (grasshopper3d.com), a plugin developed by David Rutten for Rhinoceros (rhino3d.com), a program developed by Robert McNeel.

References

Elrehim, A., Mostafa, Z., Eid, M.A., Sayed, M.G.: Civil engineering: structural optimization of concrete arch bridges using genetic algorithms. Ain Shams Eng. J. (2019)

Ariza, I.S.M.: Decoding details : integrating physics of assembly in discrete element structures. S.M. Arch dissertations, Massachusetts Institute of Technology (2016)

de Brito, J., Saikia, N.: Recycled Aggregate in Concrete. [Electronic Resource] : Use of Industrial, Construction and Demolition Waste. Green Energy and Technology. Springer, London /New York (2013)

Bächer, M., Bickel, B., Whiting, E., Sorkine-Hornung, O.: Spin-It: optimizing moment of inertia for spinnable objects. Commun. ACM **60**(8), 92–99 (2017). https://doi.org/10.1145/3068766

Brown, J.B., Naheswaran, S.: Tiltwallism : A Treatise on the Architectural Potential of Tilt Wall Construction. The Images Publishing Group Pty Ltd, Mulgrave (2014)

Clifford, B.: The McKnelly Megalith: a method of organic modeling feedback. In: Velikov, K.: Projects : ACADIA 2016, Posthuman Frontiers: Data, Designers, and Cognitive Machines : Projects Catalog of the 36th Annual Conference of the Association for Computer Aided Design in Architecture, University of Michigan Taubman College of Architecture and Urban Planning, Ann Arbor, pp. 440–449. Association for Computer Aided Design in Architecture, Dover (2016)

Cupkova, D., Azel, N.: Mass regimes: geometric actuation of thermal behavior. Int. J. Architectural Comput. **13**(2), 169–193 (2015). https://doi.org/10.1260/1478-0771.13.2.169

Dibner, B.: Moving the Obelisks : A Chapter in Engineering History in Which the Vatican Obelisk in Rome in 1586 Was Moved by Muscle Power, and a Study of More Recent Similar Moves. Publication (Burndy Library): No. 6, Norwalk, Connecticut (1991)

Green, E.A.: Amusement Railway. Specification forming part of Letters Patent 678,243 (1901)

Hilbert, D., Cohn-Vossen, S.: Geometry and the Imagination, p. 1952. Chelsea Pub Co., New York (1952)

Hunt, T.L., Lipo, C.P.: The Statues That Walked : Unraveling the Mystery of Easter Island. Counter Point Press, Berkeley ©2012 (2012)

Jewett, J.: Design, Fabrication, and Testing of Plain Concrete Beams Using Topology Optimization. Mech. E dissertation, Massachusetts Institute of Technology (2018)

Liew, A., López López, D., Van Mele, T., Block, P.: Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor. Eng. Struct. **137**(April), 323–335 (2017). https://doi.org/10.1016/j.engstruct.2017.01.075

Lipo, C.P., Hunt, T.L., Haoa, S.R.: The 'walking' megalithic statues (Moai) of Easter Island. J. Archaeol. Sci. **40**(June), 2859–2866 (2013). https://doi.org/10.1016/j.jas.2012.09.029

Peng, B., Flager, F.L., Wu, J.: A method to optimize mobile crane and crew interactions to minimize construction cost and time. Autom. Constr. **95**(November), 10–19 (2018). https://doi.org/10.1016/j.autcon.2018.07.015

Penrose, L.S.: Self-reproducing machines. Sci. Am. **200**(6), 105 (1959)