MASS

RETHINKING CONCRETE IN THE DIGITAL ERA

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SPLINE
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ABSTRACT
Curvature has always been present in architecture though largely explored for structural purposes. It can be found in Roman arches and domes, in the catenary vaults of Antoni Gaudí, and in the hyper paraboloid shells of Félix Candela, as the result of form-finding techniques. Questions of materiality arose parallel to the development of these techniques, enabling the common use of concrete. Concrete allowed for the production of custom stones and replaced traditional hand-carving methods of making.

Concrete is one of the most ubiquitous materials in the built environment, yet it is often cast in orthogonal repeating parts. Why is such a supple and liquid material, capable of any form, limited to the conceptions of the industrial era? The building industry commonly assumes that formwork must be repeatable, yet the prevailing goal of the digital era is serial variability. Therefore, a gap exists between the goals of the computational revolution and the standards of material production.

This research states that it is possible to reconsider the role of concrete in the digital era via the aid of robotic fabrication. If formwork is commonly informed by the goal of efficiency and economics, this research asks what emerges when it is informed by environmental, structural, or formal concerns.

This thesis proposes a specific way of making that emerges from a computational understanding of spline geometries. The process allows the designer to materialize data into a complex geometry that has been programmed to perform one or more architectural parameters. Fabrication methodologies today are leading architects to reclaim the role of the masterbuilder. This thesis argues that designing and making are part of a single process. Architects should not design materially uninformed architectural spaces; rather, they should design through the making process while integrating geometrical and material concerns. Therefore, what kind of architecture emerges when the spline is foregrounded in a process of concrete construction?
Architectural history has always, in some way, involved curvature. While early examples such as Antonin Gaudi’s cantenary vaults, Felix Candela’s thin shell roofs, and Frei Otto’s tensile hyperbolic paraboloids developed a language of curvature that pushed the limitations of structural development in architecture, Modern examples have ushered in an era of computational understanding of curvature that allows for a complex understanding and processing of the math that allows curves to be both defined and produced. The modern development NURBS software [Non-Uniform Rational B-Splines] has ushered in a new era and tool for architects and designers. While the understanding of computational curvature of which the former is a product of, can be traced back to rival car manufacturers in Paris during the 1960’s, however, the term Spline which today is synonymous with computational curvature can be traced back much further. Splines were originally developed in naval architecture as a way to understand curved strips of wood that defined smooth cross sections of boat hulls in a process called lofting which had been practiced since antiquity. The development of 3D software has in large part, taken the geometric development of curvature for granted in favor of “point and click” facile design. This problem is the result of the highly technical underpinning of mathematical equations that usually define and develop the expressions of curvature in 3D geometric design which limits most designers and architects in their ability to use one of the most promising curvature design tools, the spline.
A SIMPLIFIED MAP OF SUCCEEDING DEVELOPMENTS THAT LED TO NURBS, SUBDIVISION SURFACES, AND THEIR RECENT UNIFICATION UNDER A COMMON REPRESENTATION: T-SPLINES. THE DOTTED LINES REPRESENT LATER RELATIONSHIPS DERIVED THROUGH MATHEMATICAL GENERALIZATION. ORIGINAL DIAGRAM: HTTP://WWW.ALATOWN.COM/SPLINE/
HYDRODYNAMIC
AERODYNAMIC
ERGONOMIC
ARCHITECTURE
STRUCTURE
ACOUSTICAL
THERMAL
DAY-LIGHT
AMOUNT OF CONTROL POINTS

SPLINE 14
NURB CONTROL POINTS
MINIMUM RADIUS

SPLINE 16
MATERIALIBILITY
NURBS SUBDIVISION
MATERIAL FLEXIBILITY

minimum radius
PARAMETERS

While there has been a large revolution in terms of digital computation and the exploration of new possibilities that have emerged through its development permeated our profession, there is still a large gap between its digital development and its physical manufacturing. While digital fabrication has in some ways enabled the development of these complex geometries, there hasn't been the same revolution in making that will allow a linked process between designing and making these geometries.

This thesis proposes a specific way of making that emerges from a computational understanding of spline geometries. Allowing the designer to materialize data into complex geometry that has been programmed to perform one or more architectural parameters such as structural, material, acoustic, thermal, or day-lighting. As a way to develop a process from a geometric understanding of splines through design and manufacturing, day-light was selected as the main design parameter as way to improve the development the control of light that is often sought after in sky lights, windows, and atriums. Working simultaneously with design and manufacturing parameters allows us reclaim the role of the architect as masterbuilder. This thesis argues that designing and making are means to be thought of as a single process. Architects should not design materially uninformed architectural spaces, but rather design through the making process itself integrating geometrical and material concerns.
PARAMETRIC SOLVERS

01
Azimuth Vector

02
Minimum Radius

03
Human Scale
DAY-LIGHT

SKYLIGHTS

DIRECT LIGHT

INDIRECT LIGHT

Centro de estudios Hidrográficos 1960-1963, Madrid, Miguel Fisac (viga hueso)

LUISEL ZAYAS 25
01
DIRECT LIGHT

NURBS SURFACE

SPLINE 26

LIGHT ANALYSIS
03
DIRECT LIGHT

NURBS SURFACE

SECTION

SPLINE 28

LIGHT ANALYSIS
DIRECT LIGHT

SECTION

LIGHT ANALYSIS

NURBS SURFACE
05
DIRECT LIGHT

NURBS SURFACE

SECTION

SPLINE 30

LIGHT ANALYSIS
DIRECT LIGHT

NURBS SURFACE

SECTION

LIGHT ANALYSIS

LUISEL ZAYAS 31
07
DIRECT LIGHT

NURBS SURFACE

SECTION

SPLINE 32

LIGHT ANALYSIS
09
DIRECT LIGHT

NURBS SURFACE

SECTION

SPLINE 34

LIGHT ANALYSIS
INDIRECT LIGHT

NURBS SURFACE

SPLINE 36

SECTION

LIGHT ANALYSIS
13 INDIRECT LIGHT

NURBS SURFACE

SECTION

LIGHT ANALYSIS

SPLINE 38
INDIRECT LIGHT

NURBS SURFACE

SECTION

LIGHT ANALYSIS
INDIRECT LIGHT

NURBS SURFACE

SECTION

SPLINE 40

LIGHT ANALYSIS
CASE STUDIES

Digital materiality facilitates the diversity of designs and evokes a higher complexity in geometry. This forms are informed by conditions or in this case parameters, that help to address design solutions to particular architectural problematics. For the purpose of this thesis three case studies were chosen. This case studies provided a wide range of parameters such as: climate, thermal, day-light, and structure. Day lighting was chosen as the main parameter, meaning that, the design would satisfy this above the rest of the conditions. After the effects of lighting were achieved, modifications were made to account for the rest of the parameters. A balance between structural and thermal concerns was optimized to coexist in the same form. For example, the thickness of the concrete was varied to generate thermal mass where needed, minimize the contact with the ground and with the sun as may other optimizations strategies use to generate the final geometries. All these parameters were use to develop three site specifics programmed geometries.

The Sahara Desert, Kebili Tunisia $36^\circ 50\ N \ 10^\circ 9\ E$ was chosen for its drastic change in temperature between day ($130\ F^\circ$) and night ($40\ F^\circ$), and its azimuth condition ($20^\circ$-$56^\circ$).

The Amazon Rainforest, Tefe Brazil $3^\circ 21\ S \ 64^\circ 42\ O$ was chosen for its tropical humid climate (95%) receiving more than 100 inches of precipitation annually, and its azimuth condition ($85^\circ$-$106^\circ$), in particularly the two moments in the year where it reaches a perpendicular position to the sun vector. [September 1 and March 12].

The Arctic Circle, Bodo Norway $67^\circ 17\ N \ 14^\circ 23\ E$ was chosen for the natural phenomenon that occurs here, the midnight sun. The sun remains visible for the full 24 hours around the summer solstice (approximately 21 June in the north and 22 December in the south). The azimuth condition is extremely low ($-6^\circ$-$27^\circ$).
KEBILI, TUNISIA
36°50' N 10°9' E
AZ 20-56°

130 F
40 F
KEBILI, TUNISIA
36°50 N 10°9 E
AZ 20-56°
KEBILI, TUNISIA
36°50 N 10°9 E
AZ 20-56°
TEFE, BRAZIL
3°21'S 64°42'O
AZ 85-106°
ARCTIC CIRCLE

BODO, NORWAY
67°17' N 14°23' E
AZ -6°27'

MIDNIGHT SUN
FABRICATION

This thesis argues that designing and making are part of a single process. Architects should not design architectural spaces that disregard material parameters; rather, they should design through a making process that integrates geometrical and material concerns. To address this position, the thesis asks what kind of concrete architecture could be imagined and built when the geometric possibilities of the spline are foregrounded in a process of construction?

After testing different materials and methods for realizing this process, concrete was chosen as a material because it is one of the most ubiquitous materials in the built environment, and as supple and liquid material, it is capable of any form. This material chose led to experimentation with its formwork. The building industry commonly assumes that formwork must be repeatable, yet the digital era has enabled a serial variability. Therefore, a gap exists between the goals of the computational revolution and the standards of its material production. This gap mirrors the initial goals of this thesis, and thus led to an experiment in digitalizing formwork. By using an adaptable mold, different forms could be cast with a reusable mold that is not limited to one form and does not require the expense of constantly building singular molds to build large scale complex geometries. By positioning this mold on a robotic arm (KUKA) the freedom in the surface of the mold and position of the mold opens up large possibilities in flexible casting to produce complex geometric architecture. To produce the final results a mixture of glass fiber reinforced concrete (GRFC) that could be sprayed onto the mold was developed. This allows only one surface to be necessary for casting, allowing the single adaptable surface on the Kuka to be used for the entire production. This meant that complex geometries could be sprayed in place, one after another, by discretizing the original geometry. The Kuka adjust the global position to allowing the maker to manufacture the entire form.
-12,000,000 reactions between limestone and oil shale during spontaneous combustion occurred in Israel to form a natural deposit of cement compounds.
12,000,000 REACTIONS BETWEEN LIMESTONE AND OIL SHALE DURING SPONTANEOUS COMBUSTION OCCURRED IN ISRAEL TO FORM A NATURAL DEPOSIT OF CEMENT COMPOUNDS.
FORMWORK TIMELINE

CHRONOLOGICAL DIAGRAM OF FABRIC & FLEXIBLE FORMWORK LINERS.
* ORIGINAL DIAGRAM BY ANDREOLI, 2004 [53]
ROBOTIC FABRICATION TIMELINE

THE RESEARCH PROJECTS HERE MENTION ARE BASED UPON THE INTEREST OF THIS THESIS.
PRECEDEMENTS

GEOMETRY

NERVI
TORROJA
CANDELA
GRAMAZIO & KOHLER

FABRICATION

TAILORCRETE
ADAPA MOULDS
ODICO
C.A.S.T.
ADAPTABLE LINEAR ACTUATORS BY ADAPA MOULDS

Point control adaptable formwork, various manufacturers and fabrication researchers are using flexible formwork to minimize the cost of production and the waste of moulds materials.

This methodology presents multiple advantages and disadvantages. For example, the initial mould is expensive, but it can be reused multiple times, the linear actuators have a maximum and minimum range, limiting the geometry. Actually, this method only presents the possibility of precasting the elements. The biggest advantage is the long life of the mould and that its material waste is zero.

REUSABLE WAX
3 AXIS MILL
BY TAILORCRETE

Multiple manufacturers use machinable wax to mill double curvature custom formwork. The waste is then collected and melted for reuse.

LOW COST EPS-FOAM
3 AXIS MILL
BY TAILORCRETE

Multiple manufacturers use EPS-foam to mill double curvature custom formwork. For multiple reasons:

1. Low-priced
2. Light weight / easy to ship
3. Easy to mill

1 cubic foot of EPS-$4.50 and weights 1 pound. Advance CNC machines can mill up to 1200 inches per sec.
6 AXIS HOT WIRE CUTTER FOR EPS-FOAM, HAS BECOME A COMMON METHOD TO GENERATE FORMWORK. HOT-WIRE CUTTING PROCESSES HAVE BEEN COMMONLY USED IN THE FOAM INDUSTRY FOR MAKING SCULPTURES, EXTRACTION OF RAW MATERIALS. THE PROCESSING TIME OF HOT-WIRE CUTTING METHODS ARE COMPARATIVELY FASTER THAN OTHER MANUFACTURING METHODS. POLYURETHANE FOAM'S INHERENT PROPERTIES OF A LOW MELTING POINT AND SOFTNESS FACILITATES THE PRODUCTION OF DESIRED SHAPES EFFORTLESSLY, MAKING IT ONE OF THE MOST POPULARLY AVAILABLE MATERIALS USED WIDELY IN CREATION OF MOULDS, SCULPTURE AND VARIOUS OTHER EXPERIMENTAL FORMWORKS.

ADVANTAGES
1. LOW-PRICED
2. LIGHT WEIGHT
3. FAST
4. GOOD FINISHING
5. HIGH VOLUME

DISADVANTAGES
1. LIMITED TO DEVELOPABLE SURF.
2. GENERATE WASTE
3. LIMITED BY THE ROBOT RANGE

COMMON APPROACHES OF FORMWORK

IF FORMWORK IS COMMONLY INFORMED WITH THE GOAL OF EFFICIENCY AND ECONOMICS, THIS THESIS ASKS WHAT EMERGES WHEN IT IS INFORMED WITH STRUCTURAL, ENVIRONMENTAL, FORMAL, OR PROGRAMMATIC CONCERNS. I SEEK TO BROADEN THE DISCOURSE OF ROBOTS IN ARCHITECTURE BY USING EXISTING TECHNOLOGIES THAT WE CAN FIND TODAY IN FABLABS, LOOKING TO EMBODY INTELLIGENCE IN CASTING PROCESSES THROUGH A DIRECT FEEDBACK THAT PRODUCES A RECIPROCAL RELATIONSHIP BETWEEN FORMWORK, CASTING AND DESIGN.
1. APPLICATION

AIR COMPRESS CONTROL DOUBLE CURVATURE SURFACE. PRESENTS THE CAPACITY TO ADAPT TO MULTIPLE POSSIBLE GEOMETRIES, WITHOUT THE COST OF HARDWARE.

2. ADAPTATION

REALTIME ADAPTABLE FORMWORK, PRESENTS THE POSSIBILITY OF GENERATING A CLOSE LOOP BETWEEN THE PHYSICAL CAST AND THE DIGITAL MODEL, RECALCULATING THE OVERALL GEOMETRY TO ACCOUNT FOR TOLERANCES.

ADVANTAGES

1. REALTIME INTERACTION
2. TOLERANCE ADAPTABLE
3. ADAPTABLE CAPABILITIES
4. COMPLEX GEOMETRY
5. REUSABLE
6. ZERO WASTE
7. DIGITAL FEEDBACK
PROPOSAL

ADAPTABLE MOLD

ROBOTIC ARM

PROGRAMABLE FORMWORK
SPRAY IN SITE
DEPLOYMENT

CAT TL 975 C WITH STABILIZERS
APPROX. REACH = 75'

JLG TELEHANDLER 450 LRT
APPROX. REACH = 45'

KUKA KR300 R2500 ULTRA
APPROX. REACH = 12'

KUKA AGILUS KR 6
APPROX. REACH = 6'

LUISEL ZAYAS 73
MINIMUM RADIUS

SECTION 01
MIN RADIUS ↓ 18"

SECTION 02
MIN RADIUS ↓ 18"

SECTION 03
MIN RADIUS ↓ 18"

SECTION 04
MIN RADIUS ↓ 18"

SECTION 05
MIN RADIUS ↓ 18"
RELAX MODEL
MIN RADIUS = '18"
SURFACE DISCRETIZATION
15,000 cu ft approx.
190 index surfaces
ASSEMBLY LOOP 01
9 Toolpaths
ASSEMBLY LOOP 02
13 Toolpaths
ASSEMBLY LOOP 03
16 Toolpaths
ASSEMBLY LOOP 04
16 Toolpaths

SPLINE 80
SURFACE INDEXATION
+/- 20" X 20"

CONTROL POINT
REBUILD 4 X 4

CURVATURE ANALYSIS
MEAN ANGLE

Z VALUES
NURB SURFACE

CASTING
PLASTER / GFRC

DEMOLDING
RETRACT THE Z AXIS
1. ADAPTABLE MOLD
2. FAST SETTING PLASTER WITH FIBERGLASS CHOPS
3. GFRC
   PORTLAND CEMENT
   POZZOLANA ALTO-POZZ
   FINE SAND
   GLASS FIBER CHOPS
   SUPERPLASTICIZER
   DEFOAMING AGENT
   SET ACCELERATOR
   GLASS FIBER MESH
4. CONCRETE SEALER
5. SPRAY INSULATION FOAM
SPLINE
RETHINKING CONCRETE IN THE DIGITAL ERA
CASE STUDIES

- Amazon Rainforest
- Bridgeway
- Arctic Circle
- Sahara Desert

FABRICATION

- Fabrication processes
- Material studies
- Assembly techniques

SPLINE 110
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