Medial representations for driving the Architectural creative process

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1 Introduction

Medial representations of shape provide a powerful framework for the analysis and genesis of architectural forms, layouts, landscapes, cityscapes. In this paper we explore their potential use in driving the architectural creative process for 2D and 3D applications. We consider both the aspects of (i) the analysis of existing architectural layouts, and (ii) the genesis of novel ones.

The archetypal medial representation of shape is the “medial axis” of Harry Blum (circa 1960) [4, 34]. Boundary elements, the outline samples of the objects of interest, are used as the source of a wavefront propagation, for which the quenching points constitute axial symmetries. In 2D layout applications the resulting medial axis \( \mathcal{MA} \) takes the form of a graph which unites geometry and topology of the objects and the field they occupy in one single framework (Fig.1).

In the following we first survey the topic of shape representation via medial structures and consider their specific use in architectural analysis and genesis. We then report of early works in extending such ideas for novel applications relevant to architecture.

2 Medial Representations for Architectural Analysis

Nearly 50% percent of the world population now lives in cities (closer to 75% in industrialized countries), up from 4% in 1800 and 14% in 1900 [5]. The needs for the 3D modelling of large cities to support efficient urban


Figure 1: Adapted from Gert van Tonder’s website (www.cis.kit.ac.jp/~gert/medax/medax.html). “Whereas ripples on water traverse through each other (A), one also find ‘waves’ that can block each other (B).” Blum imagined a grassfire which spreads from sources (here dots) and eventually coalesces along a (medial) line at equidistance between the sources (B). A propagation initiated from a triangular source outline (C), stops along the “Y”-shaped \( \mathcal{MA} \) inside the figure (NB: convex shapes have no outside \( \mathcal{MA} \) parts). The grassfire metaphor is equivalent to tracing the centres of the largest (maximal) discs that can just fit inside or outside (if concave) the source outline figure (D).
information systems are present and growing, in particular in the domains of urban planning and management, civil protection, environment surveillance and crisis mitigation, and sensor network modelling. One key aspect that requires new technological development is in the management of reconstructed 3D scenery in a geographical context [30]. This in turns calls for a representation of 3D data permitting spatial queries going beyond today’s essentially 2D GIS (Geographical Information Systems) [29].

Spatial queries in a 3D graph structure have been proposed by Jiyeong Lee et al. to be based on the “straight” $\mathcal{M}A$, i.e., a simplified medial axis restricted to the description of polygonal layouts [27, 28, 24]. One advantage of abstracting 3D volumes via a medial graph structure is to allow for a hierarchical organization of the data at multiple scales, which is supported by studies on human abstraction of geographic space [10]. In the system of Jiyeong Lee et al., a series of 2D $\mathcal{M}A$ for the communication network (e.g., the hallway structure), augmented to capture all useful horizontal connectivities (e.g., between rooms), are stacked-up and connected vertically to capture the spatial relationships between 3D entities of an entire building. Each augmented 2D $\mathcal{M}A$ represents a level in a building, i.e., typically a floor layout.1 This 3D GIS has been augmented to integrate a ground transportation system together with the hierarchical representation of buildings, in the context of emergency responses in times of crisis (such as due to natural disasters, fires, terrorism) [24].

In the context of the built environment, spatial analysis is also fundamental to humans, to create internal images of the urban area, the city, the village. The representation of the built structures is understood as “cognitive maps” which are used to plan movement, and navigate by different means, such as driving, cycling, walking. In particular, predicting human spatial behaviour in urban environments has been modeled by a space syntax based on axial maps [20, 38]. These maps are constructed from “lines” derived from the main means of communication between or within buildings, such as roads, alleyways, corridors, and so on. An axial map consists of a minimal set of axial lines which preserves the connectivity of the space, such that every axial line which may connect a pair of otherwise unconnected axes, is included [47]. The concept of an axial line itself comes under various definitions, from the straight centerline of a communication pathway, i.e., its straight $\mathcal{M}A$, to lines connecting vertices of “obstacles” (e.g., corners of buildings), thus delimiting “isovists,” i.e., the free space that can be seen from a vantage point [2].

An axial map for a given cityscape (Fig.2) is then used to measure certain spatial properties such as “connectivity” and “integration” [21]. Connectivity is a local measure computed for a particular axis based on the number of other connected axial branches. Integration is a more global measure which evaluates how many axes need to be traversed to reach a particular goal; this can also be understood as the (topological) depth in the graph one

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1This use of stratified 2D layouts abstracted by a graph structure, through the $\mathcal{M}A$, is favored as (i) it naturally captures the important topological structures of human-made buildings, and (ii) it permits to more easily extend existing 2D-based GIS systems. Note also, that this construction of a “3D” $\mathcal{M}A$ by stacking-up a sequence of 2D (horizontal) $\mathcal{M}A$’s is similar to the Intensity Axis of Symmetry concept of Gauch and Pizer to model topography [18].
needs to traverse to reach a certain goal from a starting point.

According to Le Corbusier, architecture is “based on axes” [13]. Axes are defined by walls, corridors, lighting, the spatial layout of other design elements. “Good architectural design thus enables the observer to extract relevant spatial information” [54]. This is particularly relevant in wayfinding in a building and is known as “architectural legibility” or “intelligibility,” i.e., the capacity of a space to give clues to the understanding of the whole system [20]. The complexity of an axial system for a building can be evaluated in terms of linearity (how straight a path is), connectivity (as for the space syntax above), and consistent alignment with respect to main reference axes (e.g., when moving from floor to floor) [54].

Another major issue in architecture is to capture form and function in a uniform, integrated framework. Typically, form is encoded in sets of connected floorplans and profiles delimiting the outlines of main walls, doors, stairways, bathrooms, windows, and so on. Function encodes the integrated relationships of these different elements; that is, not only their respective position and label, but how they interact: e.g., how a door relates one room to another, how a staircase loops around a set of walls. In architecture “axial systems” capture the “symmetry between objects” [39, 40]. Applying the 2D MA to floorplans and profiles offers the possibility to capture the tracing of symmetric outlines — as the envelopes of maximal contact disks centered on the MA or via sweep functions. Furthermore, it also captures how various elements are interconnected, and how movement through the intermediary created space is possible.

The 3D MA offers the additional possibility of capturing how volumes are created both within and outside the architectural structures, specifying their form, volume and topology [31, 32]. The 3D MA also captures the detailed traces of ridges and associated main central axes of many structural elements used to construct the basic frames of buildings, including walls, floors, ceilings, stairs, ramps, and so on. This is useful for structural analysis as well as for shape rendering in graphics packages based on defining central axes, and sweeping profiles (i.e., the generalized axis representation). A generative theory of shape by Michael Leyton has been applied to architecture, where axes of symmetry (in 2D or 3D) are information carriers summarizing the structure of a building [35, 36].

### 2.1 Medial Representations for Landscape Analysis

When contemplating a garden, we often select what we feel are better viewpoints to admire the structure and layout of the landscape, its plants, flowers, rocks, sculptural elements, and so on. Recently, it was shown by van Tonder et al. that some famous 15th century Japanese garden layout can be modelled by an approximate 2D MA which represents a perceptual (visual) tension flow field [53, 52, 49, 50].

The design of the Ryoanji garden has been a long lasting mystery; van Tonder et al. have shown how by using the rock and plant structures of a garden as the generators of a propagation alike Blum’s grassfire, an approximate oriented flow field they call the HST (Hybrid Symmetry Transformation [51]) indicates the best viewing locus. The dichotomous tree structure of the empty spaces between the five rock clusters of the Ryoanji garden is elucidated by the HST, showing various properties specific to this structure. It clarifies the hierarchical branching pattern, strict branching rule, approximate uniformity of branch nodes, consistent sloping of each branch towards the viewing verandah, convergence of the empty space onto the classical viewing location of the garden, and visual balance of the global structure. Path length over each branch level increases asymptotically, as one would expect for branching structures found in nature. The entire structure repeats locally in the left most rock cluster of the design. The approach enables a new level of formal comparison between different Japanese dry rock gardens, and even between Japanese gardens and their counterparts from various locations around the world [52].

The above study of van Tonder et al. on the use of the 2D MA to describe and apprehend the spatial layout of a garden is echoed in the works of Richard Toth on developing a theory and language for landscape analysis [46]. Toth proposes that relationships between spatial units can be understood as figure/ground patterns which can be characterised, in particular, via Arnheim’s “structural skeleton” [1].

### 3 Medial Representations for Architectural Genesis

While the 2D MA proves useful to study the “horizontal” structure of a garden, the 3D MA is often used to help model plants’ architecture, where the branching structure is built as an assembly of generalized cylinders each representing a branch [14], or more generally via modular graph structures where each module may represent roots, a set of branches, a single branch, a set of leaves, a leaf and its venation pattern, petals, and so on [41]. Shlyakhter et al. use images of actual trees, flowers, and such, to first obtain a 3D volumetric description of the plant by constructing a visual hull from multiple snapshots around it [43]. An MA is then computed to
approximate the main trunk and branches of the original tree. Finally, this skeleton is fed to an “L-system” [37, 42] to re-generate a close approximation of the plant which can be used in off-the-shelf graphics renderers; such a process can then be used to populate an entire ecological “context,” for example in applications to forestry, agriculture, horticulture, landscaping.\(^1\)

In (architectural-size) sculpting, Brower Hatcher et al. have developed a concept for biomimetic sculpture, i.e., sculpture which either mimics living organisms (animals, plants) or incorporates in its form the influence of the environment, e.g., sun exposure, rain, wind, or the proximity of humans. The resulting sculptures take the form of layered scaffoldings constituting a volumetric matrix into which smaller sculptural elements can be integrated. The layering approximates a discrete 3D wave propagation [19].

The 3D MA proves useful in two ways when simulating this biomimetic sculpting process. First, given an initial layer, e.g., giving a description of a natural form, the MA indicates the singularities for the growth, and can therefore be used to automatically either stop propagation or slow it down when near these. This is necessary to obtain a matrix which can be built and can sustain its own weigh. In particular, minimal angles on the final scaffolding nodes need to be imposed (Figure 3). Second, a regular mesh for the 3D MA sheets can itself serve as a set of initial layers to be grown to generate biomimetic scaffoldings [19].

While at IBM Latham and Todd developed the FormGrow and Mutator systems from 1987 to 1993 [26, 8, 45, 44, 3]. FormGrow is a kind of construction kit for creating organic-style 3D computer generated forms. It uses a hierarchical system, building up complex forms from primitive shapes. The central FormGrow construct is a “horn” which consists of n ribs; repeated primitive shapes in the form of generalised cylinders — a tubular specialisation of 3D MA forms. Variants of the basic horn are made by applying elementary transforms: stack (a translational effect), bend, twist, and grow. Mutator allows forms to be “grown” using life-like techniques such as cross-fertilisation (marriage) and mutation. A form — as obtained via the FormGrow system — is expressed as a sequential set of instructions, which constitute its encoding. Mutator reads FormGrow instructions to be combined (if coming from various parents) or modified (simulating mutations). In the original work, the “survival” of a form was governed by human selection (typically embodied by the artist Latham seen as a kind of “gardener” or “breeder” or art-forms) or by closeness to some pre-defined measure (Figs. 4 and 5).

3.1 Genetic architecturas — FormGrow revisited

Recently, Latham and Todd joined Fol Leymarie at Goldsmiths College and founded the Mutator Research Group to revisit and extend the FormGrow and Mutator systems for shape genesis. The initial goal was to bring these ideas closer to realm of biology and to nature’s way of exploring the “shape-space” of possible forms. In a first approach a set of look-up tables were devised to be able to read real DNA and transform this genetic information into FormGrow instructions [25].

In a second approach, more refined information about the use of DNA to build-up proteins was devised. The approach of directly using DNA sequences to generate FormGrow shapes ignores the biochemical characteristics of the amino acids which are the building blocks of proteins and the basic product of the genes encoded in DNA. A protein, in the form of a chain of amino acids, folds into a specific shape, governed by the properties of the amino acids. The general nature of the fold depends upon the general make-up of the amino acid chain. Therefore if we summarise the amino acids content of a protein into a set of numbers, this provides a reasonable overview of the nature of the protein, and how it is related to other proteins. This approach leads to a two-step process for creating FormGrow structures from genes. First, the DNA sequence for the gene is converted into a histogram denoting the relative frequencies of each amino acid type and grouping. We summarise the protein by counting how many of its amino acids fall into each group and also count the amino acids of each type. This produces a histogram “profile” of the protein’s amino acid content. Secondly, these values are used as input into a fixed FormGrow structure.

Recently we used this approach to navigate the shape-space provided by the evolutionary (phylogenetic) tree by tracking proteins back and forth in time via their DNA (Fig.6). This approach allows us to produce 3D architectural visualisations of protein functionalities as carried by their amino acid content (and hence, their original DNA content); a few examples are illustrated in Fig.7; details can be found in [25].

This work is directly in line with the old work of Latham and Todd which represented the origins of a computational realisation of the ideas of Darwin and d’Arcy Thompson crossed with the remodeling of nature such as conceived by architects Capability Brown and Gaudy. The more recent studies on “emergence” of form in “morphogenetic design strategies” is also a source of inspiration for our work [11, 15, 16]. In order for us to pursue

\(^2\) They call their graph structure a Voronoi skeleton, as it is based on algorithms computing the Voronoi diagram of a cloud of points for the vertices of the visual hull.

\(^1\) L-systems (also called Lindenmayer systems or parallel string-rewrite systems) are made from productions rules used to define a tracing of piecewise linear segments with joints parameterized by rotation angles [37, 42]. These rules also are a compact way to iteratively repeat constructive sequences in the description of fractals, often used to model groups of plants, flowers, leaves, and so on [17].
Figure 3: Production of a biomimetic sculpting using the 3D MA (with permission from Brower Hatcher and Karl Aspelund of Mid-Ocean Studio, Providence, RI, USA). (a) A toy bear was laser scanned at coarse resolution to get a 3D solid rendering. (b) The wire-mesh for (a) is used as a source of propagation in 3D. (c) and (d) two steps (layers) of propagation where self-intersections are apparent in the propagation (automatically detected and avoided by the use of the 3D MA [19]). (e) Final biomimetic sculpting rendered in the style of Brower Hatcher.
Figure 4: From [45, Fig. 2.12, p.25] “Nine forms generated by Mutator. The ticks and crosses indicate judgements the artist has made on the forms.”


Figure 5: Examples of organic-like 3D forms produced by the combination of FormGrow and Mutator systems of Latham and Todd [45].
Figure 6: (From [25].) Divergent evolution of two proteins. This is not a conventional evolutionary tree. It shows how ancestor ([9] thinks the proteins are related, based upon the sequence of the proteins in modern organisms. This does not necessarily correspond to the true evolutionary tree, since the signal of evolution in protein sequence is sometimes lost in the “noise” of mutations over billions of years. The arrows show the route of the History of the Species film in visualising the devolution of one protein then the evolution of another.

this line of work we need to build in our design systems better control mechanisms for shape genesis, for example to avoid collisions due to growths, reflect the designers’ ideas at various scale, provide shape analysis guidance (e.g., in the computation of isovists).

3.2 Genetic architecturas — L-systems and GP

Why L-systems and Genetic Programming (GP)? In order to explain the choice of L-systems and the use of the isospatial array, one must make a distinction between the use of genetic algorithms to optimise parameters to a given geometry, and the use of evolutionary algorithms to generate form.

In the case of the optimising approach (used for the past 30 years by engineers) the macro decisions about form, and the fundamental design decisions are already taken. For instance in the well documented procedures for developing the hull of a boat, while the algorithm can develop a set of appropriate spline curves to make up the shape, using random perturbations of spline curves, and a model of hydraulic drag on the developed surface, it would not be possible for such an algorithm to generate a multi hulled solution (catamaran), since the initial problem description has specified a solution space that only includes single hulled morphologies.

The problem with such attempts is that nothing more than fine tuning can take place. The aim of the current research is to try as far as possible to avoid over specifying of the problem domain, in the hope that the evolutionary algorithm will be able to search over a wider area of possible solutions. In order to do this we have to find a neutral description of 3D form, which is capable of embodying the widest possible range of objects, and a methodology of form generation which is responsive to evolution and not predefined by a particular technology ([7, 6, 12]).

The isospatial grid

The fact that the Cartesian coordinate system is so universally adopted in mathematics, software design and the design professions generally has lead to an over reliance on orthogonal geometry, and a tendency to assume that cubic tessellations are the natural way to represent 3D form. The Cartesian grid with its three planes and 3 major axes per point, while capable of representing any arbitrary object, is nevertheless fundamentally aligned to the idea that the three dimensional objects are just projections of the two dimensional plane, which in CAD terms are usually defined as two and a half dimensional. Things which are not projections of the plane are much more difficult to model than simple orthogonal objects.

The orthogonal grid also has built in to it a lack of homogeneity (and a bias in favour of orthogonality) because the orthogonal distances between points are not the same as the diagonal differences. In the Cartesian grid, the distance between a point and its 27 neighbours (plus or minus one cell away in all directions) varies between the unit distance along the 3 axes, the distance to edge joining cells, and the distance to vertex joining cells. In a cellular automata for instance, where neighbour counting is the basis of state change rules, it is necessary to build in weighting factors to overcome the problem of the three different distances between the neighbours of a point (face, edge and vertex).
Figure 7: Stills from the animation “History of the Species” (http://hos.mrg-gold.com).
The isospatial grid on the other hand, is defined as a point and its 12 neighbours as defined by a dodecahedron. This repeats across 3d space, just as the orthogonal grid does, but without the three different point to point distances of the orthogonal grid. Carter Bays and John Fraser (Bays 87,88) (Frazer 95) have both used this grid in cellular automata, in place of the cubic grid, and triangular tiling rather than square tiling has been adopted for 2d cas as well. This grid, with its 12 same distance neighbours from any point would seem to represent a more "neutral" method of representing spatial objects, and in particular offers generative algorithms a simpler and more robust set of relationships between particles of the system. With 6 axes and 4 planes of symmetry it is a superset of the Cartesian grid, and can accommodate orthogonal relationships, but does not presume them.

In a project where the aim is to work towards the evolution of form with the minimum of preconceived notions of what constitutes it, this geometry seems more appropriate than many, hopefully leading to novel objects where the form could truly be said to emerge from the process of fitness testing, rather than being an artifact of the method of representation.

Co-evolution starting with the basic growth mechanism and testing with a variety of fitness functions it was shown that the system is responsive morphologically to a range of evolutionary pressures. however to satisfy the above stated desire to explore more emergent outcomes a series of co-evolutionary systems have been defined where a group of L-systems evolve together.

1. mutually supporting structures where the fitness of one system is defined as how well it supports the others
2. served/service collections where the fitness of the served spaces is defined by how well served they are, and the fitness of the service system is defined by how well it services the spaces. in this case the service system is seen as circulation the served as usable space

the screen shots show outcomes for the load model system and earlier experiments on self supporting structures.

4 Future work

Med. rep. to control/drive the creative process

4.1 2D layout mechanisms

There is the series that looks at directionality of places due to relationships of edges (Fig.8) and one that looks more in the Gert van Tonder way at the decision making point and how objects/edges/points configure into compositions to create points of potential = decision-making (Fig. 9). There are also the images of slopes towards the medial lines. In reference to Voronoi diagrams, the ridges and the so far ‘invisible’ points between edges and medial lines constitute gradients of adherence to a space, or possibly tendencies of directions.

The images are not strictly generative more analytical, but they could become generative if indicative analysis would influence the way edges are transformed and new edges set. this doesn’t ahve to be in an urban context. For the project at Aedas infact, we thought it best for internal architectural spaces, but then we need really a 3D tool.

All the images related to this section (Figs.8, 9 and 2) have been produced with a prototype java program developed at the R&D department at Aedas Architects. The intention of the prototype was to test and develop medial axes based representations and analysis of spaces. Right now it incorporates a simple geometry editor which allows to interactively create and modify polygons, which can represent building volumes or other type of bounded enclosure. This interactivity allows to design the distance fields and medial axes for simple diagrams: in the interior of the polygons this can be used for planning circulation paths and natural light exposure; outside it suggest a partitioning of space and the appearance of a structure of potential routes equidistant to the closest buildings. Some of the results of these first experiments suggest a correspondence between the medial axes and the routes one would follow intuitively on a space; the prototype suggests thus the interest of investigating empirically this apparent correspondence, and assessing the relation between medial axes and the actual movement of people in a space.

4.2 Application to Architectural Massing

Architectural massing is "the act of composing and manipulating 3D forms into a unified, coherent architectural configuration" [55, p.31]. The architectural massing task is one of combined synthesis and analysis of 3D form. The synthesis gives the initial impetus to the design process, while the analysis provides the necessary feedback mechanism.
The design process is regulated by “divide and conquer” actions; the popular regulating element for this activity is “the symmetry or alignment line” used as a reference or meta-element for other design elements (at lower levels) [55, p.35]. This is an instantiation of Gestalt-like principles permitting to relate, and define, the whole with its parts [32]. The whole and parts relationships lead to the notion of hierarchy, useful in dealing with the layered complexity of architectural designs. Axial lines are used as explicit representations — e.g., corridors, of oriented space — as well as “implicit” (virtual) ones, used to constrain the design process — e.g., an axial gesture indicating the growth of an architectural mass, limiting a roof angle, etc.

Numerous studies in the strategic use of representation in architectural design have been carried out (e.g., refer to [22, 48, 23, 55]). These studies seek a better understanding of the specific cognitive processes contributing to design in order to help the designer improve the management of the overall design process through strategies that facilitate the discourse with their graphic representations. One of the studies, by Akin and Moustapha [55], focused on architectural massing and contended that designers use the medium of representing massing elements to manage the design process itself. Moreover, a major issue of concern in the study was the lack of computational support for massing strategies and the ability to restructure massing configurations was highlighted as the area in which computational support should focus on. In turn, we propose to take advantage of the properties inherent to Medial Scaffolds (a 3D extension of Blum’s MA) to support feedback and analysis mechanisms in the architectural massing process.

**Medial Scaffolds for Architectural Massing**

Medial (and shock) scaffolds were recently introduced in 3D computational shape theory to help in the analysis and recognition of free-form objects, as well as in the modeling of the geometric aspects of complex scenery, such as environments populated by multiple objects [31, 32, 33]. The underlying theoretical framework for such scaffolds is the notion of “symmetry sets,” the loci of centers of bitangent spheres in contact with structural elements, such as architectural massing bounding surfaces. While the symmetry sets are made of intersecting surfaces in 3D, the medial scaffolds are 3D graphs made of medial nodes connected via medial links. To each node and link is associated a radius function which captures the diameter of the contact spheres relating “symmetric” architectural massing boundary elements; thus the constraint in space of an axial line is made explicit in the medial scaffold representation.

One advantage of using a geometric formalism as provided by medial scaffolds is in capturing explicit representations of massing elements and space, this for potentially arbitrary complexity in form; e.g., the free-forms associated to sculpture. Two types of regulating lines are used to this purpose: (i) proper axial links which captures the medial symmetries typically drawn by the architect or designer (either as explicit axes or implicit ones), and (ii) ribs of surface ridges, which capture sharp or rounded angles are encoded by the radii functions which are allowed to go to zero, thus making explicit the sharpness of a surface ridge.

While in the field of shape theory where these constructs were devised, the medial scaffolds are meant to be used mainly for (visual or perceptual) analysis, we propose to extend their application to the support of feedback mechanisms (synthesis – analysis) typical of the design process, and provide an implemented prototype to test their usefulness. The formal grounding of the theory also permits to tackle issues of topology versus geometry (e.g., holes appear as explicit loops in the medial scaffolds), build hierarchies in the representation (e.g., distinguish the significance of various symmetry relationships), capture a typology of deformations (e.g., based on the seven transition of medial scaffolds), such as protrusions and indentations, elongations and splits, compressions, surface torsions, attachments.

**Development of a teaching aid**

The development of architectural massing for any urban or architectural project is part of a cyclic iterative design process incorporating considerations of function, unity, magnitude, expression and structural, constructional and other technical considerations. Any one of these fields of study can lead to the preliminary generation of architectural form. Forms established in any of these fields must then be tested against the requirements and constraints of all other fields.

The development of form generation using medial scaffolds has synergies with the architectural form finding process. Our work aims to test these synergies through a series of student design projects using specially adapted medial scaffold form generating software and to evaluate the results against existing physical and digital form finding tools, this with a view to developing the software as a teaching and design aid.
References


