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Designing and Making a Movement Infrastructure

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Abstract

The geometry and symmetry characterizing the regular and semi-regular polyhedra has a major impact in the manmade world of building systems. The geometric properties of polyhedra can be applied not only to the world of design and construction but can also be used to interpret the proportions and movement of the human body. This paper describes a computational methodology to design and build three-dimensional structures for movement practices based on the regular convex polyhedra —also called Platonic solids. A parametric approach is applied to design these structures —here defined as “movement infrastructure". Contemporary design and fabrication technologies are applied to the theories of movement by Rudolf Laban, which were introduced in the first half of the twentieth century but still have a major influence in the field of dance and human movement analysis. Prototypes have been built assembling parts fabricated using 3D printing technologies and off-the-shelf components. Such a parametric approach can be further applied to design and build a “movement infrastructure” at several scales and made of different materials, varying from private indoor home use to public outdoor settings.

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Keywords: 3D printing, Cube, Design, Dodecahedron, Geometric Form, Laban Icosahedron, Movement Infrastrucutre, Octahedron, Parametric Models, Platonic Solids, Rapid Prototyping, Science Technology Engineering Art Mathematics, Spherical Symmetry, Structural Form, Tetrahedron

1. Introduction

Rudolf Laban (1879-1958), one of the most influential theorists of human movement, developed a taxonomy of movement routines related to the five regular polyhedra: tetrahedron, cube, octahedron, dodecahedron, icosahedron

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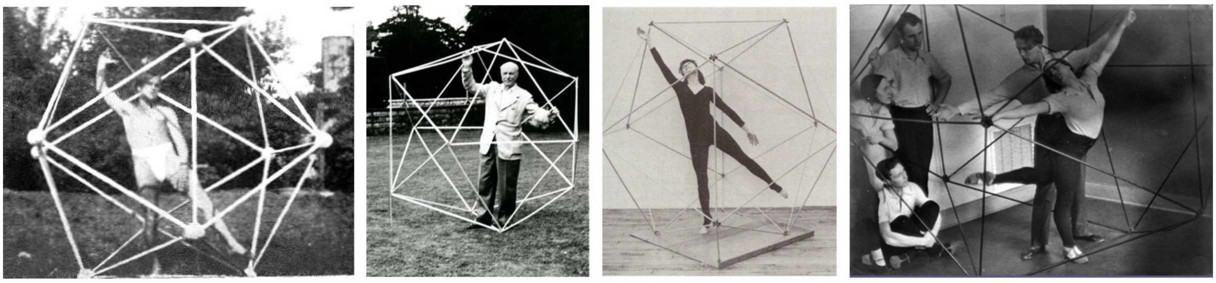
[1, 2, 3]. His theories were illustrated with drawings and models built constructions based on the Platonic solids, were used in dance training and performances. The icosahedron was the polyhedron most used by Laban and, in the field of dance, is often referred to as "Laban icosahedron". Photographs of dancers, practicing and performing inside an icosahedron, date back to the second decade of the XX century, when Laban lived and worked in the colony of Monte Verità in the Swiss town of Ascona [5, 6]. The Laban icosahedron has continued to being used in dance as well as in and other performing arts.



a b c d

Fig. 1. The Laban icosahedron and movement practices: (a) photo of dancer from *Choreographie*; (b) "Photographs" (1955), Rudolf Laban: NRCD. URL: <http://www.dance-archives.ac.uk/media/1207>; (c) Image retrieved from http://www.amplab.ca/2014/10/23/labanotation-topology-moving-body/; (d) Image retrieved from http://www.dcd.ca/exhibitions/sutcliffe/icosahedron.html

Although the icosahedron was the most prominent polyhedron in the theory of movement developed by Laban, the relationship between human movement and the other four Platonic solids was explored as well [7]. But while the icosahedron was built at human scale, the movement studies relating to the other four solids —often called "crystals" by Laban and his scholars— were mainly documented by sketches, artists renderings, diagrams and scale models [8, 9].

The relationship between human movement and geometry is also the research topic of the author's doctoral study. The research quantitative methodology is mainly based on data collection from movement practices inside a built "movement infrastructure" related to the Platonic solids. The design and construction of the five regular polyhedra —of such size and structural strength to accommodate a performer— has become an essential component of the research. Ease of fabrication and cost affordability are also design constraints which suggest the use of ready-made components.

This paper outlines the design and fabrication of a "movement infrastructure" comprised of custom parts and off-the-shelf components. The parametric and CAD modeling process of the Platonic solids —described in the other paper published by the author in these proceedings [10]— is further developed for the design of custom components. These components have been 3D printed as prototypes but also designed for other fabrication processes.

Nomenclature

CR	radius of the circumsphere whose surface contains the vertices of the polyhedron
EL	length of polyhedron edge
a	polyhedron dihedral angle
b	angle defined by the centre of polyhedron and sets of two vertices endpoints of each polyhedron edge
f	golden ratio equal to numerical value 1.618033988 [11]

2. The Five Platonic Solids Geometric Properties

A general definition of the geometry of the five Platonic solids assists in the quantifiable parameters of design and fabrication for the "movement infrastructure". Table 1 summarizes the geometric properties which will be used in later sections to establish computational design rules. A more complete description of the Platonic solids can be found in the other paper by the author published in these proceedings [12].

Table 1. The Five Regular Polyhedra as Geometric Entities

Polyhedron Name	Number of Faces	Number of Edges	Number of Vertices	Schläfli Symbol {n, q} [13]	a angle	b angle
Tetrahedron	4	6	4	{3, 3}	70.53°	109.471
Hexahedron (Cube)	6	12	8	{4, 3}	90°	70.529
Octahedron	8	12	6	{3, 4}	109.47°	90.000
Dodecahedron	12	30	20	{5, 3}	116.57°	41.810
Icosahedron	20	30	12	{3, 5}	138.19°	63.435

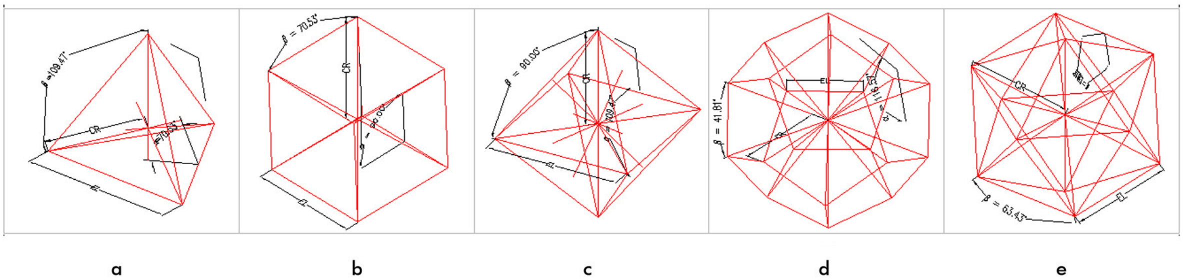


Fig. 2. The Platonic solids and their angles: (a) tetrahedron; (b) hexahedron; (c) octahedron; (d) dodecahedron; (e) icosahedron

3. The Human Body Proportions and the Icosahedron

The design and construction of the "movement infrastructure" brings human and ergonomics factors relating to the movement to be performed inside each geometric shape. A detailed discussion of such factors goes beyond the scope of this paper but a summary can be essential to understand the design and fabrication process.

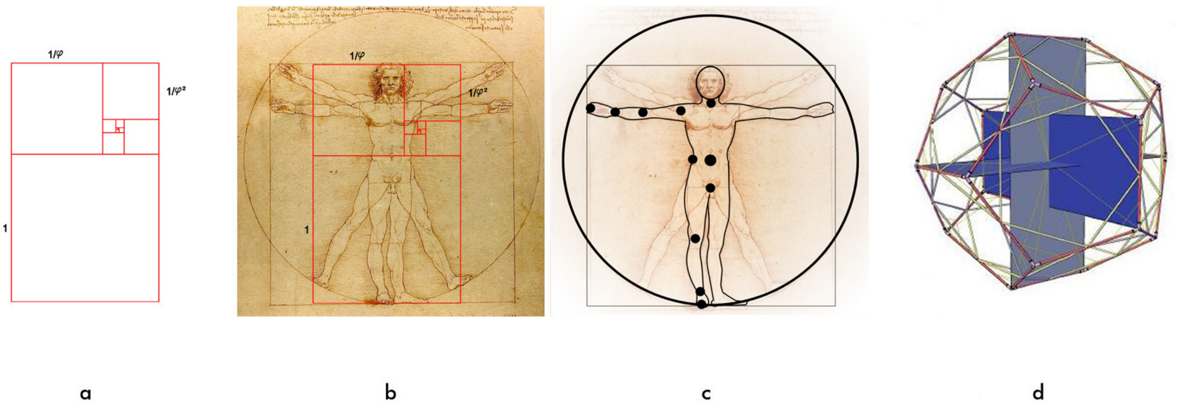


Fig. 3. Human proportions and the icosahedron: (a) rectangles following the golden ratio; (b)Vitruvian man and golden ratio; (c) Virtruvian man and movement rotations joints; (d) the three anatomical planes inscribed in the vertices of the icosahedron

According to several studies on human proportions [14, 15] the ratio between the height and the distance between the navel and feet of a human body can be approximated to the golden ratio f; such distance can also be considered an approximate location of the center of gravity of the human body. The vertices of an icosahedron can be grouped to define three sets of orthogonal rectangles whose sides are proportional to the golden ratio. These rectangles also lie in the three anatomical planes —sagittal, frontal, and horizontal— of a human body whose navel is at the center of the icosahedron.

4. The Platonic Solids Become a "Movement Infrastructure": From Digital Models to Fabricated Parts

The "movement infrastructure" designed by the author comprises a set of five regular polyhedra designed according to the proportions of her body, and built as an hybrid system. A numerical relationship essential in the design of the polyhedra is the relationship between CR and EL where CR represent the navel height in the human body.

$$EL = 2 \cos\mathbf{b} \; CR$$

Each polyhedron is defined as a hollow structure geometrically composed of a set of vertices and edges; the faces of the polyhedron are eliminated for these purposes. The edges are made of off-the-shelf components while custom designed vertices act as joints which connect the edges. The geometry of the vertices/joints of the polyhedron is defined by the intersection of the q edges meeting at each vertex as specified by the Schläfli symbol {n, q} in Table 1.

4.1. Defining and Specifying the Polyhedron Edges

The polyhedron edges, which are geometrically defined as lines, represent a dominant quantitative entity as well as a simple geometry –a line identified by two endpoints. They can be fabricated from off-the-shelf components, selected according to functional requirements. The function determines the structural characteristics and related material; the outdoor or indoor settings define the material specifications as well as the required thickness and profile. The following geometric characteristics are considered:

- hollow or solid profile
- profile geometry —e.g. circle, triangle, square.

These properties determine the design of the vertex/joint. Three different concepts have been explored and designed for all the five Platonic solids.

4.2. Finding an Aesthetic Intention in Designing and Fabricating the Polyhedron Vertices

The design of the joints connecting the edges of the polyhedron represents the main exploration in the construction of the "movement infrastructure". This process leads not only to the fabrication of an utilitarian object, but is also characterized by an aesthetic intention. The geometry of the regular polyhedra defines and inspires also the geometry of movement sequences and is expressed in the vertices/joints. There are several commercially available connectors for the assembly of pipes/tubes, including spherical joints and other connections systems utilized in space frame structures [16]. Nevertheless the expression of the specific geometric relationship of each polyhedron configuration was the motivation which led to design custom solutions for 3D printed prototypes of connectors. The custom designed joints can be grouped in three different concepts.

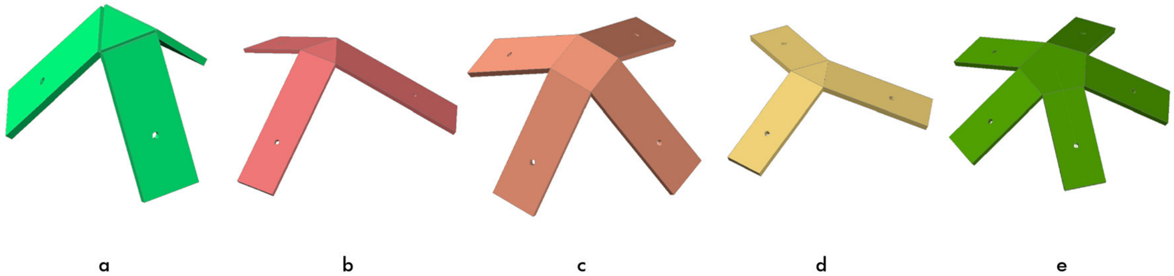


Fig. 4. Vertex as a structural connection: (a) tetrahedron; (b) hexahedron; (c) octahedron; (d) dodecahedron; (e) icosahedron

Concept "A" (figure 4) deals with vertices/joints connecting edges with a polygonal profile, e.g. a square. This design is best suited for metal sheet cut and bent to follow the polyhedron b angle. The bent metal joint/vertex is then fastened to the edges made of polygonal tubes.

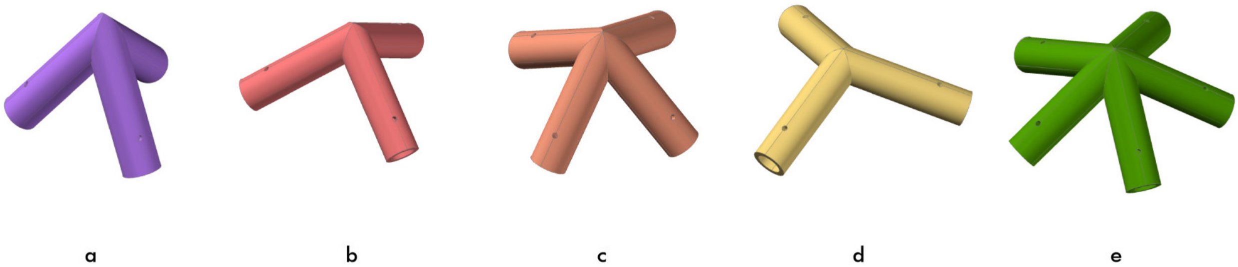


Fig. 5. Vertex as a structural connection: (a) tetrahedron; (b) hexahedron; (c) octahedron; (d) dodecahedron; (e) icosahedron

Figure 5 shows design drawings for concept "B" developed for edges made of tubes or pipes with a circular profile. The joint is a circular tube acting as male or female connector, which geometrically can be considered a continuation of the edges. A q number of such tubes tilted at a b angle are extended to their intersection with each other. A suitable fabrication process is based on welding of metal tubes, each sliced at an angle equal to 360 degrees/ n, where n is the number of sides of the polyhedron face, specified by the Schläfli symbol {n, q} in Table 1.

Concept "C" (figure 6) is also based on edges with circular profile. The vertex connector continues the cylindrical extrusions of each edge. Each pair of adjacent cylindrical extrusions is then connected by solids generated by sweeps or lofts of profiles offsetting the edges profile. This vertex connection is geometrically the most complex as shown by the graphic construction in figure 6. The fabrication processes for such joint include injection molding and metal casting.

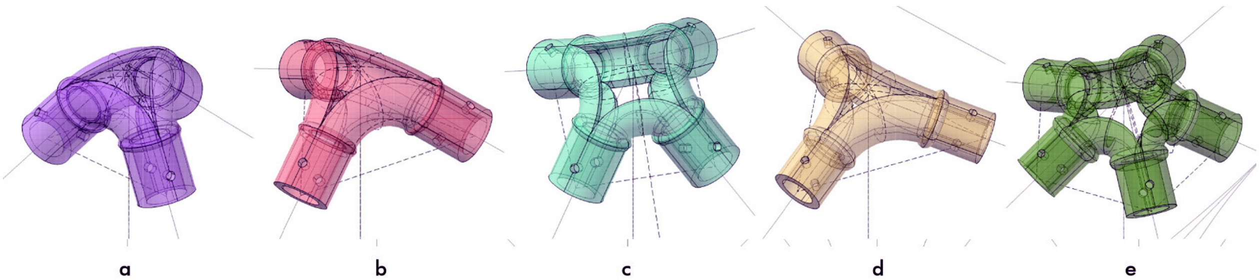


Fig. 6. Vertex as a structural connection: (a) tetrahedron; (b) hexahedron; (c) octahedron; (d) dodecahedron; (e) icosahedron

5. Fabricating and Practicing in the "Movement Infrastructure"

"Movement infrastructure" prototypes have been fabricated with 3D printed vertices/connections and PVC pipes. The length of the CR (defined in the nomenclature) is relevant for the movement practice since it refers to human proportions —as summarized in section 3. The connections have been fabricated of PLA and ABS plastic using the 3D printers Makerbot Replicator and XYZprinting.

A set of the five Platonic solids of a CR measuring 150 centimeters has been built with concept "B" connections and PVC pipes of ¾ inches diameter. This movement infrastructure has been located in outdoor settings and several movement practices have been performed inside the icosahedron (figure 7). The edges of the icosahedron guide the performer in movement alignments, emphasizing the geometry of the human body.

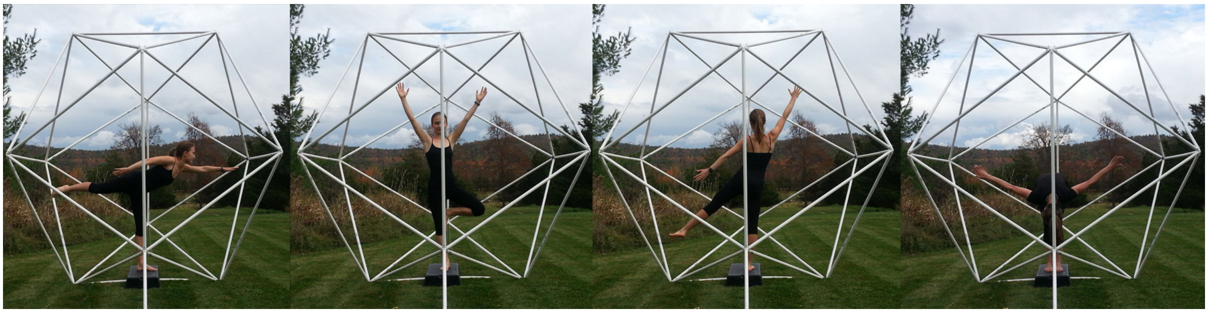


Fig. 7. Outdoor movement practice in the icosahedron

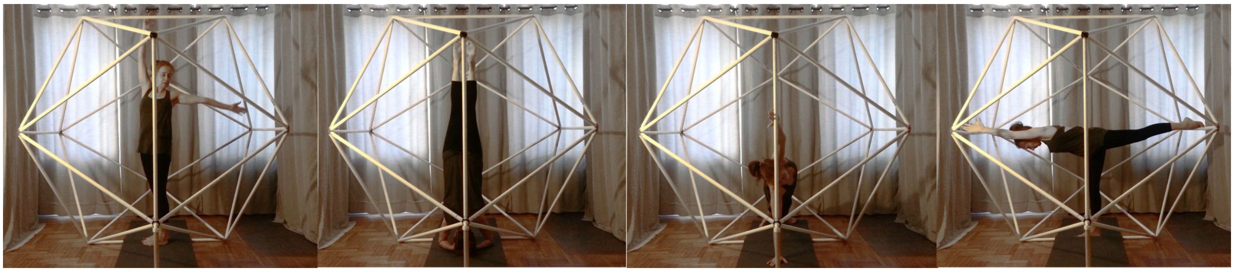


Fig. 8. Indoor movement practice in the icosahedron

A second "movement infrastructure" prototype has been fabricated only for the icosahedron. The connections follow concept "C" and have been 3D printed from ABS plastic. The CR measures 100 centimeters which is the performer's navel height. This icosahedron is located indoors and it has been used for daily movement practices inspired by the polyhedron geometry. The initial vertices-edges relationships generate a multitude of more complex geometric explorations associating the performed movements to intersecting spirals, helices and Hamiltonian paths.

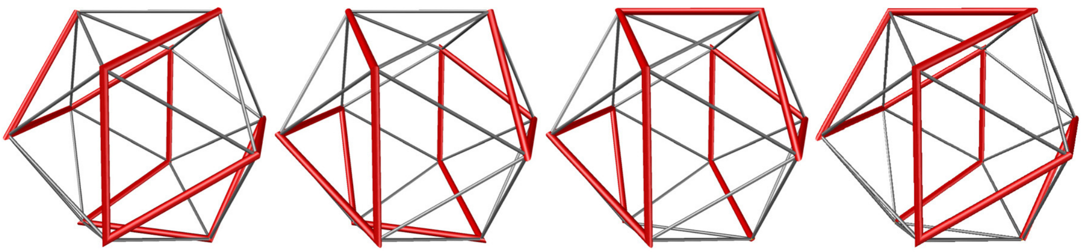


Fig. 9.Hamiltonian paths in the icosahedron

In Laban's theories [16] there are several references to Hamiltonian paths —mathematically defined as "a graph path between two vertices of a graph that visits each vertex exactly once" [17]. Figure 9 shows four different Hamiltonian paths inscribed in the same icosahedron. Movement sequences are being designed according to the movement of a leading arm following each Hamiltonian path. The mapping of movement data to geometric forms is currently being developed, using motion tracking, computer animation and video postproduction.

6. Conclusion

This paper has summarized the relationship between Platonic solids and human proportions, which was explored in Laban's theories on human movement. Prototypes of a "movement infrastructure" have been designed and built using 3D printing and off-the-shelf parts, with the intent to further investigate Laban's theories in the context of the geometric properties of movement. The author plans to develop further prototypes for home fitness equipment and public art.

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