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Development of Virtual Reality Environments to Visualize the Fractals of the Dragon's Curve Using Plato's Polyhedra

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Abstract

This article presents the adaptations for creating a set of Dragon Curve fractals using the Platonic polyhedra. The modeled fractals were inserted into environments programmed with Virtual Reality (VR) resources, which allow the visitor to manipulate and visualize each iteration used to construct these fractals. The structures of HTML page hierarchies were used through geometric transformations of homothety, rotation and translation in both phases of this work: in the modeling of fractals and also in the construction of virtual rooms. The resources presented in this article can be used in the classroom to visualize polyhedra fractals using immersive glasses, in addition to Augmented Reality (AR) using smartphones or tablets. The objective of this article is to show the use of simple and free technologies, which can be used to create teaching materials with a great contribution to improving the teaching of Fractal Geometry, in addition to other areas that use graphic representations of 3D objects.

Keywords: virtual reality, fractals, Platonic polyhedra, dragon curve

1. Introduction

Students' understanding of subject content that involves concepts in three dimensions (3D) becomes more efficient and attractive with the use of auxiliary resources. Applications and web environments significantly contribute to the learning of Physics (Komikesari et al., 2019; Rozal, Ananda, Zb, Fauziddin, & Sulman, 2021) and Biology concepts (Delgado, Bhark & Donahue, 2021) and have been used as an interesting alternative to help of students learning. The concrete materials, made with 3D printers, can be used in Biology classes (Olumorin, Babalola, & Ayoola, 2022), Mathematics (Quigley, 2021) and in subjects with content that involves development and spatial skills (Karaismailoglu & Yildirim, 2023).

Learning content that involves three-dimensional concepts can be more effective through the use of objects modeled with virtual technologies. Virtual Reality (VR) allows the creation of an immersive and interactive environment with the objects manipulation through controls and immersive glasses (Marougkas, Troussas, Krouska, & Sgouropoulou, 2023).

The creation of programmed environments in VR can help in constructions simulations (Soliman, Pesyridis, Dalaymani-Zad, Gronfula, & Kourmpetis, 2021), simulations of training situations (de Geus et al., 2020), Medicine (Pottle, 2019), educational games (Pirker, Dengel, Holly, & Safikhani, 2020), visualizations of physical, biological or chemical phenomena (Kumar et al., 2021), and other areas linked to education (Melinda & Widjaja, 2022).

The polyhedra used in Fractal Geometry are defined with the characteristics of 2D fractals, expanding the concepts used in 2D constructions to 3D objects (Jacomeli & Souza, 2020). Studies on 3D fractals are expanding (Husain, Gomada, Megham, & Asish, 2021), and these solids help in studies of the applications of these objects in tree leaves and algae, blood and lung vessels, clouds and rain areas, coastal craters, mountain ranges, snowflakes, among others (Nutu & Axinte, 2022).

Other recent applications of using polyhedron modeling with the concepts of Fractal Geometry involve studies on concrete rupture loads (Kotov, Volchuk, Zeziukov, & Pavlenko, 2023), fractal modeling for water treatment (Lorevice et al., 2023) and modeling of complex sets of viruses for the molecules encapsulation (Wang et al., 2023).

Furthermore, Fractal Geometry has been an important area of knowledge used in modular robotic flight systems

(Garanger, Epps, & Feron, 2020), transport and interaction of double concentration fluids (Chai, Yeoh, Ooi, & Foo, 2024), studies of the effects of energy on porous structures (Bogahawaththa et al., 2024) and modeling of elements that are part of virtual environments landscapes (Bravo & Pinto, 2023).

Virtual environments programmed in VR can assist in the Fractal Geometry study, as students can interact and visualize solids and their properties in a more effective and meaningful way (Cangas et al., 2021). VR can help students interact with representations of modeled polyhedra, facilitating the visualization and understanding of object properties.

This article presents the algorithm and constructions for creating the Dragon's Curve fractal set using Platonic polyhedra. These fractals were modeled using JavaScript and HTML libraries that allow the insertion of these objects in immersive environments using VR and Augmented Reality (AR) technologies. In these environments, visitors can manipulate the modeled fractals and modify the number of iterations. When viewing the fractals using AR technology, links to the developed pages in VR are made available.

Visitors can view and manipulate polyhedra fractals from different points of view on pages programmed in AR. Furthermore, pages programmed in VR can be accessed by visitors to manipulate the modeled solids using mobile devices, computers or even immerse themselves in the scene using VR glasses.

The objective of this article is to show the construction of teaching materials that use VR and AR resources, which help to visualize polyhedra fractals in the teaching of Fractal Geometry. The teaching resources shown in this article can be used in the classroom to manipulate and visualize the fractals of the Dragon's curve made with Plato's polyhedra, contributing to student learning and enriching classes on fractals and polyhedra using virtual classrooms such as complement to traditional teaching materials.

This article contains 4 sections, including this introduction. In section 2, the concepts and commands used to construct the Dragon curve fractals are presented. Section 3 shows the Virtual Reality immersion rooms with modeled fractals. In section 4, conclusions and suggestions for future work are presented.

2. The Dragon Fractal

The Dragon Fractal, also called the Dragon curve, Heighway curve, or Jurassic Park Dragon, is a popular self-similar shape that appears in the book Jurassic Park by Michael Crichton. The properties of this fractal began to be investigated by NASA physicists John Heighway, Bruce Banks and William Harter and were described by Martin Gardner in the American scientific column Mathematical Games in 1967 (Großkopf, 2020; Kamiya, 2022).

The Dragon Fractal can be constructed from a straight line segment that serves as a base, repeatedly replacing this segment by two segments perpendicular to each other and rotated by 45º alternately to the right and to the left. Figure 1 shows the first 10 iterations of this fractal construction from a straight line segment with measure a.

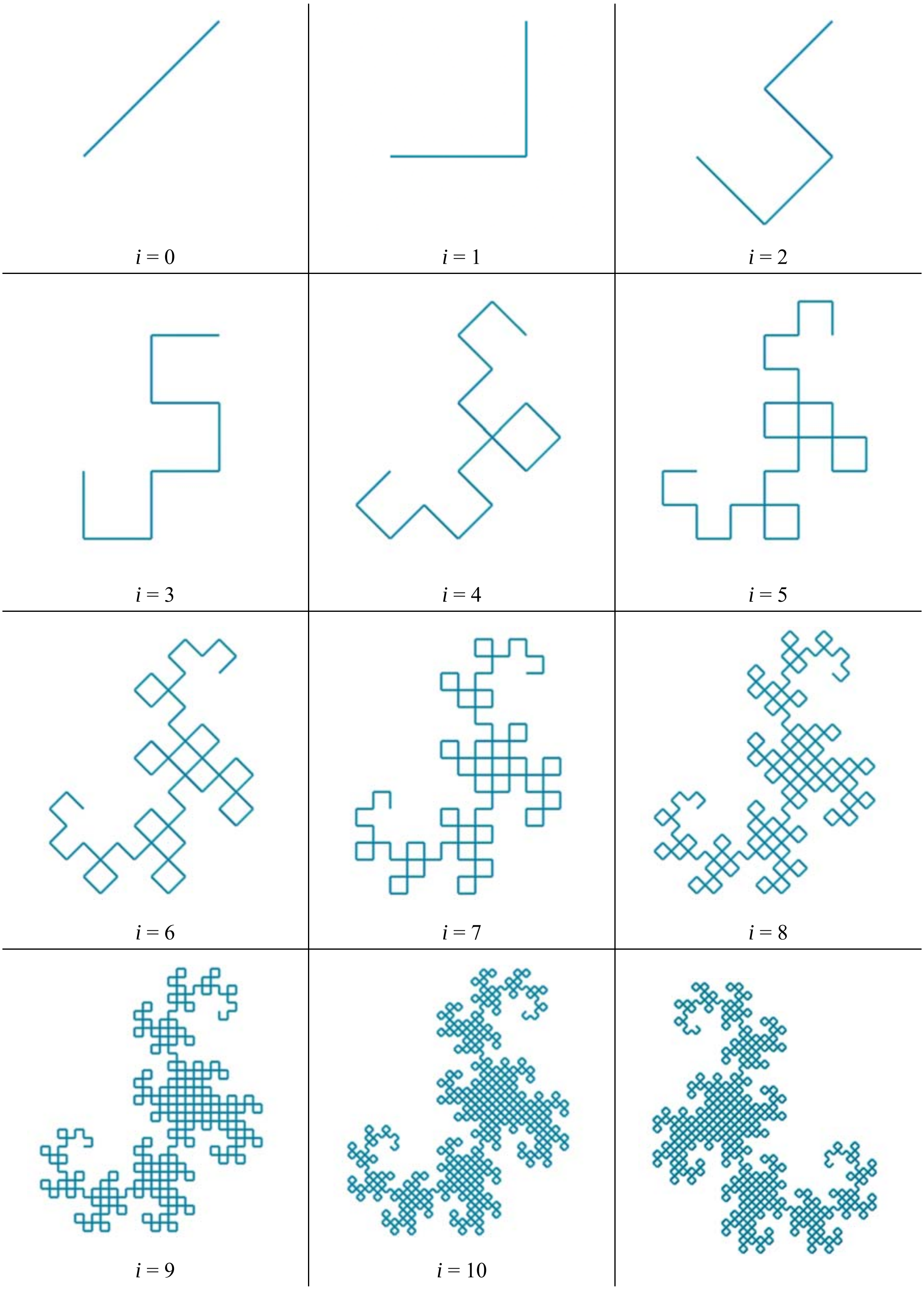

Figure 1. Construction of the Dragon Fractal with 10 iterations

Source: Großkopf, 2020.

In each iteration, the measurement of segment a undergoes a reduction corresponding to the right-angled triangle formation, with sides equal to b and hypotenuse of measurement a. Therefore, applying Pythagoras' theorem to this right triangle we have:

$$a^2=2b^2 \Rightarrow b^2=a^2/2 \Rightarrow b=a/\sqrt{2} \Rightarrow b=a\sqrt{2}/2 \tag{1}$$

The formation law adaptation of the Dragon Fractal to Plato's polyhedra can be done using a segment, which serves as the basis for the solids rotations. This segment can be parallel to an edge, a diagonal or any segment that defines some symmetry between the polyhedron vertices.

In the regular tetrahedron case, we can choose the segment c that joins the midpoints of two orthogonal edges. The rotations made from this segment define the Dragon Fractal tetrahedron, with angles measuring 45º. Figure 2 shows the generation of Tetrahedra 1 and 2 from Tetrahedron 0.

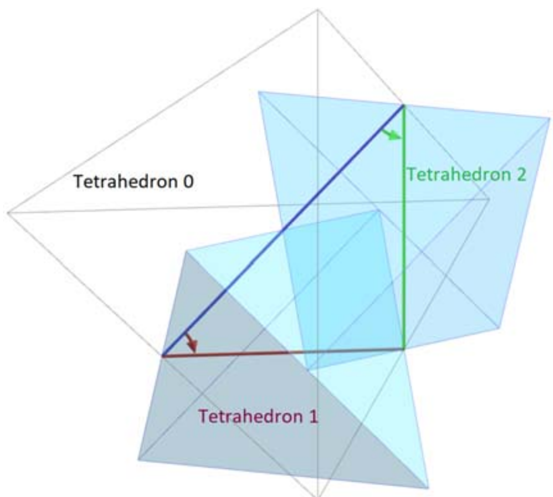

Figure 2. Construction of the Dragon Fractal from a regular tetrahedron with 2 rotations per iteration

Consider the following input parameters: maximum number of *n* iterations; a tetrahedron with edge measure *a*; and the segment of measure *c*, which joins the midpoints of two orthogonal edges. The algorithm with the recursive function for creating the Dragon Fractal of regular tetrahedra, with the mentioned input parameters, can be described as follows:

Algorithm

```
1. Inputs: polyhedron = regular tetrahedron of edge a; n (iterations); segment c that joins the midpoints of two
   orthogonal edges of the tetrahedron;
2. Function: Dragon {
3.          Construct the polyhedron with edge measuring a;
4.          Define segment c of the polyhedron;
5.          For i = 1 to n {
6.                For j = 0 to 1 {
7.                      angle = 45 * (-1) ^ j;
8.                      pos = c * j;
9.                      rotate polyhedron: (0, 0, angle) around (-pos, 0, 0);
10.                     a = a * sqrt(2) / 2;
11.                     c = c * sqrt(2) / 2;
12.                     Dragon(a);
13.               }
14.         }
15.         Show the constructed fractal;
16. }
```

The input data is defined in line 1 of the algorithm. Lines 3 and 4 define the tetrahedron and the segment used as the rotation axis. The counter in line 5 controls the number of iterations, while the counter in line 6 controls the angle (positive or negative) and the center of rotation (at the beginning or at the end of segment c). Between lines 7 and 11 are the commands to perform the rotations and the recursion effect is used in line 12, done by calling the fractal construction function.

In this article, the modeling of polyhedra was done using the solids from the A-frame library (2024), with the hierarchy structures of HTML programming codes. Figure 3 shows a part of the code with the elements and functions programmed in A-frame for the regular tetrahedron. Between lines 10 and 12, the polyhedra configurations and the positions resulting from each algorithm iteration are defined at the midpoints of the legs of the right triangle with side *c*. Iteration 0 is defined between lines 16 and 18, with only one tetrahedron visible.

In iteration 1, defined between code lines 19 and 22, the two tetrahedra are inserted with the coordinates (-*c*/2,0,0) and (*c*/2,0,0), which correspond to the ends of the segment *c*. Between lines 23 and 32 are the commands for representing iteration 2. All of these commands were generated from the algorithm shown in this article. With the representation of 10 iterations, the code has 6,188 lines. In each iteration, two new tetrahedra are created for each existing tetrahedron. Therefore, after 10 iterations we have a fractal formed by 1,024 polyhedra.

```
1     <!DOCTYPE html>
2     <html>
3      <head>
4       <script src="https://aframe.io/releases/1.3.0/aframe.min.js"></script>
5      </head>
6      <body>
7      <a-scene>
8       <a-entity camera></a-entity>
9      <a-assets>
10      <a-mixin id="poli" material="opacity: 0.92; color: #04aadd;"
          geometry="primitive: tetrahedron; radius:2.6;"></a-mixin>
11      <a-mixin id="p1a" position="-1.06,-1.06,0" rotation="0,0,45"></a-mixin>
12      <a-mixin id="p2a" position="1.06,-1.06,0" rotation="0,0,-45"></a-mixin>
13     </a-assets>
14     <a-sky color="aliceblue"></a-sky>
15     <a-entity scale="2.5,2.5,2.5" position="0,0,0">
16       <a-entity scale="1 1 1" id="nivel0">
17         <a-entity mixin="poli"></a-entity>
18       </a-entity>
19       <a-entity scale="0.7071,0.7071,0.7071" id="nivel1" visible="false">
20         <a-entity mixin="poli p1a"></a-entity>
21         <a-entity mixin="poli p2a"></a-entity>
22       </a-entity>
23       <a-entity scale="0.5,0.5,0.5" id="nivel2" visible="false">
24         <a-entity position="-1.5,-1.5,0" rotation="0,0,-45">
25           <a-entity mixin="poli p1a"></a-entity>
26           <a-entity mixin="poli p2a"></a-entity>
27         </a-entity>
28         <a-entity position="1.5,-1.5,0" rotation="0,0,45">
29           <a-entity mixin="poli p1a"></a-entity>
30           <a-entity mixin="poli p2a"></a-entity>
31         </a-entity>
32       </a-entity>
      …
6185   </a-entity>
6186   </a-scene>
6187   </body>
6188  </html>
```

Figure 3. Code in A-frame and HTML to create a Dragon Fractal of tetrahedra

The result of applying the proposed algorithm to the regular tetrahedron is presented in Figure 4. The polyhedra are rotated around axes parallel to the *z* coordinate axis, alternating the centers of rotation between the initial and final ends of segment *c* of the tetrahedron considered in each iteration.

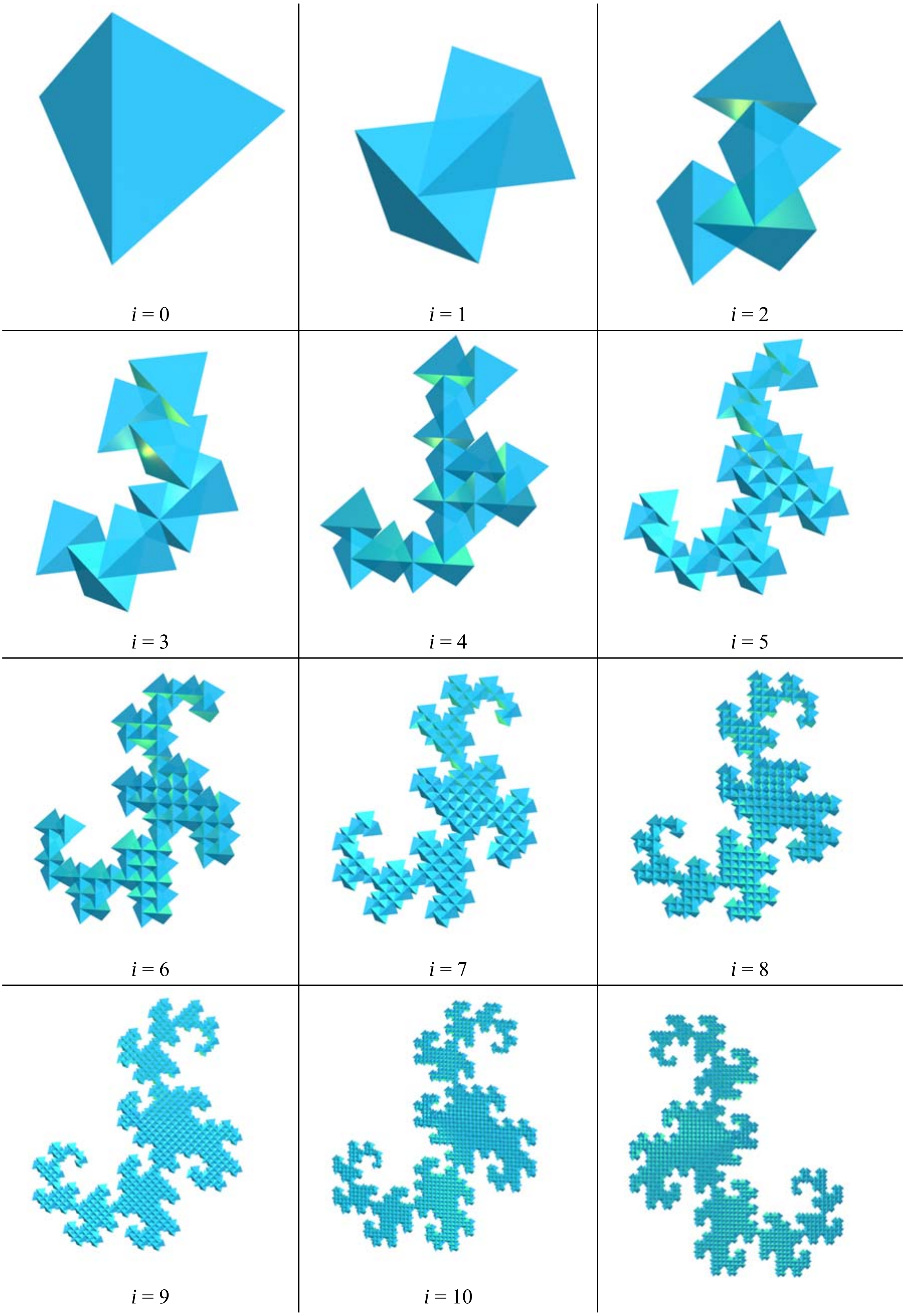

Figure 4. Dragon Fractal made with regular tetrahedra in 10 iterations

For the other Platonic polyhedral, the segment c can be defined in a similar way to the tetrahedron. In the cube, this segment passes through the centers of two parallel faces. In the dodecahedron and icosahedrons cases, the segment *c* passes through the midpoints of two parallel edges. Figure 5 shows the generation of Octahedrons 1 and 2 from Octahedron 0, where segment *c* defines one of the main diagonals of this polyhedron.

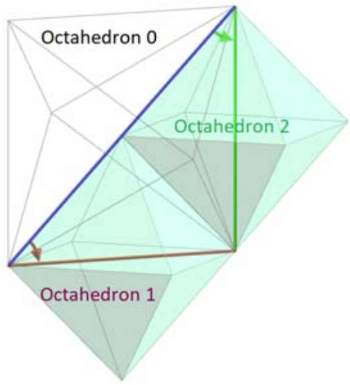

Figure 5. Construction of the Dragon Fractal from regular octahedron with 2 rotations per iteration

Considering a third rotation of each polyhedron in each iteration, now around axes parallel to the *x* coordinate axis, a modified Dragon Fractal is obtained. The result of applying this adaptation in the proposed algorithm to regular tetrahedra is shown in Figure 6. In this case, each existing polyhedra from one iteration generates another 3 polyhedra in the next iteration. Therefore, after 10 iterations the fractal is defined by 1,536 polyhedra.

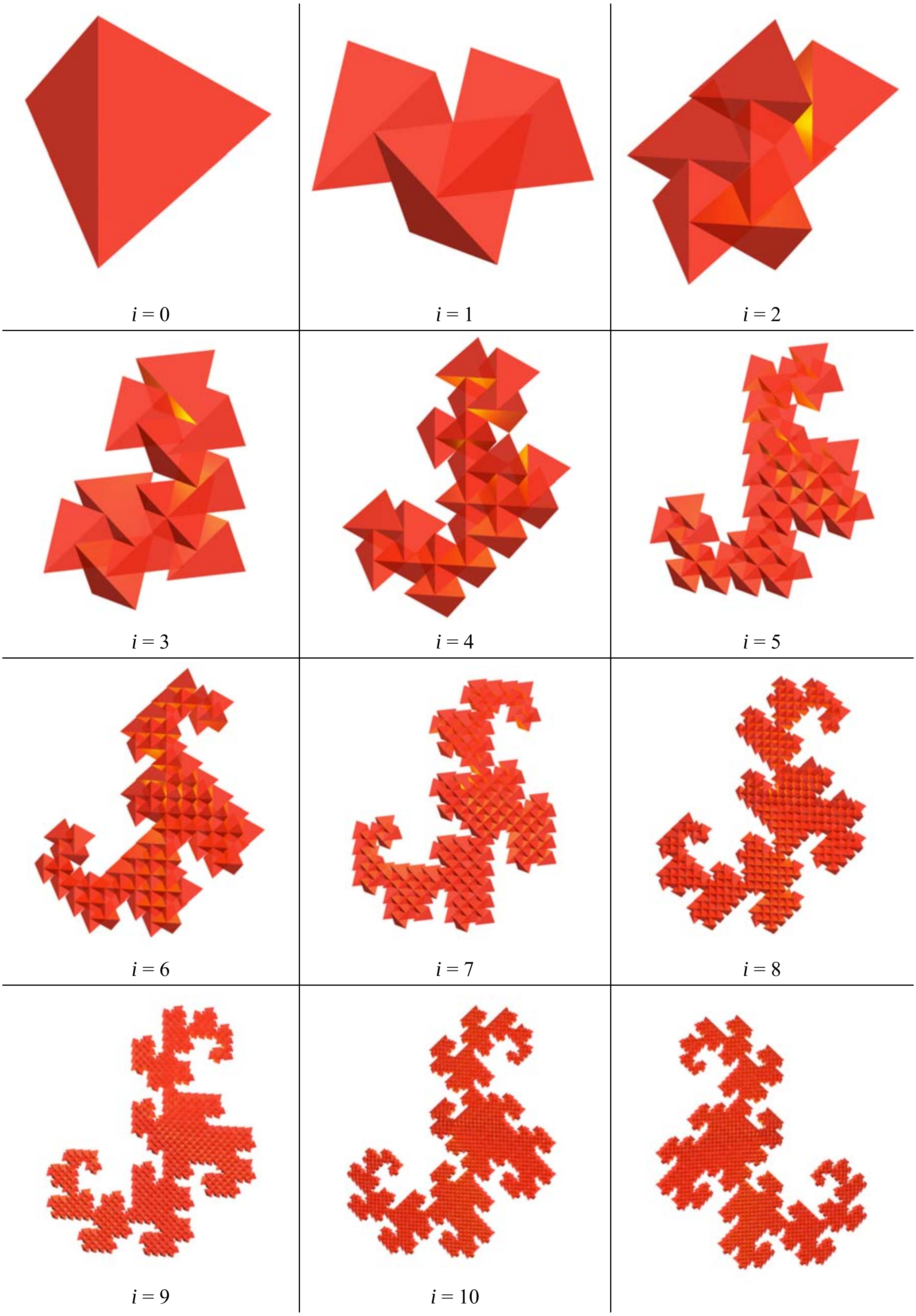

Figure 6. Dragon Fractal made with regular tetrahedra with 3 rotations in each iteration

Figure 7 shows the Dragon Fractals of Plato's other polyhedra in iterations 6 and 10. The commands used to create the other polyhedra are native of the A-frame library (2024) and the codes used to generate the other fractal polyhedra are similar to the code shown in Figure 3.

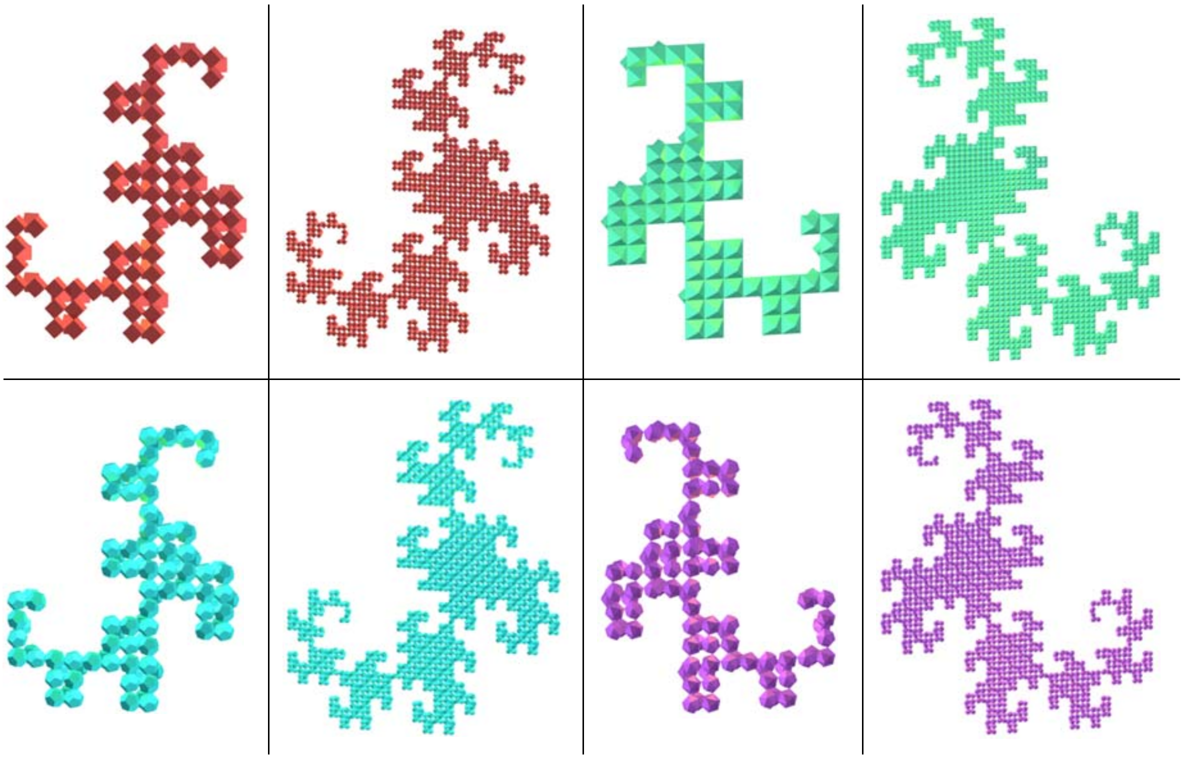

Figure 7. Dragon Fractals made with cubes, octahedra, icosahedra and dodecahedra

The fractals modeled in this article are available with Virtual Reality and Augmented Reality resources on the page: https://paulohscwb.github.io/polyhedra2/fractalplatonic/

3. Immersive Rooms with Modeled Fractals

The modeled Platonic polyhedra fractals were inserted into a VR immersion room, which can be accessed using any device with internet access. A support table for the fractals, an equirectangular background photo, and a projection screen with fractals properties were inserted into the programmed virtual environment. Figure 8 shows an overview of the virtual room environment with dragon fractals and a fractal tree, without the equirectangular background image.

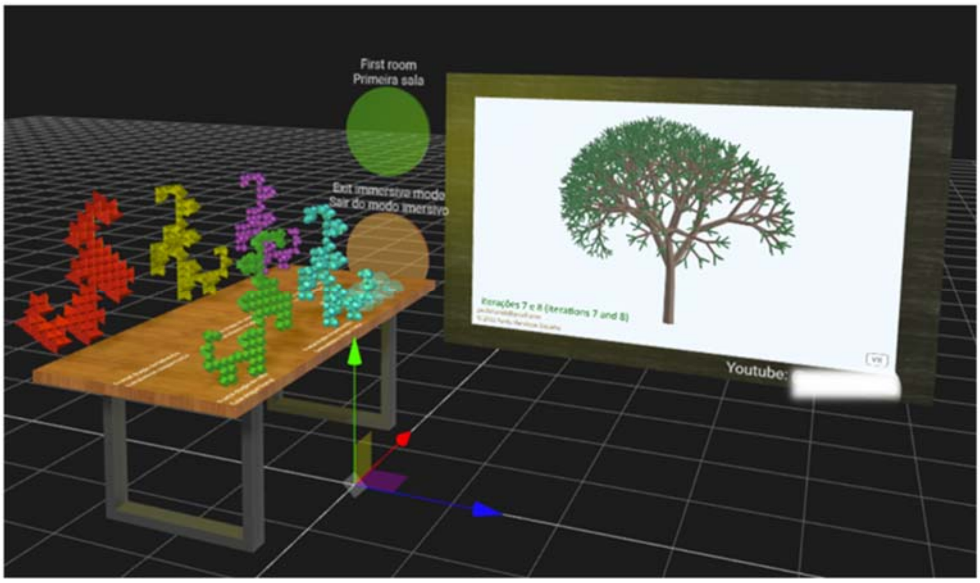

Figure 8. Overview of a virtual room with polyhedra fractals

The A-Frame's gravity and shadow effects properties were programmed into the virtual rooms, with the aim of improving the feeling of immersion. Figure 9 shows a table with Dragon Fractals made with Platonic polyhedra, with the insertion of the background image in equirectangular format (Hemul, 2024). The fractal tree shown on the immersive room's projection screen can be built using the same reasoning presented in this article, with the rotations of truncated cones and the insertion of polyhedra that represent the tree's fruits or flowers.

The fractal models of polyhedra are placed on the table, with labels containing the respective names in English and Portuguese of each fractal. Using controls from immersive glasses, the click of a mouse or the touch of a smartphone or tablet, the visitor can move the polyhedra, change virtual rooms and leave the immersive environment. Furthermore, the visitor can choose the number of iterations with the buttons inserted on the virtual room table. Figure 10 shows the use of the Virtual Reality glasses manipulation controls in the room containing the dragon fractals.

Figure 9. Detail of the virtual room with the table containing polyhedron fractals#

Figure 10. Details of the immersive room with polyhedron manipulations using the VR glasses controls

In addition to virtual rooms and individual polyhedron viewing capabilities, Augmented Reality (AR) technology can be used to visualize each modeled polyhedron fractal. The programming codes for the pages created in AR are the same as those shown in this article for the pages programmed in VR, with the insertion of the programming codes for reading QR codes for each dragon fractal (Siqueira, 2021). Figure 11 shows the use of the AR feature to visualize the Tetrahedron Dragon fractal shown in this article. The visitor can click on the blue circle that appears over the marker to access the VR modeled fractals.

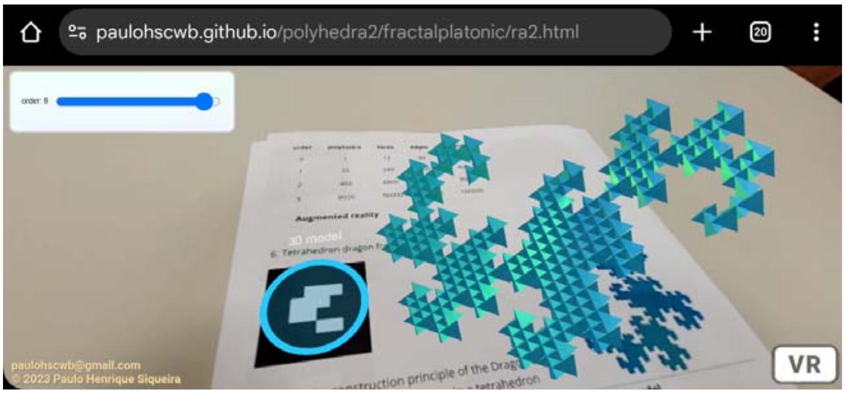

Figure 11. Visualization of the tetrahedron Dragon Fractal using the Augmented Reality feature

4. Conclusions

This article shows the adaptations and the algorithm used to create Dragon Fractals from Plato's polyhedra. The ends of the base segment of each iteration, used in generating the Heighway Dragon Fractal, should be considered as centers of the rotations of Plato's polyhedra. In this way, the constructions of these new fractals are possible and can be adapted to other polyhedra.

Web environments were created to visualize these polyhedron fractals, using Virtual Reality and Augmented Reality technologies. Using the printed markers, visitors can view the fractals in AR on any device with a webcam and internet access, with links to the VR views.

The modeling of polyhedra fractals and the creation of the virtual rooms shown in this work use the hierarchical structures of web page programming with A-Frame scripts, facilitating the insertion of several fractals on the same page. The result shows that it is a useful tool for use in the classroom, as it allows students to view and manipulate graphic representations of polyhedron fractals on their devices or to use VR glasses for complete immersion in virtual classrooms.

The programmed environments can be explored in Geometry classes, helping to understand the fractals and polyhedra properties or simply visualizing each modeled solid. The elements that form the modeled fractals can be viewed in VR and AR, and visitors can move the scene camera to find the best views of the solids, using tools developed for the A-frame to orbit the camera around of objects.

The teaching resources developed in AR and VR for visualizing fractals with Plato's polyhedra serve to improve the quality of teaching in the areas of Fractals and Spatial Geometry, as they help in visualizing polyhedra and fractals and understanding their properties. It is worth remembering that teaching resources are complementary instruments to traditional teaching materials, and that they help transform ideas into facts.

The web page programming tools used in this article are simple and intuitive, and can be applied to the creation of teaching materials or with immersive glasses in the classroom. Students access the page programmed in AR, view the solids with their respective printed markers and can interact with the polyhedra programmed in VR. In virtual rooms, students can interact, move, visualize and choose the number of iterations of each fractal representation through the controls of the immersive glasses. With the algorithm and constructions shown in this article, visitors can explore the geometric concepts of polyhedra fractals efficiently and dynamically.

The modeling presented in this article can be used in other sets of polyhedra, such as Archimedean, Catalan or non-convex polyhedra. Suggestions for future work include modeling objects that use other polyhedra sets, inserting gamification tools and programming other interactions forms with visitors in virtual rooms.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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