

# Sensors-Based Virtual Reality Environment for Volumetric CT Analyses of Agricultural Soils Samples

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**Abstract**—Virtual Reality (VR) is based on the use of sensors, and the customization of its use for agricultural analysis is still a challenge. This study presents a solution for the analysis of agricultural soils based on sensor devices, signal conditioning, X-ray tomographic images, and a VR interface. In such a context, tomographic images from soil samples can be submitted through a user interface to a process of manipulation and volumetric visualization based on graphic-computational resources which add functionalities like immersion for the user's interaction with the samples. Validation was based on a case study involving the analysis of the porosity of agricultural soils samples in which preferential paths for water flow were reconstructed and manipulated by VR interaction techniques. In fact, by using 59.6 keV of energy and a time window of 10 seconds for sampling of each tomographic projection, it was possible to reconstruct digital tomographic images from agricultural soils to be analyzed using such a system. Results indicated both a new and non-invasive way for the evaluation of the spatial organization and physical properties of agricultural soils and its potential use for food production.

**Keywords**—X-ray Sensors; Virtual Reality Sensors; Digital Image Processing; X-ray Tomography; Agricultural Soil Porosity; Decision-making Process.

## I. INTRODUCTION

Evaluating the current evolution in the soil sciences, one can observe an increasing interest in the scientific community in the development and application of non-invasive techniques for the study of physical characteristics of agricultural soils. Since the 1980s, one of the noninvasive methods used for the evaluation of water movement into soil due to morphology as well as aggregates distribution has been the application of sensors and Computed Tomography (CT) for agricultural soil imaging [1]–[8]. From that time, it has been observed an expressive decreasing in the use of the invasive gravimetric and neutron probes techniques for water content measurements in agricultural soils [9][10]. Additionally, combined with the development of CT, new methods of three-dimensional (3-D) reconstruction have been developed, mainly motivated by the lack of information from two-dimensional models for a precise diagnosis in studies that require volumetric information [11]. Other challenges regarding such aspects were associated with the image reconstruction process, as well as with reconstruction algorithms, computational capacity, and handling large amounts of data [12]. Therefore, since then, it has been understood tomographic reconstruction must consider large

amounts of data and the need to have a large processing capacity [13][14].

Moreover, owing to the advent of precision agriculture, it has become imperative to have adequate models for management based on data analyses not only related to spatial variability, but also due to the temporal variability in the areas used for agriculture. In this sense, the standardization of data storage and the architecture of distributed information systems that allow integration of different types of data in a simple and transparent way have become quite important for the development of new methods for non-invasive analyses in agricultural industry [15]–[20]. For example, digital agricultural soil images are obtained by tomography and take into account several projections. Moreover, because one soil sample is scanned at different angles, a large amount of data needs to be computationally processed. Nowadays, the use of tomography not only allows us to obtain information about soil density and moisture at the pixel level, but also allows quantification of the pore volume and its representation in three dimensions. The soil pores vary in size and shape and can be interconnected.

In 1982, Bouma highlighted the importance of determining the continuity of the pore network for the flow of water in soil [21]. Therefore, not only pore diameter, but also pore continuity, interferes with the process of redistribution of soil water. In such a context, it is important to assess the porosity of the soil, because, depending on the soil management strategy adopted for planting, restriction of soil water flow may occur, thus compromising plant growth. To determine the soil porosity, volumetric measurements are conventionally used [22][23]. For this, it is necessary to collect undisturbed soil samples for quantitative evaluation of its porosity based on the use of tomographic scanners.

Methods based on volumetric reconstruction have been developed for such a purpose, mainly due to the inadequacy of information provided by two-dimensional models for accurate diagnosis in studies that need volumetric information. Thus, such methods suggest the composition of surfaces and volume of the samples under analyses and contribute to the increase of precision in the process of information extraction. However, it is still a challenge gathering all the information from agricultural soils, i.e., the continuity, size, and shapes of the pores in a soil sample, among others.

CT is one methodology that allows observing the structural components of the soil, allowing better visualization of the behavior of the structure and soil porous space. However, the interconnection for preferential flow

requires additional methods which can be beyond what CT can provide. Sensors-based VR techniques can be combined with CT to assist noninvasive research through immersive and interactive processes.

VR was born in the eighties to help differentiate traditional computational simulations of the synthetic worlds, and researchers like Bolt [24] and Lanier [25] played a key role in its development. VR transports a person into a fully immersive and interactive experience with a degree of realism. Academics, software developers, and researchers are still trying to define a VR based on their own experiences. However, it is possible to observe in specialized literature that all of them technically consider the term related to a immersive and interactive experience, i.e., based on images generated by computers, rendering, or not in real time [26]-[29]. In fact, the concept of sensors-based VR is related to the use of sensors in external devices, i.e., digital gloves, video-helmets, digital caves, digital tables, among others. In 1994, Machover stated that the quality of a VR system is a significant consideration, because it stimulates the user to the maximum in a creative and productive way, providing feedback coherently regarding the user's movements [30].

Presently, only some units of research have developed projects using sensors-based VR applications in the area of scientific visualization, such as tomographic reconstruction, due to the high cost and technical difficulties involved in such processes. However, some proposals have appeared to minimize the difficulties of development and maintenance of the systems and necessary programs.

Additionally, a better organization of human resources has now been observed to integrate areas of the knowledge leading to the application of such advanced methods based on the connection and use of those technologies. Thereby, the main objective of this work is to present the development of a VR system to support the analysis of 3D reconstructed soil samples using innovative immersive visualization and interaction techniques by integrating sophisticated external sensors-based devices.

Specifically, this paper presents the organization and implementation of a synthetic environment that makes possible the visualization, analysis, and manipulation of soil samples produced by an algorithm of volumetric reconstruction of X-ray tomographic images through graphic computational tools and non-conventional sensors-based VR devices, aiming immersion and user interaction at the scene entities, making possible the non-destructive analysis of agricultural soil samples, as shown by a case study in Soil Science.

The materials and methods used in this work are described in Section 2. In Section 3, the obtained results are discussed, and the conclusions are presented in Section 4.

## II. MATERIALS AND METHODS

The conceptual and methodological structuring applied to the development of the sensors-based VR system dedicated to the inspection of digital tomographic images from agricultural soils uses data obtained by means of a volumetric reconstruction algorithm. Figure 1 shows a general view of the sensors-based VR system dedicated to

the tomographic inspection of agricultural soil samples, as well as the dataflow. From this tomographic image data, soil samples can be reconstructed, imported, and treated by several VR processes, focusing on the analysis related to the soil science area.

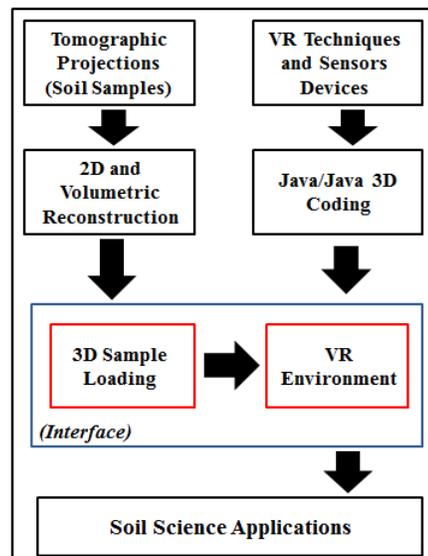


Figure 1. General view of the sensors-based VR system customized for the inspection of tomographic samples of agricultural soils, as well as a view of the dataflow from the acquisition process to the visualization process.

The software system was organized based on the concept of classes. In object-oriented programming, a class is an extensible program code template used for creating objects, providing initial values for states (member variables), and implementations of behavior (member functions or methods). In this work, the following classes have been considered: *Reconstruction*, *Loader*, *Transformations*, *Polygonal Attributes Extraction*, *Filter*, *Transparency*, *Illumination*, *Coloring*, *Conventional Collision*, *Non-conventional Collision*, *Conventional Model Manipulation*, *Non-conventional Model Manipulation*, *Conventional Scene Manipulation*, *Non-conventional Scene Manipulation*, *Quaternion*, *Visualization*, and *VR Environment*.

All classes were implemented using the Java programming language and the *Java3D* API [31].

A CT scanner from Embrapa Instrumentation was used to obtain the tomographic image data. All of the tomographic projections allowed image reconstruction, i.e., turning possible generation of mass attenuation coefficient maps given in  $\text{cm}^2/\text{g}$  with spatial resolution equal to or larger than 1 mm. All of the soil samples were submitted to the acquisition process using an amount of energy of 59.6 keV and a time window equal to 10 seconds for sampling of the points for the tomographic projection.

For two-dimensional reconstruction, an algorithm of *Filtered Back-Projection* (FBP) was used, with a filtering based on the use of the *Hamming's* window, implemented under 1-D *Fast Fourier Transform* (FFT), using the C++ language [32]. After that, a suitable filtering technique was

also used with the 2-D reconstructed images. The filtering technique was based on the use of the *Wavelet Daubechies Transform* (WDT), which allowed filtering of only certain image areas preserving borders and details, i.e., through using a window with 76 coefficients [33].

An interpolation-based overlapping algorithm of reconstructed two-dimensional slices was adopted for volumetric reconstruction. Such a technique consists of setting up the plans generated by the function  $f(x, y, z_i)$  for  $i = 0 \dots (n-1)$ , where  $n$  is the number of reconstructed plans. Consequently, specific two-dimensional slices were interpolated to reconstitute the spaces left among these overlapped plans.

Figure 2 shows the overlapping original plans and the interpolated plans. This method was used to reduce the computational costs and the radiation time, with the use of interpolation in between the spaces of the reconstructed slices based on the use of *B-splines* [34]. Thus, with only a few slices, the algorithm was prepared to estimate and complete the entire information.

The sensors-based VR system for the inspection of agricultural soils samples was organized based on the CT images and a set of non-conventional sensors to support the VR environment. In addition, for the evaluation of the preferential paths for the water movement in soil, sensors were used to detect motion based on the use of gloves and the space based on 3-D visualization (using a CCD head-mounted display) as well as microelectromechanical actuators based on piezo-electrical devices [35][36]. Such sensors were necessary to translate movement and to help the users understand the relation of the workspace with the agricultural soil samples.

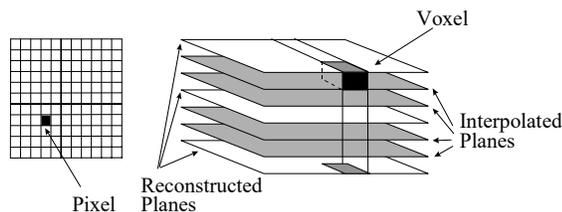


Figure 2. Volumetric reconstruction based on a set of reconstructed slices and the use of B-spline interpolator.

At the end of the process, the volumetric model is converted into the *Wavefront File Format* (.obj) using the *vikOBJExporter* class from the *vikOBJExporter.h* package of the visualization toolkit. This format has been chosen for its high performance and flexibility when importing such models to a virtual environment, where all their attributes can be customized for graphic APIs.

The *Attributes Extraction* class obtains the voxels data from a volumetric image, using those above-mentioned input non-conventional devices, i.e., supplying the users' information on a specific point of the volumetric representation. Initially, the objects of the classes *PickCanvas* and *PickResult* are instantiated, and these objects are responsible for activating the data extraction of a *Canvas3D* object and storing such data in vectors of event

results. Based on user interest, a region can be selected and attributes extracted using a coordinate  $z$ , since it can be stabilized on the selected region in the display, allowing selection through a two-dimensional viewport in an intuitive way.

Thus, the available data for picking operations under instances of *Shape3D* and their respective methods are: the borders, with *getBounds*; the scene graphs, with *getLocale* and *numBranchGraph*; the geometries, with *getGeometry*; *ColoringAttributes*, with *getColoringAttributes*; the material under the Hue, Saturation, Lightness (HSL) and Red, Green, Blue (RGB) formats, with *getMaterial*; the *transparency.getTransparency*; and the polygons, with the *getAppearance.getPolygonAttributes.getPolygonMod* class.

In addition, an object is instantiated, belonging to the *PickIntersection* class, also of the *com.sun.j3d.utils.picking* package, responsible for sheltering the collision point between an entity/node and the two-dimensional cursor. Thus, this instance stores in its content the intersection product among an entity of *PickResult* with the chosen *Canvas3D* point, which is passed to the *getClosestIntersection* method as the parameter. The *PickIntersection* class can offer through its events: the distance between the point and the observer with the *getDistance* method; the coordinates of the point with the *getCoordinates* method; the coordinates of the closest vertex with the *getClosestVertexCoordinates* method; the normal straight line of the point with the *getNormal* method; and the transformation head offices with the *getMatrix* method.

The classes *PickIntersection* and *PickResult*, as well as the *Attributes Extraction* class, can allow the reading of each mass attenuation coefficient value, present in the tomographic volume. In this context, these values can be obtained through the gray level tones, which are represented by luminance, index "L" from the HSL pattern, obtained by using the class *getMaterial* method.

The *Non-conventional Scene Manipulation* class is one of the most important for user interactivity and immersion in the *VR environment*, since it allows user browsing in all directions through the synthetic scene, approximating and going into the reconstructed structures using data gloves *P5Glove* [37]. For the accomplishment of such events, the manipulation classes and the model of the scene are both based on another auxiliary class called *FPSGlove*, which is available in the *com.essentialreality* package offered by the device manufacturer. The *FPSGlove* classes is responsible for including all the parameters regarding non-conventional devices, and include the positioning, orientation, and finger bending, i.e., making it possible to detect the proximity and inclination, and thus launch a series of customized events.

On the other hand, in relation to the constructor method of classes, additional parameters of the same importance can be activated, such as: (1) *P5\_Init*; (2) *P5\_setForward*; (3) *P5\_setMouseState*; (4) *P5\_setFilterAmount*; and (5) *P5\_setRequiredAccuracy*. These classes are responsible for initializing, determining the positive direction, and turning off the mouse, filtering the sign and determining the precision movements, respectively. Soon afterwards, the methods responsible for detecting the position of the glove in

the real environment are declared. The methods are the *getXPosition*, *getYPosition* and *getZPosition*, which map the triggers mentioned before to launch an event type; it means, they monitor the values received by the glove through instances of the class *P5State*, a class responsible for determining the current state of the glove. Thus, through the *filterPos* method of *P5State*, the exact position of the device is obtained and then assigned to the methods to check if the limits were or were not outdated.

In a manner similar to the positioning detection methods still in the *FPSGlove* class, the methods *getYaw*, *getPitch*, and *getRoll* are described, as a solution for detecting the inclination of the device in the Y, X, and Z axes, to determine if the established limits for the flags were reached.

After having implemented the monitors and triggers of events with the auxiliary class, the *Non-conventional Scene Manipulation* class is also used with the *ViewingPlatform* class. In such a way, two other specific parameters are included, each of them related to the translation and rotation steps respectively. Such an arrangement is responsible for defining when the virtual models will be moved or leans in each movement of the device in the real world and recognized by the *FPSGlove* class.

Once such a process is concluded, the instance of the *Non-conventional Scene Manipulation* class should be harnessed to the object of the *ViewingPlatform* class of the current *Canvas3D* object, so that all of the movements can be related on the scene and not the volumetric model, i.e., through the *setViewingPlatform* method. The *Non-conventional Model Manipulation* is a class responsible for accomplishing the three-dimensional representation movement through real movements of the data glove *P5Glove*, where the user can change the positioning and orientation of models in real time in all directions and angles, contributing to the VR environment interactivity in six degrees of freedom. To operate such a process, it is important to consider the *Non-conventional Scene Manipulation* class, in which the current implementation uses the support *FPSGlove* class.

Thus, the *Non-conventional Model Manipulation* class is an extension of the *Behavior* class, a class that describes behaviors, customized for reactions to the movements of the device. Furthermore, after assigning the methods *getXPosition*, *getYPosition*, and *getZPosition* to obtain the positioning, and the methods *getYaw*, *getPitch*, and *getRoll* to obtain the orientation under instances of the *FPSGlove* class, the method *rotateQuaternion* is called. Such a method, responsible for converting rotations is accomplished based on the Euler angles in Quaternion coordinates and is useful to establish rotations with complex numbers and imaginary axis, in order to contribute to the movement's precision.

The *rotateQuaternion* method assigns to its class the axis and angles parameters in Euler coordinates and returns a quaternion description; a set used in the same *Quat4f* constructor, constructing a quaternion of float, and after a *setRotation* executes a rotation with instances of *Transform3D*.

At the end of the process, the product of *Non-conventional Model Manipulation* class is encapsulated in a

*BranchGroup* object and assigned to the transformation group, *TransformGroup*, which conducts the three-dimensional representation movements in a distinct way from the previous class. In such a way, not only all of the movements' detection but also the effective positioning change and the entities orientation produce effects under the current models in the *Canvas3D* object.

The *Non-conventional Collision* class treats the implementation of a collision detection algorithm added to the *Non-conventional Scene Manipulation* class and is restricted to events that use non-conventional input data devices, specifically those provided by the data glove *P5Glove*. In that way, through the algorithm, the users are also prevented from crossing the faces of a three-dimensional representation during the browsing process in synthetic scenes, allowing only the cameras transpositions inside the empty spaces among such faces, simulating real physical processes.

Thus, each spatial position of the glove is tested as the current instance of itself; each direction of movement is limited to a specific moment, where the possible alternatives are: left, right, up, down, forward, and back. After identifying the positioning of the glove in the moment of a supposed collision, the *Non-conventional Collision* class can block the device movement. Thus, the last movement of the glove when a collision has been stopped is recorded, although the glove can freely be moved in the real environment. This is caused by a new instantiation of the current position of the glove, assigning empty vectors to them, in other words, initialized in the origin, i.e., causing the immediate stop of the device movement.

Additionally, at the same time, when accomplishing any other move that does not take them to a continuation of the blocking, the class interprets them and allows continuing the valid movements series through a new instantiation of the mapped positions of the glove, using as parameters the position where the collision began and the linear step was adopted by the class. At the end of this process, a *Shape3D* is added to *PhysicalBody* to detect the browsing of the scene being used by a user, allowing interaction and selection of each three-dimensional face. The algorithm of such a class allows both preventing the browsing to continue (or not) in a scene, as well as providing information of the direction of the glove movement since it became active.

The *Quaternion* class implements a conversion algorithm so that the system stops using just rotations on the x, y and z axes, and starts to accomplish orientations on some intermediate axis, defined by a vector that goes through the origin and reaches a point in space. Such a type of an axis can be represented by a specific coordinate of the real device, e.g., the Cartesian coordinates (x, y, z) of one of the eight LEDs present in the controller tower which is used with the glove [38].

To accomplish this operation, it uses imaginary bases and complex numbers, providing an alternative parameter for the *setRotation*, method of the *Transform3D* class, which allows using a quaternion as an argument. Thus, calling an instance of *Quaternion* to accomplish a rotation with the non-conventional device *P5Glove*, the orientation of the glove is

interpreted by the *FPSGlove* class and translated by *Non-conventional Scene Manipulation* or *Model*, is converted from the Euler system to the *Quaternion* base, returned for the system new orientation coordinates, to then be executed by the *Quat4f* method of *Transform3D*, which encapsulates the entire functioning of the quaternion as previously described.

For the implementation of the *Visualization* class, the system interface prepares a volumetric tomographic image to be visualized. This way, the volumetric tomographic image is prepared to be adjusted to the 3-D model, i.e., to occupy the whole extension of the *Canvas3D* object, so that all of the spaces are taken advantage of, contributing to the visualization quality.

### III. RESULTS AND DISCUSSIONS

Based on the use of the tomographic projections and the two-dimensional reconstruction FPB algorithm, it was possible to get volumetric images by means of use of the *B-spline* algorithm.

Figure 3 presents examples of the volumetric tomographic images obtained for stratified agricultural soil, degraded soil, and a clay soil sample, respectively. Based on the *Attributes Extraction* class, intrinsic characteristics of the scene and of agricultural samples could be obtained through the use of either the mouse or the *P5Glove*, with a data origin in the three-dimensional representations in the VR environment. The data set was divided into two categories: one concerning the scene, and the other concerning the CT measurements.

In relation to the first category, the synthetic scene data are related to: borders, which have represented the geometry limits or the geometry limits that involved it; the scene graph, that has represented the node hierarchy in the tree; the current geometry in the model and its composition, the distance of a certain voxel in relation to the coordinates chosen in the scene, the closest vertex to the chosen point in the scene, the three-dimensional coordinates, and the normal straight line in the closest face, which involved the chosen coordinates.

Secondly, concerning the tomographic data, the obtained data were: color attributes, which represented the individual color of each voxel, independent of illumination intensity; the mass attenuation coefficients values of the agricultural soils, which are represented by the colors of each analyzed voxel, and are related to the light intensity in each position; transparency attributes; and polygons attributes, and finally the saturation and matrix of the HSL coefficients.

An experiment for validation of the result was prepared considering a digital and volumetric tomographic image obtained from a latosol soil. For such a volumetric image, the value of an arbitrary voxel was taken as presented in Figure 4.

Based on the developed method, the attributes can be obtained from the latosol soil tomographic image at the sensors-based VR environment, i.e., under the two mentioned aspects, through the choice of any voxel coordinates, assuring the reliable recovery of the sample data.

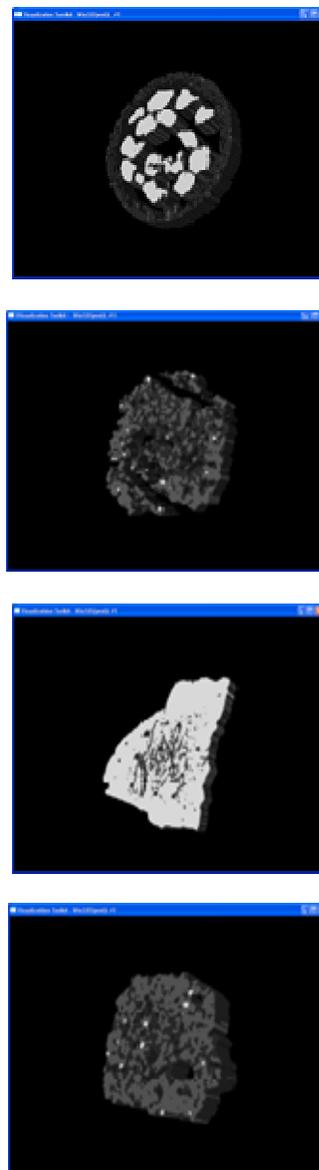


Figure 3. Volumetric images reconstructed by FBP and the B-Spline algorithm.

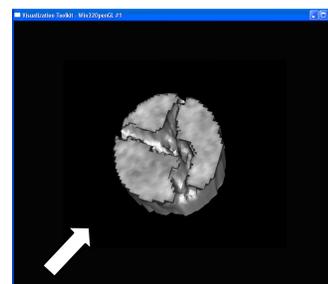


Figure 4. Resulting data obtained from a latosol soil sample where an arbitrary point is chosen using a conventional device (mouse) or a non-conventional one (glove). The coordinates of the voxel are directly selected and the respective information can be exhibited for the users.

As an example of such a result, attributes can be obtained and presented as below:

**Colors:**  
 Color=(0.03, 0.07, 0.04) | ShadeModel=SHADE\_GOURAUD

**Materials:**  
 AmbientColor=(0.4, 0.4, 0.4)  
 EmissiveColor=(0.0, 0.0, 0.0)  
 DiffuseColor=(0.71, 0.70, 0.65)  
 SpecularColor=(0.3, 0.3, 0.3)  
 Shininess=128.0  
 LightingEnable=true  
 ColorTarget=2

**Transparency Level:** 0.3

**Polygons:** Planes

**Gray Level:** 156.82

**Saturation:** 22.86

**Mass Attenuation Coefficient (cm<sup>2</sup>/g):** 0.6521

**Virtual borders:**  
 Lower=-0.87 -1.0 -0.15  
 Upper=0.875 1.0 0.15

**BranchGraphs:** 3

**Geometry:** Triangles

**Point Distance:** 10.28

**Closest Vertex:** (0.92, -0.25, -10.24)

**Point Coordinates:** (0.75, -0.25, -10.26)

**Point Normal Axis:** (1.0, 0.0, 0.0)

In relation to the *Non-conventional Scene Manipulation*, the feedback produced by the class implementation has indicated absolute control of user browsing on the scene using the *P5Glove*. In this context, according to device positioning, the users can browse through the scene where the displacement of their hand is faithfully translated in scene movements, including moving the environment cameras in real time. Analogously, such movements are also translated in the three-dimensional displacements.

Practically, such movement with a glove should commence with closed hands, where the sensors are activated by bending fingers, thus starting the action. The *Non-conventional Model Manipulation* class simulates the manual support of 3-D samples, as well as its total movement inside the scene, with 6 degrees of freedom.

Also, the *Quaternion* class, when evaluated, presented an adequate conversion from Euler's coordinates to Quaternion's coordinates. In addition, the results of application of the *Transform3D* class produced smooth orientation changes. Table I presents an example of results for the 180° rotation, considering the initial position of the LED = (-1.0, 1.0, 0.0), and the origin of the three axes that is at coordinates (0.0, 0.0, 0.0).

Figure 5 presents the visual results of the applied transform. Such a result has demonstrated that the three rotations were composed by commutation of four other rotations of smaller angles. Also, the transposition of an orientation for another happened in a soft way, without leaps or arbitrary paths, leading to an intuitive result.

The three-dimensional samples were examined immersively by the Head Mounted Display through the *Visualization* class. First, *Canvas3D*, responsible for the rendering of three-dimensional images, was maximized to omit the parts related to the main interface in the device to focus only on the region where the sample was shown. Thus, each display of HMD forms an image which is shown and interpreted by the user's brain with a larger depth effect.

Secondly, such an effect also has allowed performing the analyses of the preferential paths of the water flow into the agricultural soil samples, called *fingering effects*, as well as the verification of the percentage of pores in the samples.

TABLE I - EXAMPLE OF RESULTS FOR THE ROTATION USING QUATERNIONS

Initial Position (sample point)	Quaternion	Final Position (sample point)
(0.0,0.0,0.0)	vector: (0.0,0.0,0.0) scale: 0.9238	(0.7071,0.7071,0.0)
(0.7071,0.7071,0.0)	vector: (0.2705,0.2705,0.0) scale: 0.9238	(0.9999,0.9999,0.0)
(0.9999,0.9999,0.0)	vector: (0.3826,0.3826,0.0) scale: 0.9238	(1.2928,1.2928,0.0)
1.2928,1.2928,0.0)	vector: (0.4947,0.4947,0.0) scale: 0.9238	(1.6862,1.6862,0.0)

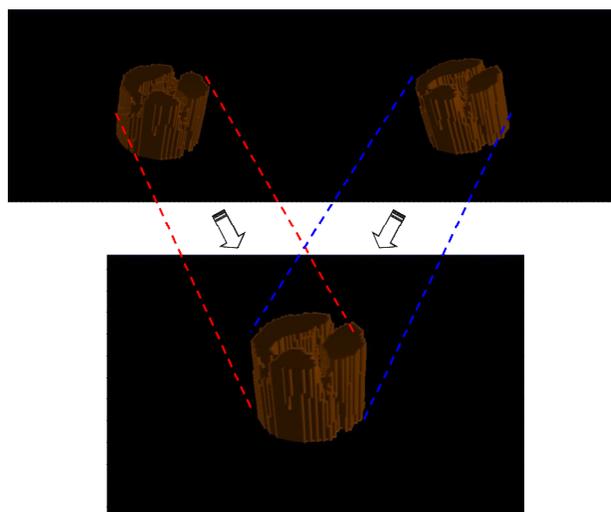


Figure 5. Representation of the rotation described around the stippled axis defined by the coordinate of LED = (1.0, 1.0, 0.0), and passing through the origin of the axis.

As described in the *Non-conventional Scene Manipulation* class, as the cameras are moved with the navigation processes, activated by keyboard interaction, or data glove *P5Glove*, the traveled paths can be demarcated; leaving the itinerary registered under visual and mathematical form. Furthermore, for each device movement identified, a new position for the camera is established, i.e., given by new coordinates (x, y, z).

Such positions are unique and occupied only one at a time. Thus, activated by the demarcation process, forming any point, the traveled path can be simulated for a certain water flow, i.e, when working with an agricultural sample. When accomplishing a certain movement, the current point occupied by the camera receives a *Shape3D* under the form of a blue sphere, which simulates the presence of a fluid drop

occupying the previous position of the camera, leaving a bluish trace through where the camera passed. Similar to the simple scene manipulation, such demarcation obeys the laws imposed by the *Non-conventional Collision* class, i.e., the traveled path is prevented from passing over the non-porous faces of the agricultural sample, leading the flow of fluids to pass through the related pores, which are the preferential paths.

The process can be repeated several times in ways similar to real situations. It is also possible to make border calculation where the limits of three-dimensional samples are identified in space, as in the case of *Attributes Extraction* class through the use of *getBounds* on *Shape3D* instances combined with a three-dimensional borders detection algorithm called *Polytope*, available in the *Bounds* package of *Java3D* API.

Besides, by using such an algorithm has become possible drawing plans around of the surfaces of the soil samples images, i.e., to delimit their borders exactly. Thus, it allows the nonporous parts of the samples, including the internal ones, to be identified, allowing the verification of its volume in  $\text{cm}^3$ .

Figure 6 presents the results of the case study based on a tomographic image from degraded agricultural soil, where the sample is in gray tones and the water flow is represented with a blue color, demarcating the traveled paths.

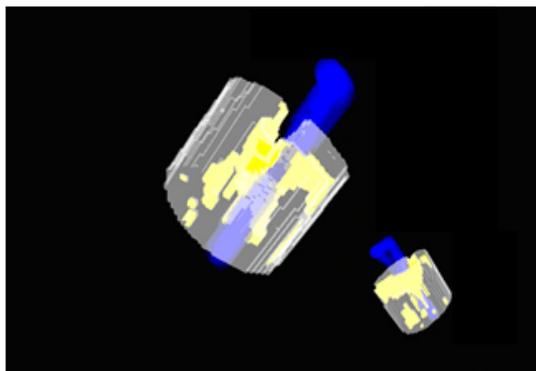


Figure 6. Result of the case study using a degraded soil sample, i.e., with representations of the non-porous soil portion (gray), emptiness (yellow), and water flow (blue) in between the soil pores.

In fact, once the non-porous part has been identified, the remaining portions were recognized based on the emptiness of the sample, which present the color that corresponds to those voxels in which there was an absence of the photons attenuation. The porous voxel was filled out with a semi-transparent yellow color, seeking a larger prominence close to the sample. With such available data, it is possible to calculate the total volume of the sample (sum of the non-porous parts with its complement) in  $\text{cm}^3$ . Thus, starting from the total volume and the individual volume of the non-porous part, it is possible to calculate exactly the volume represented by the emptiness of the three-dimensional sample.

## IV. CONCLUSIONS

This work presented the development of a new method which considered the integration of a sensors-based VR environment with a CT for the dedicated inspection of agricultural soils. Results have shown both the possibility of accessing CT digital images of the agricultural soils and the opportunity of handling three-dimensional manipulation and graphic visualization processes through computational devices. Such a developed method allowed the addition of immersion and the user's interaction with soil samples. These resources involved rendering control, illumination, coloring, attributes extraction, and physical transformation, as well as the integration of non-conventional data input and output devices, such as a Head-Mounted Display (video-helmet), and digital gloves.

In addition, it was also observed that the *Java3D* API provided, in its group of classes, essential methods for HMD programming. Such development has encapsulated practically all of stereoscopy programming. Furthermore, the case study demonstrated the applicability of the method in visualization processes and agricultural soil sample analysis, considering the progress and facilities when accomplishing non-invasive inspections.

Finally, the integration of CT and sensors-based VR made possible the measuring of volumes of emptiness of the samples, i.e., the pores, and simulation of the water flow path for the formation of preferential fingering. Future work will consider embedded systems based on the use of the *Field Programmable Gate Array* (FPGA), as well as use of the augmented reality concepts.

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