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Multiple DOF for X-ray CT Hydrocarbon Exploration

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Abstract

Explorations of visualisation of computed tomography (CT) volumes involve multiple types of observations and interactions at various viewing positions. This short paper presents a case study using a new framework that leverages having multiple DOF for computer graphics visualisations of X-Ray CT 3D reconstructed volumes for hydrocarbon exploration within Drishti, an industrial visualisation software package.

CCS Concepts

• ***Human-centered computing*** → ***Interaction techniques; Scientific visualization;*** *Interaction devices;*

1. Introduction

Over the past few years, numerous geoscientists have used the visualisation of computed tomography (CT) volumes to support ongoing petroleum exploration activity. Much of the explored data is currently used to aid the understanding and subsurface evaluation of offshore carbon storage and other key energy transition solutions. A novel computing framework called Library for Interactive Settings and User-Modes (LISU) [SMT20] was built to enable all of the input controller setups to be simultaneously applied and linked to the interactive visualisation environment for the manipulation of these image samples.

This paper explores the interfaces and the specific use of input devices with multiple degrees-of-freedom (DOF) via LISU, enabling efficient computer graphics manipulation of these 3D reconstructed CT data volumes providing an intuitive impression of the gas phase distribution.

2. Background

In geoscience, carbon capture and storage (CSS) is used to reduce anthropogenic CO_2 emissions and thereby mitigate potentially green-house gas emissions. In this context, a significant mechanism identified to store CO_2 in the subsurface reliably and rapidly is capillary trapping. Capillary trapping states how much CO_2 can be stored securely per unit rock volume. Geoscientists have utilised visualisation of CT volumes to determine the porosity distribution of a core sample [AK03]. If two fluids occupy pore space in unknown proportions, CT can be used to determine the saturation of each fluid, providing that the fluids have adequate attenuation contrasts.

CT scans are used in processes for decoupling fossil fuel use and carbon emissions. CO_2 capture and storage in geological formations are recognised methods for this. CO_2 injected into geological formations is expected to be trapped by several mechanisms against buoyancy. This will displace the resident fluid, usually brine and, in some cases, hydrocarbons [KBB*15]. As a result, CO_2 bubbles are eventually trapped in porous media.

The purpose of this trial study is to reconstruct a 3D model that represents the residual gas trapping in packed beds of glass beads at the pore scale. Then, explore via LISU the efficiency of a user to obtain a specific clipping volume using different input devices each with multiple DOFs. The volume data dimension is of $521 \times 503 \times 1292$ voxels.

3. Methods

The task consisted in exploring a volume which is a dataset of two 3D parts of a Ketton carbonate core of 5 mm in diameter and 11 mm in length scanned at 7.97 μvoxel resolution. The user is required to create a final volume as part of an image visualisation step for capillary trapping using rotations and translations of specific parts as well as importantly clipping plane functions.

The first 3D dataset includes a dry [Cq17] Ketton carbonate and the second consisted of a reacted Ketton carbonate using hydrochloric acid. The user is required to remove noise and apply auxiliary functions to define which voxels were visualised based on the absolute and gradient values of the opacity.

3.1. Hardware

The experiment was run on a Windows 10 Pro, Dell Optiplex 7010, with an Intel Core i7-3770S processor, clocked at 3.10 GHz. Four hardware input controller setups were selected to be cross-evaluated; an Oculus Go Standalone Virtual Reality Headset - 32 GB, an Xbox 360 game controller, a custom setup consisting of a Keyboard + Mouse, and two 3DConnexion SpaceNavigators.

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Table 1: *Keywords and their description used for the five HCI devices setup used for VE's controllers to analyse the trapping* CO_2 *by capillary forces in the rock pore space.*

Keyword	Description
KMW	Keyboard + Mouse (3DOF)
HMD	Oculus Go + Controller (3DOF)
GPC	Xbox controller (6DOF)
SNW	One 3Dconnexion SpaceNavigator + Keyboard + Mouse (10DOF)
SN2	Two 3Dconnexion SpaceNavigators (12DOF)

Both SpaceNavigators devices have an advanced 6DOF optical sensor, simultaneously pan, zoom and rotate 3D models and two programmable function keys. Table 1 shows the HCI devices setup derived and used in this evaluation.

3.2. Software

The 3D X-ray CT images were segmented into solid, water and gas phases (obtained from the British Geological Survey (BGS) database [Cq17]). This segmented volume was converted to be imported to the ANU Drishti software for visualisation [Lim12]. This study used the LISU framework to enable all of the input controller setups to be simultaneously applied and linked to the interactive visualisation environment. Programming was done within Python (v.3.7) and the 3D visualisation software API (ANU Drishti version 2.6.4 for image processing). Drishti has been selected because it is straightforward to explore and present volumetric datasets without extensive training. Python was selected for being practical and easy to work with Drishti and its simplified syntax.

3.3. Interaction

Interaction is based on an asymmetrical bimanual paradigm where one hand was used primarily for positioning and reorienting of 3D content. For example, volume or clipping plane and the other hand was used mainly for selecting functions and activating or deactivating commands. Interaction with the available 3D content was facilitated by segmenting the volume data into 3D subblocks called "*bricks*".

3.4. Image processing

- Figure 1(a) shows the initial state of the experiment, which consisted of loading two volumes datasets of Ketton carbonate in Drishti. Volume one is binary, representing the first dataset of dry Ketton carbonate as a reference; volume two is greyscaled, representing the reacted Ketton carbonate using hydrochloric acid to clip the greyscale volume leaving the binary volume intact.
- Figure 1(b) shows the rotation of the camera and the pre-created bricks to control and manipulate the 3D volume and get an extract of the explored volume.

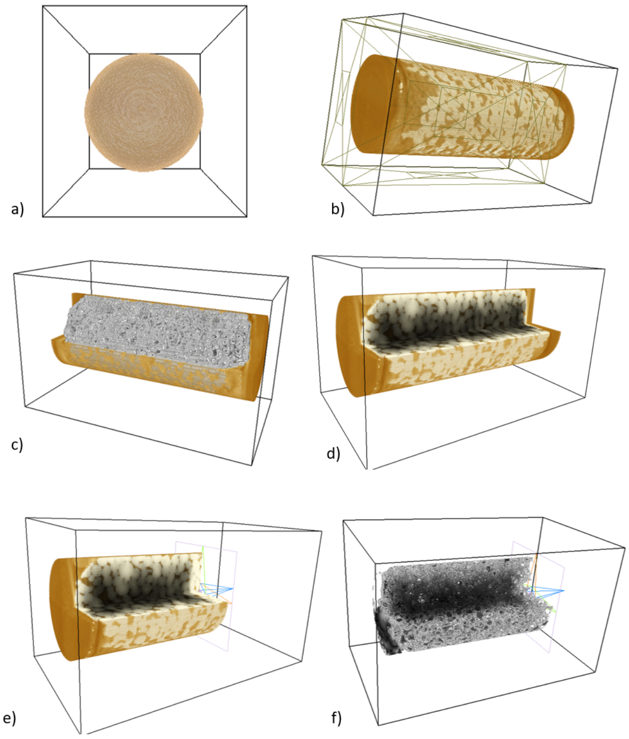

Figure 1: *Screenshots of the performance of the image processing of the capillary trapping of* CO_2 *in Sandstone: a) initial state where two volumes of the same dataset are loaded in the 3D visualisation package; b) bricks created for this volume; c) shows the inner exposure of the volume after translating one of the bricks out of the screen view; d) shows the removal of a second brick, showing the pore-throat portioning of the dataset; e) shows the clipping plane applied to reach the coordinates* $(521, 503, 1292)$*; f) final resulting image used for the contact angle measurement.*

- Figure 1(c) shows how we used bricks with clipping turned on for brick showing grayscale volume; then, we set a transfer function for brick one representing the binary volume and another transfer function for brick two that describes the grayscale volume.
- Figure 1(d) shows the initial geometry of the Ketton carbonate core and the flow-field within it computed using single-phase flow computed using the lattice Boltzmann method [CD98] by translating the brick two.
- Figure 1(e) shows another clipping plane applied to reconstruct a new volume with the coordinates $(521, 503, 1292)$.
- Figure 1(f) shows the 3D reconstructed image, which can be processed appropriately to enhance the contrast and boundaries between the different physical phases: gas, water, and solid. This final image shows the pore space where one can extract networks to analyse the multiphase flow and relative permeability.

Table 2: *Analysis of variance (ANOVA) for time completion for the capillary trapping on Ketton carbonate core with the five means of interaction, with a multiple pairwise comparison (Post-hoc comparison) analysis using Tukey HSD test, FWER = 0.05.*

Source of variation	df	F statistic	*p* value
Performance	4.0	6.49	0.000185
Residual	65	–	–

Group 1	Group 2	Difference between the group means	Adjusted *p* value
HMD	SN2	-40.647	0.0069
HMD	SNW	-34.759	0.0295
HMD	KMW	-37.59	0.015
HMD	GPC	0.263	0.9
SN2	SNW	5.887	0.9
SN2	KMW	3.056	0.9
SN2	GPC	40.910	0.0064
SNW	KMW	-2.831	0.9
SNW	GPC	35.022	0.0277
KMW	GPC	37.854	0.014

3.5. Experimental setup and procedure

We present in full detail all the steps conducted for the replication of this experiment where the duration of this test lasted five days (from March 21, 2021, to March 26, 2021). The user was asked to obtain as close a result to a given volume rendering image. The time required for task completion was measured, along with the number of attempts needed to complete each task. To determine the number of attempts needed to obtain the desired result, we counted a single attempt at the beginning of each task, and we added a new attempt whenever:

- The user would reset the orientation of the volume (except at the very beginning of the task);
- The user would move the volume randomly (e.g., mistakenly dragging the mouse or rotating their hands);
- The user would lose control of the volumes' rotation (either by accident or frustration) and would have to try again.

4. Results and discussion

In this section, we present the main observations made during the test and the difficulties encountered during the evaluation.

- The average completion times were **HMD** (M = 113.35*s*, SD = 27.59*s*), **SN2** (M = 72.71*s*, SD = 15.94*s*), **SNW** (M = 78.59*s*, SD = 28.46*s*), **GPC** (M = 113.62*s*, SD = 49.22*s*), and **KMW** (M = 75.76*s*, SD = 20.44*s*) (see Table 1 for reference of the keywords).
- Notably, the top ranking of devices setups was **SN2** (12DOF). An explanation for this was that the user could freely move in the simulated environment, so it was more straightforward to apply multiple actions simultaneously, although the interaction was asymmetric. This further supports the observations made by Guiard [Gui87].
- A one-way ANOVA revealed that the ratio of mean squares is highly statistically significant ($F(4,65) = 6.49$, $p < 0.05$). There are significant differences among performance with the five-ways of interaction. However, there was no correlation between the time used and the experience the user had with VEs.
- From ANOVA analysis, we know that performance differences are statistically significant, but ANOVA does not tell which HCI device setups are significantly different from each other. To understand the pairs of significant different HCI devices setups, we performed multiple pairwise comparison (post hoc comparison) analysis using Tukey's honestly significantly differenced (HSD) test, as seen on Table 2.
- From Table 2, there is a statistical significant difference using **HMD** and **SN2** setups compared to the standard interaction setups **GPC** and **KMW**. In Figure 2 there is a clear trend of decreasing the time completion in the **HMD** and **SN2** setups after 3 days of performance. The completion time differences between these interaction setups resulted from a steeper learning curve regarding Drishti's interface, which is expected due to the lack of familiarity using higher DOF controls for these tasks.
- Using a Shapiro-Wilk test, the *p* value > 0.05 obtained to check the normal distribution of residuals was considered not significant. Therefore, the raw data deviate severely from normality.

Figure 2 shows the graphical testing of homogeneity of variances that supports the statistical testing findings on Table 2. One major hurdle noted during the execution of these tasks, which presents the main reason for the user's poor performance, was the SpaceNavigator and Xbox lack of precision. While the user was relatively quick to identify the structures of interest, there was trouble in selecting the desired slice or placing the correct position for the clipping plane, thus increasing the time necessary to complete the task.

Figure 3 shows two graphs of the performance using the five interaction setups over the 5 days that it was the experiment duration. These results represent an emerging trend in shortening the completion time via multiple controllers after the third day. On day 3, the average completion time was for **HMD** (M = 98.95*s*, SD = 16.11), **SN2** (M = 69.79*s*, SD = 29.97), **SNW** (M = 71.79*s*, SD = 22.57), **GPC** (M = 106.45*s*, SD = 24.54) and **KMW** (M = 77.83*s*, SD = 18.39).

Figure 3 is strong evidence to state that experience and familiarity with the input devices contribute to better results. Of the five days of experimentation, we can see that during day two and day four, there was the best performances for this device setup.

A number of limitations need to be noted regarding the present study:

- Besides the unfamiliarity with the input devices used during the experimentation, the quality of the devices influenced the performance. The gamepad's thumbstick and triggers of **GPC** setup felt stiff, and many problems arose during the test when rotating

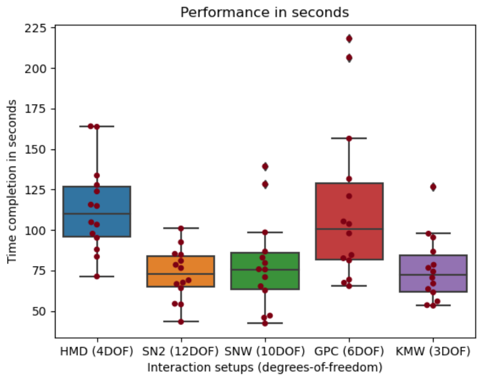

Figure 2: *Box plots of the five HCI devices setups performance. Box width is proportional to sample size. Units are in seconds.*

the bounding box's bottom side using any interaction setup with the SpaceNavigator.

- Regarding the use of the SpaceNavigator, despite autocalibrating this device, the user had to add a new function to the ontology to increase the value of the dead zone via a button and decrease any unwanted movement detected by the device. This approach was helpful, resulting in improvement during and after day 3.
- When applying clipping planes, the user would often lose a few more seconds to place the plane in the correct position. However, after day 2 (see Figure 3), the more familiar the user was with the setup controllers, the more natural and intuitive the interaction was.

5. Conclusion

With upcoming input devices for VR, new natural and intuitive interaction methods need to be considered. Here we provide a new framework for exploring and segmenting volumetric data, benefiting the oil and gas community with more accurate and precise digital reconstruction and 3D modelling in Drishti. As seen in this usability test, LISU can be used as a framework to segment computed tomography and other forms of volumetric data that is widely applicable in earth scientific researches. This work will surely fuel further multiple cross-discipline collaborations between scientific visualisation and many other fields.

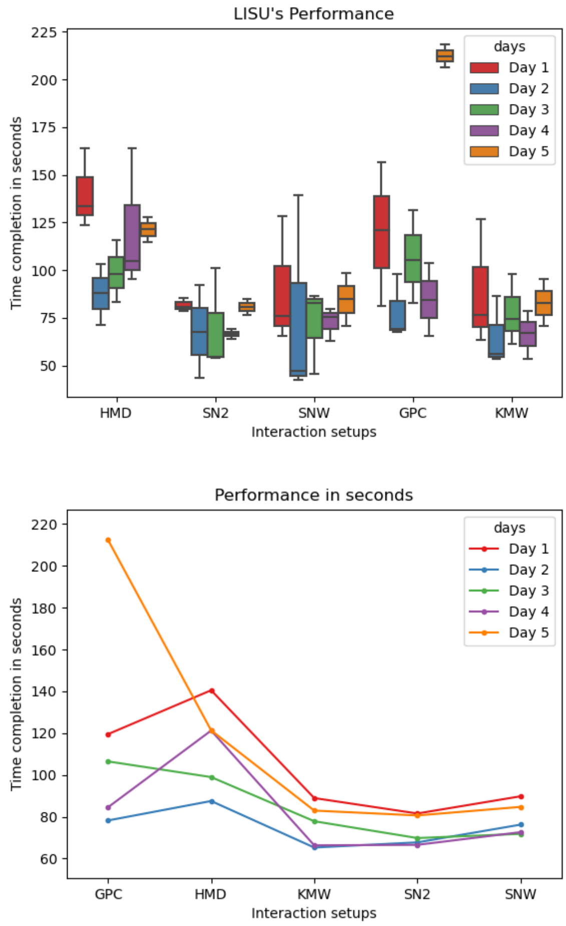

Figure 3: *Box plots and interaction plot that to visualise the means of the performance time and the lapse of days of the experiment.*

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