CAVE COLON
Cave-like Virtual Reality Environments for CT Colonography

Pedro Flores Brasil Gomes Borges
pedrobrasilborges@gmail.com

Thesis to obtain the Master of Science Degree in Biomedical Engineering
Supervisors: Prof. Dr. Joaquim Armando Pires Jorge* and Dr. Daniel Simões Lopes**
*Instituto Superior Técnico, Universidade de Lisboa
**Visualization and Intelligent Multimodal Interfaces Group, INESC-ID
October 2017

Abstract — Colorectal cancer is the second most deadly cancer in the western world, even though it has a high rate of cure, if detected early. Screening procedures are one of the most important ways of preventing this type of cancer, especially for detection at an early stage.
Colonoscopy has been the golden standard for screening colorectal cancer for decades, but, recently, CT Colonography has been classified as the leading imaging technique for CRC screening by the American Cancer Society (ACS). Still, it has some limitations that arise from the fact that it is uses a 2D interface to interact with a 3D volume. The colon is an organ that has several inflections and along its extension exhibits numerous colonic haustral folds in its interior, making it hard to navigate, and if done in the previously mentioned setup, its difficulty is even more exacerbated.
To surpass the limitation of conventional 2D interfaces, the sense of visual immersion offered by VR technology carries the promise to improve image reading and 3D perception. The goal of this thesis is to verify if VR is a suitable medium for CT Colonography, namely whether eases 3D perception and promotes a more effective interpretation of patient-specific anatomy. To achieve this, a multiscale virtual reality system that mimics CT Colonography was created.
To validate the viability and usability of the application, two different studies, one with professionals and the other with laypeople, were carried out. The results from both tests were very positive in their own way. The feedback from the medical professionals showed it to be a viable contribution to the diagnostic imaging field, one that can even be applied to other settings, while the other test helped us to better understand VR navigation, especially, in space-confined environments.
Keywords: ct colonography; virtual reality; htc vive; confined-space navigation; colorectal cancer; multiscale interface;

1. INTRODUCTION

1.1. Motivation

Colorectal cancer (CRC) is the second leading cause of cancer-related death in the western world with, an estimated 1.4 million new cases every year worldwide, half of which end in death (Ferlay et al. 2015). The preferred method of colonic examination for diagnostic purposes is optical colonoscopy. However, this procedure has many contraindications that patients often dislike, such as, bowel cleansing and general anesthesia (Levin et al. 2011), besides being expensive. These disadvantages led to the introduction of CT colonography (CTC), which can offer these patients a better alternative, due to significantly reduced side effects, while being almost as good a diagnostic tool (Barish, Soto, and Ferrucci 2005; De Haan et al. 2011; Pickhardt et al. 2011). While analyzing CTC content, the radiologist works in the current standard workstation, *i.e.*, desktop, monitor, mouse and keyboard; however, using a 2D display to analyze 3D structures can lead to missing information (Mirhosseini et al. 2015). There are benefits in using immersion to analyze scientific datasets by employing virtual reality (VR) (Kuhlen and Hentschel 2014), which would, hypothetically, translate into a faster procedure and, possibly, a higher number of lesions found.

Therefore, the main questions in this thesis are: (1) Does VR help to better visualize, read and understand the information that exists in both CT images and a 3D model of the colon? (2) Does VR help to identify occult polyps? (3) What is the best way to navigate inside the 3D reconstructed model of the colon?

To answer these questions, an interactive VR system was developed which simulates CTC in an immersed virtual reality world. Furthermore, we sought to better understand how do specialists in this area respond to this kind of setup, how it can be improved and determine the best and most natural navigation technique that can be applied to a confined virtual reality space.

1.2. State of the Art

The first created and most common navigation technique utilized to navigate inside the colon in CTC procedure is the Fly-Through. However, Fly-Through just like traditional colonoscopy can miss potential polyps that are hidden behind and/or inside haustral folds. This happens, because users can only see the colorectal tissue that it is exposed to the normal of the viewing camera, so polyps

that are not on this limited visible tissue can be missed. To adress this issue, two main visualization solutions were created: flatenning techniques and the unfolded cube projection. Flatenning techniques take the premise of opening the colon and exposing it in either 2D or 2.5D to try to reduce redundancy and to miss less polyps. The unfolded cube projection captures at the same time, six cameras normals that move together by the centreline of the model. These camera normals represent all views of the colon and by unfolding it shows all the possible views of the colon for every centreline position. While both techniques help in their own way to resolve the initial issue, their method of visualization being a more intuitive approach is subject to each user. The layout of the projections in the cube can be time consuming, since now the user needs to scan each side of the unfolded cube and the algorithms used in the colon flattening are prone to errors, due to the complexity of the 3D model. Fly-Over is another visualization technique that tries to solve the Fly-Through limitations. It was introduced by (Falk, Farag, and Hassouna 2006) in 2006. The colon, in this navigation mode, is divided in two halves by the centerline and then it is assigned a virtual camera to each half. By analyzing the volume in a perpendicular perspective, the surface coverage goes up significantly, since now the visualization of every fold, back and forward, are done almost obligatory, and it achieves a higher sensitivity. However, it still survers from the drawbacks from using a 2D interface to interact with a 3D model.

Virtual reality (VR) have been used in several components in medicine, either in rehabilitation (Rodrigues-Baroni et al. 2014), medical education (Codd and Choudhury 2011), and even surgical planning and training (Shanmugan et al. 2014; De Visser et al. 2011). On all these areas virtual reality has been a good and positive technology addition, allowing for faster results in each topic. However, the one that stays, notoriously, behind is diagnose via VR.

More than one hundred radiologists participated in two studies (Rumreich and Johnson 2003; Siegel et al. 2000) that concluded that the most important factor for radiologist productivity is good room lighting, while the negative aspect of productivity is insufficient space and number of monitors needed. SOUSA et AL, showed that VR is suitable to analyze CT images and volumes, and can minimize the disavantages of 2D interfaces.

There are five main ways of navigating in VR: physical movement, manual viewpoint manipulation, steering, target-based travel and route planning. Physical movement requires the user to walk around a tracked workspace. It has several documented benefits USOH, but the instruments are to large and can be tiring. Manual viewpoint manipulation makes use of hands to handle movement, but it can be exhausting in large environments. Steering makes the user to specify the direction and speed of movement. While it is general and effictive, it causes more simlator sickness. Target-based travel the user specifies on the direction and destination of the final point and the system handles the actual movement. Finally, route planning the user builds his own path.

With the advantages of VR in diagnostic imaging field in mind, two groups have started exploring immersive CTC experience. The first group to attempt it used CAVE (cave automatic virtual environment) (Mirhosseini et al. 2015). Placed the user in a room while the gastrointestinal walls where projected into the room walls. Although, the conclusions seem positive (potential improvement in terms of examination time and accuracy), this type of setup is unrealistic to a real clinic and CTC evaluation room, besides the fact that it's still not a real 3D interface.

The second group used an approach similar to ours, by using a real virtual reality setup - Oculus Rift (Randall et al. 2015). This study worked more like a prove of concept, since the tests done and the prototype itself were very limited. Still, the conclusions from the three professional users were mostly positive. All three reported that the immersive environment was better than anticipated and solved the tedious and complex movement done with the mouse in the conventional setting. Also, some predicted that it would be a greater benefit for those without much experience, due to the intuitive maneuvering, and an overall faster diagnose, as a result of no possible distractions with the combination of reduced fatigue.

2. METHODOLOGY

The focus of this work was to explore how can VR help with the readability and understandability of the CT model. To do this it was created a prototype to perform a CT Colonography procedure in a VR environment.

2.1. Unity3D

Unity3D is a game development environment and IDE developed by Unity Technologies. Since it was created with video game development intent, it has 2D and 3D renderers, physics model, collision detection, etc. It was chosen as the platform for developing the application due to its low barrier to entry, extensive documentation library and the built-in support for VR devices such as HTC Vive, Oculus Rift, etc. For HTC Vive, specifically, there is a package called SteamVR that helps to connect

to HTC Vive controllers and headset, in the Unity3D Editor and in scripts.

2.2. 3D Model

To perform CTC it is necessary to create a three-dimensional model of the human colon and its centerline, to, achieve the intended immersion. The 3D model was created using CT images extracted from the The Cancer Imaging Archive (TCIA) and by following a well described geometric modelling pipeline, as shown in Fig. (2.1) (Lopes 2013).

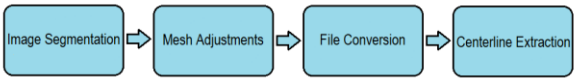

Figure 2.1 – Geometic modelling pipeline to build a 3D model from CT images.

The most important thing to consider while creating a 3D model from a stack of 2D medical images is how to extract the most relevant information from said images. To do this, it was used a method called global thresholding, where it simply partitions the image by the intensity value of each pixel, but this has a drawback, it may classify points that do not belong, because it has the same intensity value. So, to partition the images into well-defined, and homogeneous boundaries, the global thresholding method was complemented with a semi-automatic approach, the active contours method in the ITK-SNAP software 2016 version 3.6. After segmentation is over, ITK-SNAP uses the marching cubes algorithm to create the final 3D mesh. To create this mesh it was followed the methodology of the following reference, (Ribeiro, Fernandes, and Lopes 2009), where a more detailed explanation and understanding of these concepts can be comprehended.

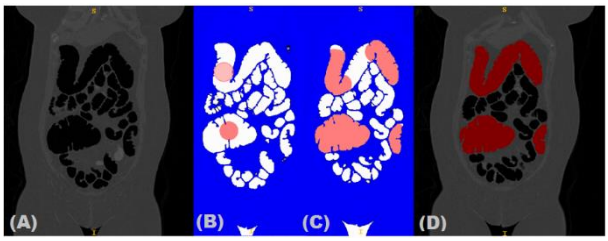

Figure 2.2 - (A) CT image before any processing; (B) CT image with low-pass filter applied, and, two snakes (red circles); (C) The active contour model in progress; (D) Final CT image with the colon segmented.

Since the volume obtained by the previous step has a rough surface and a not so much natural look, it was imported into another software, ParaView 5.3.0, to eliminate undesired mesh artefacts though a cycle of smoothing and decimating operations. Finally, it is still necessary to extract the centerline of the object. To do this, it was used a GitHub software, made available at (Tagliasacchi et al. 2012b), that resolved the skeletonization problem of a 3D mesh by using the mean curvature flow (MCF) (Tagliasacchi et al. 2012a).

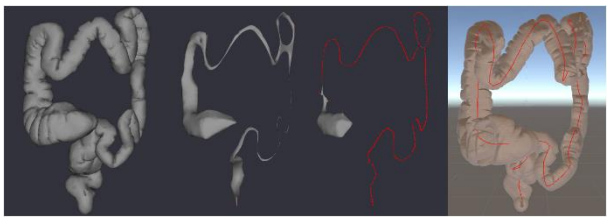

Figure 2.3 - Evolution from 3D model to its centerline by formulating skeletonization via MCF and its implementation on the Unity's Editor.

2.3. CAVE COLON

CAVE COLON is a multiscale virtual reality platform that allows the user to inspect the colon model and navigate inside it from three different navigation modes. It also comes with several tools that are necessary to do an efficient diagnosis. The application runs on a single computer at a constant 60+fps (frames per second). The computer needs to have a high end graphical card (GTX 970 or higher recommended), since VR applications can be quite graphical intense.

2.3.1. Graphical User Interface

There are 2 major ways of analyzing the volume, which is from outside and from inside the colon model. Outside view, the model is rendered like a holographic model, Fig. , with the volume being almost as tall as the user and floating from the ground, while in Luminal view the user can feel claustrophobic.

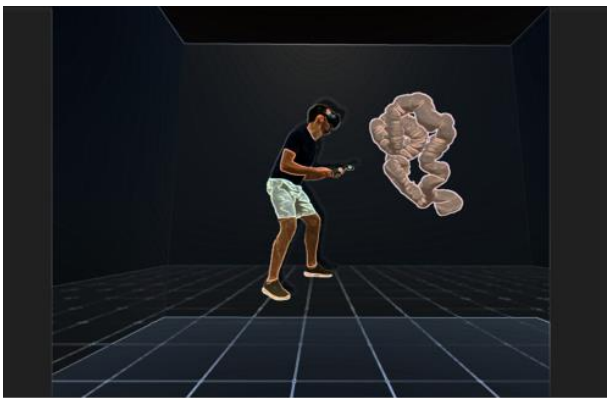

Figure 2.4 - Photo manipulation to create the representation of the Outside view from another perspective.

Figure 2.5 - Photo manipulation to create the representation of the Luminal view from another perspective.

2.3.2. Interaction

To interact in CAVE COLON, all that is need, is two HTC Vive controllers. When the application starts, the user just has to make sure that the controllers are visible to the base stations. The interaction depends on what view the user is, which means that for each view (Outside view and Luminal view) there are different actions that can be performed. The next table introduces the user to all actions possible in CAVE COLON as well as the buttons needed.

Table 2.1 – Possible action in CAVE COLON prototype.

VIEW	ACTION
OUTSIDE	Rotate the Model
	Reset Rotation
	Initial Spot Selection
LUMINAL	Automatic CT Slices
	3D Map
	Polyp List
	Ruler
	Marker
	Move Forward and Backward
BOTH	Change View

2.3.3. Navigation

The navigation techniques proposed for CAVE COLON were Fly-Through, Fly-Over and Elevator. Just like in conventional CTC, the Fly-Through navigation technique will make the user feel inside a cave. The virtual camera will follow the path without the need for the user to move its head. It can however move the head to see what's behind, below or above him. The Fly-Over in this prototype has a difference from the original Fly-Over, it doesn't break the model in half, it just analyzes the volume from a perpendicular perspective. It doesn't need to break in half, because the user can just move his head in a 360º angle to see every wall. The camera will automatically keep the perpendicular perspective in the eyes of the user, but as before the user can simply move its head to see the remaining of the colon. Elevator mode navigation technique doesn't move the camera angle rotations, making it all user responsibility, which makes for a more natural head rotation and, thus, possibly, less cybersickness during the VR trip, but it can be easier for the user to lose the sense of direction of the movement.

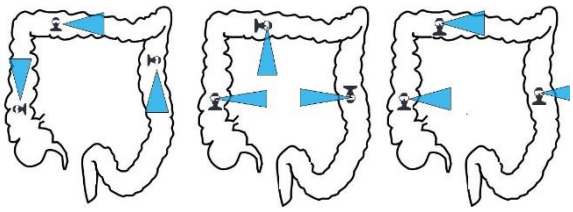

Figure 2.6 - Schematic showing how the camera moves during the three navigation techniques proposed in this work, from lefto to right, Fly-Through, Fly-Over, Elevator.

3. Results and Discussion

3.1. User evaluation tests

In order to understand the viability of the CAVE COLON application, user tests were designed to evaluate the user response and performance while experimenting this new concept in three different navigation modes. To do this, it was proposed to do an Easter hunt navigation VR challenge. This challenge consists in evaluating a navigation mode based on how well the user performs, in regard to, "Easter eggs" found, time to complete the task, and, specific to VR, the Simulator Sickness Questionnaire (SSQ) score. Since this test was made with laypeople in mind, it didn't made sense for them to try to find polyps, like it happens in real CTC, due to their limited gastrointestinal anatomy knowledge. In this case, the "Easter egg" was a capsule model colored in a darkish brown, Fig. X.

Figure 3.1 - Exemplification of how the prop looks.

3.2. Participants

In this laypeople test, eighteen participants (13 male and 5 female) have volunteered to cooperate, with ages ranging from 18 to 25 years old [Mean (M) = 21.94; Standard Deviation (SD) = 1.98]. Most participants had background in either, Biomedical, Informatics or Electronic Engineering. About 66.6% of the users never used any VR system, while the remaining 34.4% stated that their use was rare (less than 1 time per month). It was also asked if the user suffered from claustrophobia with only 1 out of the 18 answering positive.

3.3. User Test Tesults

After a superficial analysis, it is possible to say that there are subtle, but important differences in time between the three navigation modes.

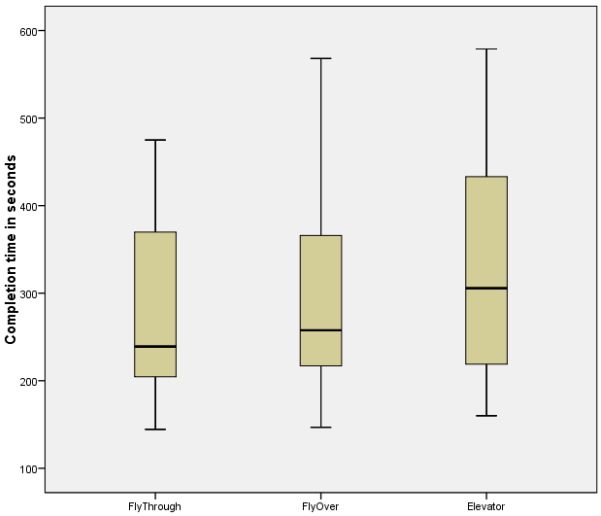

Figure 3.2 - Boxplot for each navigation mode in relation to the completion time in seconds. The graphic presents the median, first and third interquartile ranges (boxes) and 95% confidence interval (whiskers).

It was obtained a mean completion time of (M = 273.91; SD = 100.05) in the Fly-Through navigation, (M = 305.53; SD = 124.38) in the Fly-Over navigation and (M = 325.63; SD = 131.68) in the Elevator navigation. Regarding the median (MDN) value, Fly-Through had the value of (MDN = 239.12; IQR = 170.37), Fly-Over had (MDN = 257.60; IQR = 171.28) and Elevator had (MDN = 305.61; IQR = 214.50).

It was performed a Shapiro-Wilk test, a normality test, which came out negative for this set of data. So, in order to compare these three navigation modes in terms of time, it was used the Friedman test. The p-value was 0.002 which is statistically significant, so in order to understand which is better, a Wilcoxon signed-rank test was performed in groups of two. Below is a table with the results:

Table 3.1 - Statistical values (Z and p-value) of the Wilcoxon signed-rank test in regard to total time in each navigation mode.

	FLY-THROUGH	FLY-OVER	ELEVATOR
FLY-THROUGH	-	-	-
FLY-OVER	(Z = -2.548; p = 0.011)	-	-
ELEVATOR	(Z = -2.983; p = 0.003)	(Z = -1.586; p = 0.113)	-

When comparing the Fly-Through with the Fly-Over and the Fly-Through with the Elevator there is statistical significance in both these cases which means that, firstly, when performing both Fly-Through and Fly-Over navigation, the Fly-Over will be more likely to take more time, secondly, the same will happen when performing both Fly-Through and Elevator mode, where in this case, Elevator will be more likely to take more time. In regard to the final comparison, Fly-Over and Elevator, even though when looking at the mean it seems that one is effectively faster than the other, in reality, there is no statistical significance supporting that premise.

The preliminary results for the percentage of props found for each navigation mode seems to go according to the results found in conventional CTC navigation.

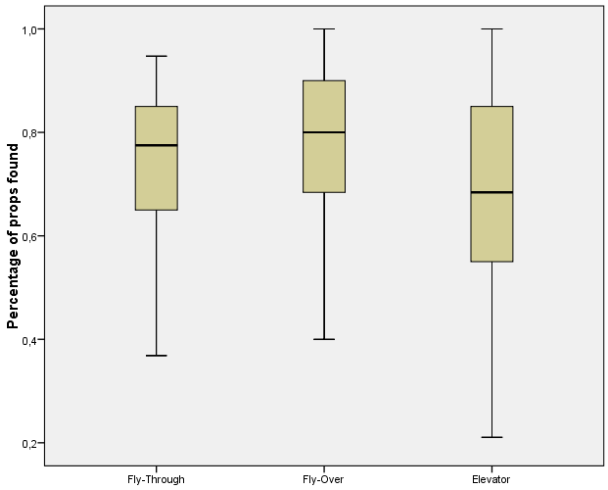

Figure 3.3 - Boxplot for each navigation mode in relation to the mean percentage of props found. The graphic presents the median, first and third interquartile ranges (boxes) and 95% confidence interval (whiskers).

It was obtained a mean percentage of props found of (M = 0.73; SD = 0.19) in the Fly-Through navigation, (M = 0.79; SD = 0.16) in the Fly-Over navigation and (M =0.68; SD = 0.21) in the Elevator navigation. Regarding the median value, Fly-Through had the value of (MDN = 0.78; IQR = 0.26), Fly-Over had (MDN = 0.80; IQR = 0.24) and Elevator had (MDN = 0.68; IQR = 0.31).

Just like previously, this set of data did not follow a normal distribution. For that reason, both tests made

previously were repeated with the new data. The Friedman test returned a p-value of 0.005, which means that this variable is statistically significant. With the positive value from the previous test, Wilcoxon signed-ranks tests were required to evaluate the navigation modes in comparison with each other.

Table 2.2 - Statistical values (Z and p-value) of the Wilcoxon signed-rank test in regard to percentage of props found in each navigation mode.

	FLY-THROUGH	FLY-OVER	ELEVATOR
FLY-THROUGH	-	-	-
FLY-OVER	(Z = -1.846; p = 0.065)	-	-
ELEVATOR	(Z = -1.113; p = 0.266)	(Z = -3.314; p = 0.001)	-

Firstly, there is no statistically significance between the Elevator mode and the Fly-Through. Secondly, there is an obvious statistically significance between Fly-Over and Elevator mode, which means that when performed both navigation modes, the user is more likely to find more props when he is navigating in Fly-Over mode in comparison with Elevator mode. Finally, while there isn't statistical significance when comparing Fly-Over and Fly-Through, the p-value is close to it, which deems for more metrics to compare. In conclusion for this variable, Fly-Over is better than Elevator mode, but when comparing both Fly-Over and Fly-Through there is no statistical significance, still the mean value of the Fly-Over is notoriously higher (0.79 vs. 0.73), but the median is rather close (0.80 vs. 0.78).

The preliminary SSQ score results are displayed below.

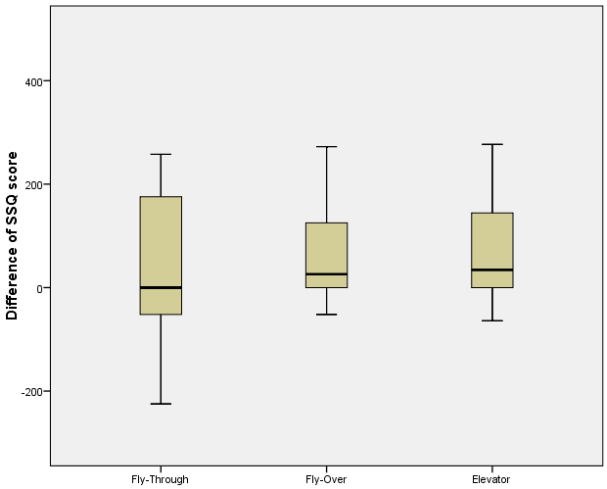

Figure 3.4 - Boxplot for each navigation mode in relation to the mean difference of SSQ score (after – before the navigation mode). The graphic presents the median, first and third interquartile ranges (boxes) and 95% confidence interval (whiskers).

The mean and the standard deviation score for each of the navigation modes were, (M = 27.37; SD = 134.87) for the Fly-Through, (M = 83.12; SD = 133.78) for the Fly-Over and, finally, (M = 225.95; SD = 277.31) for the Elevator. In regard to the median values, Fly-Through had the value of (MDN = 0.00; IQR = 234.63), Fly-Over had the value of (MDN = 26.03; IQR = 141.88) and the Elevator had the value of (MDN = 75.66; IQR = 144.44).

Like previously, a normality test was executed and found that this set of data does not follow a normal curve. The Friedman test was once again done, but in this case the p-value = 0.410, which means that no statistical significance was found when comparing these three navigation modes in terms of SSQ score difference.

After each trip into the human colon, each user had to fill the navigation survey relatively to the navigation technique he had just completed. There were 5 statements that the user had to classify with the Likert scale mentioned previously: "It's useful"; "It's easy to understand the way of movement"; "You were disoriented"; "It's easy to find the 'props'"; "You counted two times the same 'prop'".

In regard to the usefulness, the users deemed in their opinion that the Fly-Through and the Elevator navigation were the most useful, 6/6 (since Likert scales are ordinal scales, the value presented is the median), while the Fly-Through was also the easiest to understand the way of movement, 6/6. In Fly-Through navigation mode the disorientation median was 1/6, while in the other two navigation modes it was significantly higher, at 3.5/6 and 3/6 (1 – Totally disagree and 6 – Totally agree). In the last 2 statements the difference between the three navigation modes were not significant.

Table 3.3 - Median and IQR for the navigation mode questionnaire.

	FLY-THROUGH	FLY-OVER	ELEVATOR
It's useful	6 (0.75)	5 (2)	6 (1.75)
It's easy to understand the way of movement	6 (0)	5 (2)	5 (2)
You were disoriented	1 (1)	3.5 (3)	3 (3)
It's easy to find the 'props'	5 (2)	4.5 (1)	5 (1.75)
You counted two times the same 'prop'	2 (1.75)	2.5 (2)	1.5 (1.75)

About the interface used and the button schematic created, it was also done a small survey with the same layout as before, i.e., Likert Scale 6 questionnaire. It was

done 3 statements for the two operations available in this laypeople test. “It’s the adequate way to perform”; “It’s easy to perform”; “It’s easy to remember”. The results, Table (4.4), were excellent, with neither statement going lower than 6/6.

Tabela 3.4 - Median and IQR for the interface questionnaire.

	OPERATION ‘MOVE’	OPERATION ‘COUNT’
It’s the adequate way to perform	6 (0.75)	6 (0.75)
It’s easy to perform	6 (0)	6 (0)
It’s easy to remember	6 (0)	6 (0)

3.4. Professional Opinion

The main objective of this test was to get the most feedback as possible in regard to the prototype usability. The user in this test was not the focus to be studied.

Figure 3.5 - Medical professional exploring the interiors of the colon with the CAVE COLON prototype.

As previously, the questionnaire was a Likert Scale 6 questionnaire (1 - Totally disagree and 6 – Totally agree). The medical professionals deemed the prototype as really easy to use (MDN = 5.5; IQR = 1), and voiced the same opinion when asked if the model visualization was the most appropriate (MDN = 5; IQR = 0.75). The action’s questionnaire comprised three statements for all possible actions: “It’s useful”, “It’s easy to execute” and “It’s easy to remember”. The full results are in Table (4.5). Looking into the results, it is easily noticeable that the professionals found that all buttons were relatively useful, equally easy to execute and also very easy to remember. Finally, they were also asked about the graphical user interface (GUI). The professionals said that the buttons and menus very easy to use (MDN = 6; IQR = 0.75) and the visual path and arrows were indispensable (MDN = 6; IQR = 0).

Table 3.5 - Median and IQR for the actions questionnaire.

	Mov	Mea	Mar	Map	CT	List	Spot
It’s useful	6 (0.75)	6 (0)	6 (0.75)	6 (0.75)	5 (0.75)	5.5 (1)	5.5 (1)
It’s easy to execute	6 (0.75)	5.5 (1)	6 (0.75)	6 (0.75)	5.5 (1.75)	5.5 (1)	6 (0.75)
It’s easy to remember	6 (0)	6 (0)	6 (0.75)	6 (0)	6 (0.75)	6 (0.75)	6 (0.75)

Where Mov is the Movement action, Mea is the Measure action, Mar is the Marker action, Map is the 3D Map action, CT is the CT images action, Spot is the Initial Spot action.

The participant was also submitted to a small interview. There was made six fixed questions and then discussed around them. The most important points described by the professionals were:

a. the multiscale model is very helpful, mainly the holographic model, since it’s important to have a notion of the spatial distribution of the colon, while also permitting to access rapidly the locations that raised more doubts;
b. the prototype requires some familiarisation, since there are many actions and commands, and the HMD can be quite heavy, which can lead to fatigue. It can be required to make frequent breaks while the professional gets use to using the HMDs;
c. in the conventional procedure the camera is not always correctly placed and for that reason the professionals believed that accessing information outside their point of view was easy and way faster than in conventional CTC due to the free rotation of the camera; 3D perception was present and highly useful;
d. the professionals believe that when the prototype have all the features that resemble in the conventional software, reading and analysing CT Colonography images using CAVE COLON will outdate conventional software, but only if it's plug-and-play, because radiologists often don't have much time and only in the colon navigation, since the 2D images examination can be quite difficult in virtual reality.

4. Conclusions and Future Work

4.1. Conclusion

Finding polyps inside the inflexed structure that is the human colon can be a challenging procedure. Numerous complementary work has been developed over the years to help radiologists with this task, however most of them can be hard to learn or even master due to their unintuitive nature. The main problem resides in the fact that a WIMP interface is still being used to interact with a 3D volume.

Virtual reality has shown recurrent benefits when used appropriately in the medical field. In this work we investigated the use of virtual reality incorporated in an immersive CT Colonography procedure. We also explored three different navigation techniques. As a result, CAVE COLON was created.

A comprehensive experimental protocol was arranged to study which of the three navigation techniques under consideration was the best and fastest to help find props inside the space-confined colon. Eighteen participants navigated inside a human colon in three different perspectives. The results showed that the Fly-Through was the most comfortable, less cybersickeness-prone and fastest way to go through the colon. The Fly-Over was the least enjoyable to most of the users, but it was the one that on average helped the user to find more props. The Elevator was the worst: took more time than the other two methods, found less props, caused more cybersickness and was more error-prone. With these results we concluded that camera orientation is essential for a better diagnose and a faster reading of one's surroundings. The feedback from the users showed us that the use of simple and intuitive controls, namely the HTC Vive controls plus the incorporation of the virtual menu, did help the users understand and master the controls faster.

A professional test with four radiologists, being two of them specialists in CTC, was scheduled in order for specialized feedback about the usability of CAVE COLON. All professionals felt the immersed and believe that this kind of visualization will become the norm in the future. The main advantage of this setup, in their opinion, is the speed at which radiologists will be able to examine the images and diagnose the patient. In their words, "conventional CTC is cumbersome and slow", besides the fact that the software and hardware used are expensive. They believe that CAVE COLON is not ready for day-to-day use simply, because it doesn't have several features that is important in a CT Colonography procedure, like, fecal tagging, computer-assisted detection, prone and supine positions, etc. However, the main question on this work was if VR was the suitable medium to examine the virtual colon, and with their feedback, we believe that this work was very positive and with the implementation of said day-to-day features we could in the future outdate the current setting.

Virtual reality is presently an on-going and growing presence in the imaging diagnosis field. Being a portable and intuitive technology, we believe that it can be useful in this field, where getting the most of an image or volume is the ultimate goal. CAVE COLON was declared a viable, competitive and even an alternative to the conventional setting. Therefore, it is necessary to keep improving this technology by adding more features and acquiring a deeper understanding about navigation techniques in space-confined environments.

4.2. Future Work

The explored prototype and its navigation techniques leave room for improvement and open other research avenues that will be analyzed in this section.

Regarding the navigation, we think that using other navigation techniques, such as walk-in-place or steering, once they are improved, would be a good contribution to understanding how to maximize navigation in space-confined virtual environments. About the navigation techniques studied in this work: the Fly-Over navigation technique showed good results, but users didn't seem to like it. The fact that the wall was so close to them and that they did not know where they were going caused many users to raise their heads often, a possible reason for their discomfort. To address these issues, we think that giving the possibility to scale up or down the model will help the users to be more comfortable, and then they will have a better view of the colon and may further benefit this view's results. While the Fly-Through navigation technique didn't achieve the results that the Fly-Over did, users found it to be the most comfortable and most natural way to move through the colon. During the tests, we observed that most users missed polyps, simply because they would "forget" to look behind some intestinal folds. Professionals also stated that they believe that doing an antegrade and a retrograde navigation would still be needed. We believe that implementing an easily accessible camera view of the user's back would have a great impact in terms of discovering polyps inside the colon, just like the rear-view mirror of a car, and would remove the need to take both journeys.

Regarding the prototype itself, the professionals gave some insightful points. Fecal tagging, computer-assisted detection, changing between prone and supine positions, bigger CT images or just the use of the axial slice,

triangulate findings from the 3D model to the CT images (final diagnosis is from the 2D images), user-controlled scale and lighting and being able to see the lesion from the outer wall are some of the features that the professionals use on their day-to-day CTC procedures and would like to be seen applied in this setting.

Over the course of the work some limitations were found, most them directly correlated with the CT images. CT Colonography is an exam that relies heavily on the patient and on the contrast done, because if there is not done a correct intestinal cleaning, the images can be ruined, and the diagnosis and the procedure are harder to do. Future work is not exclusive to this prototype, but to all steps of CTC procedure. Advancements on a better intestinal preparation, image quality and processing, creation of better automatic pathing and model creation are necessary steps to make CTC a better exam. Another limitation in this work was the limited literature regarding navigation on space-confined environments, still we believe, just like the feedback, that the solutions created were highly appropriated.

Finally, the professionals' final remark was about the concept. He explained that nowadays hospitals are relying increasingly on multidisciplinary teams, which means that having a cooperative CTC procedure would possibly prove a better way to innovate. Other medical procedures similar to CTC, like virtual bronchoscopy and virtual arterial endoscopy would most likely benefit from using virtual reality as the medium for navigation. So, creating a multi-personal immersive exploration of space-confined virtual environments is, possibly, the way to go, but there is still much work to be done and much to create.

5. Bibliography

Barish, Matthew A., Jorge A. Soto, and Joseph T. Ferrucci. 2005. "Consensus on Current Clinical Practice of Virtual Colonoscopy." *AJR. American Journal of Roentgenology* 184(3):786–92. Retrieved (http://www.ajronline.org/content/184/3/786.abstract%5Cnhttp://www.ajronline.org/content/184/3/786.full.pdf%5Cnhttp://www.ajronline.org/content/184/3/786.long).

Codd, Anthony M. and Bipasha Choudhury. 2011. "Virtual Reality Anatomy: Is It Comparable with Traditional Methods in the Teaching of Human Forearm Musculoskeletal Anatomy?" *Anatomical Sciences Education* 4(3):119–25.

Falk, Robert, A. A. Farag, and M.Sabry Hassouna. 2006. "Virtual Fly-over: A New Visualization Technique for Virtual Colonoscopy." *Medical Image Computing and Computer-Assisted Intervention : MICCAI ... International Conference on Medical Image Computing and Computer-Assisted Intervention* 9(Pt 1):381–88. Retrieved (http://www.ncbi.nlm.nih.gov/pubmed/17354913).

Ferlay, Jacques et al. 2015. "Cancer Incidence and Mortality Worldwide: Sources, Methods and Major Patterns in GLOBOCAN 2012." *International Journal of Cancer* 136(5):E359–E386.

De Haan, Margriet C., Rogier E. Van Gelder, Anno Graser, Shandra Bipat, and Jaap Stoker. 2011. "Diagnostic Value of CT-Colonography as Compared to Colonoscopy in an Asymptomatic Screening Population: A Meta-Analysis." *European Radiology* 21(8):1747–63.

Kuhlen, Torsten and Bernd Hentschel. 2014. "Spatial Interfaces Quo Vadis CAVE." 14–21.

Levin, Bernard et al. 2011. "Screening and Surveillance for the Early Detection of Colorectal Cancer and Adenomatous Polyps, 2008: A Joint Guideline from the American Cancer Society, the US Multi-Society Task Force on Colorectal Cancer, and the American College of Radiology." *CA: A Cancer Journal for Clinicians* 58(3):130–60. Retrieved (http://www.ncbi.nlm.nih.gov/pubmed/18322143).

Lopes, Daniel Simões. 2013. "Smooth Convex Surfaces for Modeling and Simulating Multibody Systems with Compliant Contact Elements."

Mirhosseini, Koosha, Qi Sun, Krishna C. Gurijala, Bireswar Laha, and Arie E. Kaufman. 2015. "Benefits of 3D Immersion for Virtual Colonoscopy." *2014 IEEE VIS International Workshop on 3DVis, 3DVis 2014* (Vc):75–79.

Pickhardt, Perry J., Cesare Hassan, Steve Halligan, and Riccardo Marmo. 2011. "Colorectal Cancer: CT Colonography and Colonoscopy for Detection-Systematic Review and Meta-Analysis." *Radiology* 259(2):393–405. Retrieved (http://radiology.rsna.org/content/259/2/393.abstract).

Randall, David et al. 2015. "The Oculus Rift Virtual Colonoscopy: Introducing a New Technology and Initial Impressions." *Journal of Biomedical Graphics and Computing* 6(1):34–42. Retrieved (http://www.sciedu.ca/journal/index.php/jbgc/article/view/8328).

Ribeiro, N. S., P. C. Fernandes, and D. S. Lopes. 2009. "3-D Solid and Finite Element Modeling of Biomechanical Structures-a Software Pipeline." *EUROMECH Solid* (OCTOBER). Retrieved (https://dspace.ist.utl.pt/bitstream/2295/391667/2/paper.pdf).

Rodrigues-Baroni, Juliana M., Lucas R. Nascimento, Louise Ada, and Luci F. Teixeira-Salmela. 2014. "Walking Training Associated with Virtual Reality-Based Training Increases Walking Speed of Individuals with Chronic Stroke: Systematic Review with Meta-Analysis." *Brazilian Journal of Physical Therapy* 18(6):502–12. Retrieved (http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-35552014000600502&lng=en&nrm=iso&tlng=en).

Rumreich, Lori L. and Anne Johnson. 2003. "From Traditional Reading Rooms to a Soft Copy Environment: Radiologist Satisfaction Survey." 16(3):262–69.

Shanmugan, Skandan et al. 2014. "Virtual Reality Simulator Training for Laparoscopic Colectomy: What Metrics Have Construct Validity?" *Diseases of the Colon & Rectum* 57(2):210. Retrieved (http://dx.doi.org/10.1097/DCR.0000000000000031).

Siegel, Eliot et al. 2000. "The Filmless Radiology Reading Room: A Survey of Established Picture Archiving and Communication System Sites." 1(2):22–23.

Tagliasacchi, Andrea, Ibraheem Alhashim, Matt Olson, and Hao Zhang. 2012a. "Mean Curvature Skeletons." *Eurographics Symposium on Geometry Processing* 31(5):1735–44.

Tagliasacchi, Andrea, Ibraheem Alhashim, Matt Olson, and Hao Zhang. 2012b. "Mean Curvature Skeletons." *GitHub Repository*. Retrieved (https://github.com/ataiya/starlab-mcfskel).

De Visser, Hans, Marcus O. Watson, Olivier Salvado, and Joshua D. Passenger. 2011. "Progress in Virtual Reality Simulators for Surgical Training and Certification." *Medical Journal of Australia* 194(4):21–23.