SmartSnap: addressing 3D pointing anisotropy in Virtual Reality CAD application

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Abstract

Developing an industry-complaint virtual reality CAD application is difficult because of the limited understanding of the interaction techniques in virtual environments. The aim of this paper is to give a qualitative and quantitative evaluation of human precision with a 3D direct spatial input during a VR modeling session. In particular we focused on a set of frequent tasks performed in a 3D CAD system: pointing, picking and line sketching. For this purpose, we developed a specific application called SpaceXperiment to support our experiments. All the performed tests show that that user looses precision easier along the direction perpendicular to the projection screen, that we call *depth direction*. The pointing precision and accuracy values measured by SpaceXperiment allowed the design of drawing aids such as 'snaps' and 'grips' which are essential to assist the user during modeling sessions in a 3D CAD environment. The quantitative results of the tests leaded to the development of an innovative ellipsoid shaped snap called "*SmartSnap*", which overcomes the high pointing anisotropy preserving high snap resolution. The presented results offer a significant contribution for developers of modeling applications in Virtual Reality.

Keywords: *Virtual reality, human computer interaction, spatial input, CAD, 3D modeling.*

1. INTRODUCTION

One of the most limiting factors for 3D modeling, as established by many studies [24] [12], is the use of two degrees of freedom devices (monitor, keyboard and mouse) for creating 3D forms.

Nowadays, virtual reality technology provides an enhanced interface, based on stereographic vision, head tracking, real time interaction and six degrees of freedom (6DOF) input. This VR based interface is thus candidate to be the ideal workspace for next generation 3D modeling applications.

Virtual environment interaction paradigm is often based upon direct manipulation, which allows a effective transfer of object manipulation skills developed in the physical world into human-computer interaction (HCI). Direct object manipulation generally involve three elements: a controller, the physical device held in the user hand, a cursor, which is the virtual representation of the user finger, and a target, which is a particular hot spot in the virtual environment. [21].

Thanks to the recent developments in tracking system technology, new interesting insights of HCI in virtual reality can be carried out. In fact, previous tracking systems, like magnetic and acoustic ones, suffered from drawbacks in precision, latency, resolution and repeatability of measurements [15]. Due to this reason, much of the research effort was diverted towards tracking error reduction, filtering and position prediction. Newly developed high precision optical systems [1] consent nowadays a better understanding of spatial input human interaction. Different factors can be isolated and analyzed: limb posture, speed, and direction.

The term spatial input or 3D input refers in this work to interfaces based upon free space technologies such as camera-based or magnetic trackers, as opposed to desktop devices such as the mouse or the Spaceball [10].

In particular, the interaction in Virtual Environments (VE) has been proven to be strictly application and hardware dependent [3]. Literature on the specific modeling purpose is actually limited to isolated experimental implementations, and results are far to be systematic and generically applicable. The not completely explored 3D input\output interface limits nowadays the use of Virtual Reality (VR) only to academic and research world.

Figure 1: SpaceXperiment Workspace

In order to develop a virtual reality CAD application which really takes advantages of the stereoscopic visualization and the six degree of freedom (6DOF) input, a contribution is needed in the understanding the principles and the rules which govern the modeling tasks in a virtual environment.

The ongoing development by the authors of the Spacedesign application [6], a VR based CAD system (VRAD), has given rise to different issues concerning the interface design optimization such as: widget and snap dimension, tracking filtering and user's intention recognition. A VR application, called SpaceXperiment, has been thus developed to provide a configurable and systematic test bed for the 3D modeling interaction. The influencing parameters and the correlations among them are analyzed and discussed in order to improve the VRAD Spacedesign application.

The purpose of this work is to examine human bias, consistency and individual differences when pointing, picking and lines sketching in a virtual environment, and therefore to provide useful information for future computer interface design.

The goal of this work is to study those elements specifically for a modeling application by collecting significant data regarding user's sessions and configuring parameters and tools in order to improve the effectiveness of the interface. The literature about this topic is wide but very scattered as underlined in the next section.

2. RELATED WORK

Human computer interface within a 2D environment has been is object of study since the introduction of the computer. The simplest form of interaction, the pointing, has been investigated for different devices by many authors using the Fitts' law in various forms [7] [13].

Hinckley [9] presents an interesting survey of design issues for developing three-dimensional user interfaces, providing suggestion and examples. The main contribution is the synthesis of the literature available scattered results, observations, and examples into a common framework, in order to serve as a guide to researchers or systems builders who may not be familiar with spatial input.

Graham et al. [8] explore 3D spatial pointing by comparing virtual and physical interaction, using a semi-transparent monoscopic display and a 3D tracking system. Two different approach are tested: a virtual mode, displaying only computer generated images, and a physical mode, where the graphics display is turned off and the subjects can see through the mirror to the workspace below. The results suggest that movement planning and kinematic features are similar in both conditions, but virtual task takes more time especially for small targets. Moreover changes in target distance and width effect the spatial temporal characteristics of pointing movement.

Bowman [3] et al. develop a test bed to compare different basic VR interaction techniques for pointing, selection and manipulation. The authors note that the performance depends on a complex combination of factors including the specific task, the virtual environment and the user. Therefore applications with different requirements may need different interaction techniques.

Poupyrev et al. [17] develop a test bed which evaluates manipulation tasks in VR in an application-independent way. The framework provides a systematic task analysis of immersive manipulation and suggest a user-specific non Euclidean system for the measurement of VR spatial relationship.

Mine et al. [14] explore manipulation in immersive virtual environments using the user's body as reference system. They present a unified framework for VE interaction based on proprioception, a person's sense of the position and orientation of his body and limbs. Test are carried out about the body-relative interaction techniques presented.

Wang et al. [25] investigate combined effects of controller, cursor and target size on multidimensional object manipulation in a virtual environment. Test revealed that the same size of controller and cursor improved object manipulation speed, and the same size of cursor and target generally facilitate object manipulation accuracy, regardless their absolute sizes.

Paljic [16] reports two studies on the Responsive Workbench. The first study investigates the influence of manipulation distance on performance in a 3D location task. The results indicate that direct manipulation and 20 cm distance manipulation are more efficient than for 40 and 55 cm distances. The second study investigates the effect of two factors: the presence or absence of a visual clue, and the scale value, which is a variation of the scale (1 or 1.5) used to map the user's movements to the pointer. Task performance is significantly lower when using the visual clue, and when using the 1.5 scale.

Boritz [2] investigate the ability to interactively locate points in a three dimensional computer environment using a six degree of freedom input device. Four different visual feedback modes are tested: fixed viewpoint monoscopic perspective, fixed viewpoint stereoscopic perspective, head-tracked monoscopic perspective and head-tracked stereoscopic perspective. The results indicate that stereoscopic performance is superior to monoscopic performance and that asymmetries exist both across and within axes. Head tracking had no appreciable effect upon performance.

Zhai [28] presents an empirical evaluation of a three-dimensional interface, decomposing tracking performance into six dimensions (three in translation and three in rotation). Tests revealed subjects' tracking errors in the depth dimension were about 45% (with no practice) to 35% (with practice) larger than those in the horizontal and vertical dimensions. It was also found that subjects initially had larger tracking errors along the vertical axis than along the horizontal axis, likely due to their attention allocation strategy. Analysis of rotation errors generated a similar anisotropic pattern.

Moreover, many authors [19][4][11][5] developed virtual reality based CAD applications, describing the specific implementation and the results achieved. But such contribution are often single and isolated study, without a systemic performance evaluation and the definition of precise guidelines.

From the related work presented, it can be summarized that literature offer several approaches to human interaction understanding in virtual reality. Previous work has also shown how interaction techniques in virtual environments are complex to analyze and evaluate, because the variety of hardware configuration (immersive VR, semi-immersive VR, desktop VR, type of input devices) and the specific application. Some approaches try to be more general decomposing each interaction into smaller task, but specific study is necessary. This paper gives a practical and substantial contribution for CAD modeling applications.

In the next section we illustrate our experimental approach for the interaction evaluation within our VR CAD system. In particular we analyze pointing, picking and lines sketching interaction tasks.

3. EXPERIMENT DESIGN

The aim of this paper is to give a qualitative and quantitative evaluation of human performance in a virtual environment while performing modelling tasks. For our tests we selected a set of the most frequent tasks performed in a CAD system: pointing, picking and line sketching. These tasks are similar for both 2D and 3D CAD system. Using stereoscopic display and a 6DOF tracked pointer, the following tests were carried out:

- the measurement of the ability of the user in pointing a fixed point;
- the analysis of the sketched lines traced by the user when following a virtual geometry, in order to discover preferred sketching methods and modalities;
- the user's the ability to pick points in 3D space in order to evaluate human performance in object selection.

SpaceXperiment application was used for these tests. Position, orientation and timestamp of the pointer (pen tip) was recorded, for every test, for subsequent analysis.

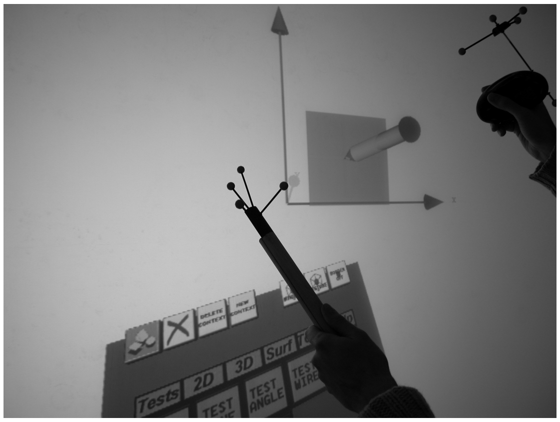

Figure 2: A picking test session

3.1 Participants

Voluntary students from the faculty of mechanical engineering and architecture were recruited for the tests. All participants were regular user of a windows interface (mouse and keyboard). None had been in a VR environment before. All the user were given a demonstration of the SpaceXperiment system and were allowed to interact in the virtual workspace for approximately 20 minutes in order to become acquainted with the perception of the virtual 3D space. Moreover all the user performed a double set of tests. The first set was considered a practice session and the second a data collection session. All subjects were right handed, and had normal or corrected-to-normal vision. Subjects had experience using a computer. Informed consent was provided before the experiment.

3.2 Apparatus

The experiments were conducted in the VR3lab at the Cemec of the Politecnico di Bari, on the VR facility which normally runs the Spacedesign application. Our experimental test bed comprises of a hardware system and a software application called SpaceXperiment.

3.2.1 Hardware

The Virtual reality system used for the experiments is composed by a vertical screen of 2.20m x 1.80m with two polarized projectors and an optical 3D tracking system by Art [ART]. Horizontal and vertical polarized filters in conjunction with the user's glasses make possible the so called passive stereo vision. The tracking system uses two infrared (IR) cameras and IR-reflective spheres, the *markers*, to calculate their position and orientation in space by triangulation. The markers, which are of 12mm of diameter, are attached to the interaction devices according a unique pattern which allows them to be identified by the system. The user handles a transparent Plexiglas pen with 3 buttons, which is represented in VR with a virtual simulacrum. The user is also provided with a virtual palette (a Plexiglas sheet) that can be used to retrieve information and to display the virtual menus and buttons (Figure 1, 2).

An Dtrack motion analysis system, based on two ARTtrack1 cameras, records the three-dimensional position of infrared markers placed on the user's devices, and stores the results in data files for further analysis.

A stereoscopic, head coupled graphical display was presented on th screen, using orthogonally polarized glasses. The experiment was conducted in a semi-dark room.

3.2.2 Software implementation

SpaceXperiment is the application addressed to the testing of 3D interaction in a virtual reality environment. It is built upon the Studierstube library [Schmalstieg 1996], which provides the VR interface, the so-called *Pen and tablet* metaphor: the non-dominant hand holds the transparent palette with virtual menus and buttons; the other handles the pen for application-related tasks.

The incoming data from the tracking system are sent directly by ethernet network to the SpaceXperiment application via the OpenTracker library. This is an open software platform, based on XML configuration syntax, is used to deal with tracking data from different sources and control the transmission and filtering.

The system is set up in such a way that the size of the virtual objects displayed on the screen corresponded to their real dimensions. Because of the similarity of the platform between SpaceXperiment and Spacedesign, test results from former can be easily applied to the latter.

3.2.3 Tracking system calibration

After following the correct calibration procedure for the tracking system, as described by the manufacturer, we performed a series of tests to verify the precision and accuracy of the tracking system by Art. We fixed the markers in 10 different position of the tracking volume and recorded the measures of the system.

We find out that the system is capable to perform an average precision of 0.8 mm in the position of the target. This result is compatible with the manufacturer specification (0.4 mm) because our system if provided of only two cameras vs. the four cameras used for the tech. specification. In any cases this error is way lower than the expected measure values, therefore we can be confident that our future evaluations will be free of systematic measure error.

4. EXPERIMENT 1: POINTING STATIONARY MARKERS

In this first experiment we investigated the ability of the user to be 'accurate' in a pointing task. This precision is statistically evaluated while the user points for a limited amount of time a marker fixed in the space.

4.1 Procedure

The user is presented with a virtual marker in the 3D workspace. He/she is asked to place the tip of the virtual pen as close as possible to the centre of the marker. Once the user has reached the centre of the marker with the pen tip in a stable manner, he/she is asked to click on the pen button and keep the pen in the same position for 5 seconds. The pointing task is repeated for 3 points in different positions in space:

- *MDP* (Medium Difficulty Point): in the normal working area in front of the user at a distance of about 500 mm
- *HDP* (High Difficulty Point): in an area difficult to reach, above the head (300 mm) and far ahead (800 mm)
- *LDP* (Low Difficulty Point): very close to the user's eyes (150 mm).

4.2 Results

Recording a position for 5 seconds on our system corresponds to approximately 310 sample points. Hence we applied a statistical analysis to the recorded data to evaluate mean, variance and deviation from the target point. In order to determine any possible anisotropy in the error values, the position vectors are projected onto three orthogonal *reference* directions:

- horizontal;
- vertical;
- depth (i.e. perpendicular to the screen).

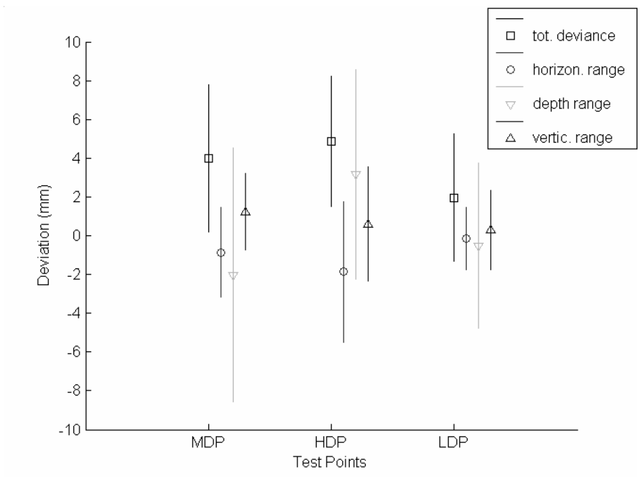

Figure 3: Average of deviation and ranges for the three test points

From Figure 3 it is possible to notice that:

- the deviation along the *depth* direction is always greater than the deviation along the *horizontal* and *vertical* directions (see Table 1);
- the magnitudes of the error along the *horizontal* and *vertical* directions are comparable and are at least 1.9 times smaller than the error along the *depth* direction (see Table 2);
- The *HDP* has always the maximum error compared to *LDP* and *MDP*;
- The higher the target distance the higher the error, but the target distance influences the error along the horizontal direction more than in the other two directions.

Table 1: Statistic error values (mm) for the performed test

	Total deviance	Horiz. Range (95%)	Vert. range (95%)	Depth range (95%)
Max Error	17,31	7,28	9,53	19,50
Mean Error	6,21	4,81	5,29	10,12

Table 2: Average Ratios between error ranges along different directions.

	Depth/ Vertical	Depth/ Horizontal	Horizontal/ Vertical
Max Error	2.0	2.7	0.8
Mean Error	1.9	2.7	0.9

5. EXPERIMENT 2: SKETCHING LINES

The intention of this test is to evaluate the user's ability to sketch as closely as possible a reference geometry visualised in the 3D environment.

5.1 Procedure

The user must follow, as accurately as possible, a virtual geometry displayed in the 3D workspace. By moving the pen with its button pressed a 3D free hand sketch is traced. As soon as the button is released a new geometry is shown and the tracing task must be repeated for the following: horizontal line, vertical line, depth line (line drawn 'out of' the screen), and rectangular frame aligned with the screen plane. The user is required to perform the experiment five times with different modalities as follows:

a) in the most comfortable fashion (user's choice)
b) in reversed tracing direction (i.e. 'left to right' vs. 'right to left')
c) low sketching speed
d) medium sketching speed
e) high sketching speed

5.2 Results

The deviation of the sketched line from its reference geometry represents how sketching precision and accuracy vary according to the sketching direction. We considered for the error metric the *deviance*, which is the distance between the pen tip and its closest point on the reference. The range of the *deviance* error is evaluated in each reference direction: *horizontal range*, *vertical range* and *depth range* (Figure 4, Table 3).

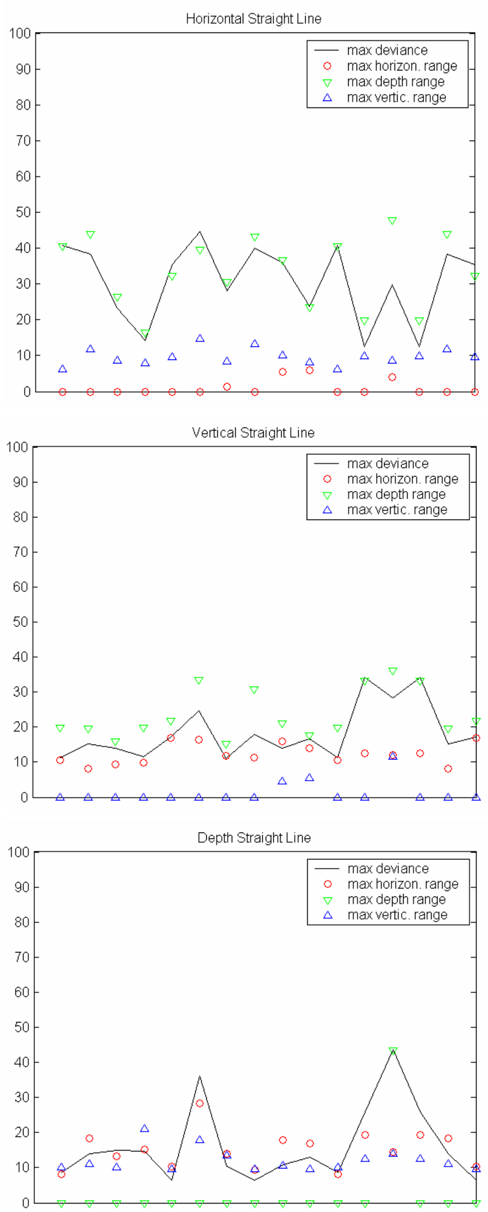

Figure 4: Deviance magnitude and deviance ranges for a line sketching task (Mode A).

The following considerations can be made accordingly to the obtained results:

5.2.1 Anisotropic error

The higher error along the *depth* direction, already noticed in the experiment 1 is confirmed: the error along the *depth* direction, is about 1,8-2,6 times the error along *horizontal* and *vertical* directions (Table 4).

Table 3: Error values (mm) for Mode A.

	Total deviance	Horiz. range	Vert. range	Depth range
Max Value	40,8	22,6	17,8	41,9
Mean Value	21,8	13,7	10,8	28,6

Table 4: Average Ratios between error ranges along different directions for Mode A.

	Depth/ Vertical	Depth/ Horizontal	Horizontal/ Vertical
Max Value	2,3	1,8	1,3
Mean Value	2,6	2,1	1,3

5.2.2 Direction influence

Each user is more comfortable in sketching the same line in his favourite direction. If the user sketches the line inverting the starting and ending points, this yields definitively worse errors along all the three reference directions. Inverting the direction, in our tests, increases the error magnitude by an average factor of 1,9 (see Table 5).

Table 5: Error ratios for normal sketching (Mode A) over reversed direction (Mode B).

	Total deviance	Horiz. range	Vert. range	Depth range
Reversed/Normal	1,9	1,2	1,3	2,1

A noticeable result is that the inversion influences more the error along the depth direction as this error nearly doubles along the other reference directions. This is an additional confirmation that the user loses

5.2.3 Speed influence

Our results show that the sketching speed influences the error not in a predictable way. We tested the usual sketching patterns at low, normal and high speed (Mode C,D,E).

For most users the error magnitude increases both at high speed and at low speed. An increase in the error can be expected at high speed, but not at low speed. This behaviour can be explained with the fact that a moderate speed tends to stabilize vibrations in human hand.

6. EXPERIMENT 3: PICKING CROSS HAIR MARKERS

The intention of this test is to evaluate the ability of the user in performing the picking of a 3D three dimensional cross hair target fixed in a random position. We analyse both precision and time performance.

6.1 Procedure

A semi transparent [26] cross hair appears in a random position of the workspace together with a highlight parallelepiped representing the target bounding-box as shown in Figure 2. The user picks the centre of the target using the pen button. We repeat the picking operation for ten different points, and the user must return in a 'home' position before picking the next target. Different sounds accompany each different step guiding the user during the test. We record: picking position, the time to pick and the time to enter into the target's bounding-box are recorded in a text file during every test session.

6.2 Results

The time interval to move from the 'home' position to the target bounding-box is related to the reaction time and suggests the maximum velocity of user's movements, whilst the time to click the centre of the marker shows how fast the user can perform accurate movements. An analysis of these parameters yielded the following results:

6.2.1 Deviance:

The error values are shown in the following Table 6. In a similar manner to the above-mentioned experiments 1 and 2, the error along the depth direction is considerably higher then the error along the other directions.

Table 6: Statistic error values for the performed test

	Deviance (mm)	Horiz. error (mm)	Vert. error (mm)	Depth error (mm)	Depth error/ Horiz. error	Depth error/ Vert. error
Max Value	24,04	12,90	16,23	32,25	2,5	2,0
Avg. Value	7,26	1,69	2,32	2,97	1.8	1.3

6.2.2 Time considerations:

The time interval necessary to perform the picking operation can be split into two contributions:

Time to pick = Time to reach the bounding box + Time spent inside the bounding box

The corresponding average times have been evaluated using statistical analysis and are shown in the following Table 7.

Table 7: Time values (milliseconds) for the performed test

	Min	Max	Average
Time to reach target Bounding-Box	1207	2448	640
Time inside target Bounding-Box	1914	3271	750
Time to Pick (total)	3121	5016	1703

Our tests have shown, as expected, that the time needed to reach the bounding box of the target is proportional to the distance of the target from the "home position". This is in accordance with the previously mentioned Fitts' Law.

Moreover the error magnitude decreases with the time spent inside the bounding-box more than with the total time to pick. This can be explained by the fact that the user moves quickly to the bounding box and then, once inside, points precisely the target

7. DISCUSSION

The high tracking precision available nowadays with optical systems allowed us to evaluate the human interaction process in VR.

All the performed tests show that that user looses precision easier along a defined direction. We can identify this direction with the direction perpendicular to the projection screen, that we call *depth direction*. The first experiment, regarding the static pointing, has firstly validated the anisotropy hypothesis, and has shown an average error of 10.1 mm along the *depth direction* and an average error of 4.8 mm and 5.3 mm along the *vertical* and *horizontal direction*.

The error evaluated is considerably higher than the precision of the system evaluated in Section 3.2.3, therefore we can assume our results valid as regards the systematic error.

The second experiment, concerning the line sketching, has confirmed the results of the previous experiment. The error reasonably increases (28.6 mm, 13.7 mm and 18.8 mm for *d*, *h*, *v* directions), effect explainable by the fact that the hand of the user is now moving, but the ratio between the error along the *depth direction* and the *vertical* and *horizontal direction* does not change considerably.

The third experiment is the most significant in our opinion, because regards the most performed task in a VR environment: the picking or selection. Also this experiment validated the error anisotropy hypothesis confirming the error ratio between the different directions.

8. APPLICATION OF RESULTS: SMARTSNAP

The SpaceXperiment application has as main goal of first testing and then improving interfaces to increase the performances of. VRAD.

The measured pointing precision and accuracy allow the optimization and calibration of smart drawing aids such as *'snaps'* and *'grips'* which are essential to assist the user during modeling sessions in a 3D CAD environment, because of the lack of a physical plane support (like the mouse pad) in direct input tasks.

SpaceDesign already implemented *'snaps'* which were the natural extension of any 2D CAD *'snap'*. The original shape was a cube where the *'snap'* semi-edge dimension was empirically defined in 35 mm.

After this set of experiments we implemented a new tool with the idea that the overall dimensions of this aid should be proportional to the average and maximum pointing error. Since our tests revealed that, in 95% of the cases, the pointing error is below 24mm, we introduced in SpaceDesign a *'calibrated spherical snap'* (Fig. 7) with *Radius = k x 24(mm)*; where *k>1* is a 'comfort' multiplying factor. A reasonable value which seems to work well with our system is *k=1,2*. This new design has brought a significant volume reduction from 343000 mm^3 to 100061 mm^3, i.e. the volume of the *'calibrated spherical snap'* is 29% of the original *'cube snap'* volume. Obviously, this volume decrease translates in a better resolution of the snap system, which can be very useful in the case of very complex models, with a high density of possible snapping points.

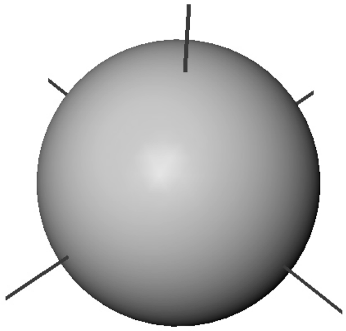

Figure 5: Spherical snap

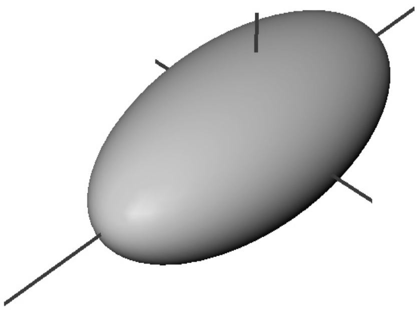

Figure 6: Ellipsoid snap

The next step was the design of an aid that could take into consideration the high pointing anisotropy encountered in all our experiments. The results showed that, although VR has the advantage of the 3D perception, the user is not capable of judging the added depth dimension as well as the other two dimensions.

Therefore, we introduced a modified *'calibrated ellipsoid snap'* with the major axis aligned along the depth direction (Fig. 8). In this case, we define the three lengths of the semi-axis as follow:

$Radius_{Depth} = k \times 24(mm)$

$Radius_{Vertical} = 0.5 \times Radius_{Depth} = k \times 12(mm)$

$Radius_{Horizontal} = 0.4 \times Radius_{Depth} = k \times 10(mm)$

With these dimensions, the volume of this snap (volume of the ellipsoid) drops down to 20846 mm^3, i.e. the 21% of the *'calibrated spherical snap'* volume and the 6% of the original *'cube snap'* volume.

We finally performed a new set of tests to verify the effectiveness of the new snap design. We just repeated the *'picking cross hair markers'* experiment checking the time needed to pick a marker with the snap activated. Results showed, as expected, that the time needed to reach the target is proportional to the distance of the target from the "*home position*". However, the main result is that no significant time difference is noticeable switching among the three snaps , while the snap volume changes considerably, as illustrated above.

Therefore, we validate the introduction of the *'calibrated ellipsoid snap'*, called *SmartSnap* in SpaceDesign.

9. CONCLUSIONS AND FUTURE WORK

High tracking precision and cheap VR reality setups are getting more and more widespread in industry and academia. In this paper we have developed the SpaceXperiment interaction test bed in order to improve the interaction techniques within our VR CAD system, SpaceDesign. The results achieved can be directly extended to other similar applications, and their context is clearly general. We introduced the *'calibrated ellipsoid snap'* to take into consideration the high pointing anisotropy while keeping an high resolution in the snap system.

At the moment, we are testing new smart snap design where the axes of the ellipsoid and its dimensions dynamically vary according to the position of the user head and hands. In the future we also intend to use some of the results carried out with the experiments described in this paper, including also the maximum and average speed values registered during Experiment 3 (see Table 8), to calibrate further aids and tools for sketching, e.g. filters to discard scattered tracking errors, line segmentation algorithms and user intention interpretation.

Table 8: Average speed values (mm/s) during the test for the three test: slow, medium, fast.

	Average values Mode C (slow)	Average values Mode D (medium)	Average values Mode E (fast)
Max speed for each user	212,7	423,0	695,8
Avg. speed for each user	66,8	153,4	379,5

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