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Controlling 3D Visualisations with Multiple Degrees of Freedom

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Abstract

In this paper, the two major components of a new multi-layer framework ideal for two-handed interaction in desktop virtual environments called Library for Interactive Settings of User-Mode (LISU) are explained. In addition, we evaluate LISU performance with a group of participants and we report some of our initial results by giving an analysis of user experiences, and interaction speed.

CCS Concepts

• **Human-centered computing** → HCI design and evaluation methods; Virtual reality; Interaction devices; • **Computing methodologies** → Graphics systems and interfaces; • **Hardware** → Signal processing systems;

1. Introduction

Although there are many input devices in the market specialised for the 3D world [MCG*19], users are still using simple two-dimensional input devices, such as the mouse, for exploring virtual environments (VE) and controlling 3D objects [Men16]. This is because controllers generally are heterogeneous with different multiple degrees of freedom (DOF) and different mappings to application aspects [RLK18] [LM10]. All this makes it complex to automatically connect and switch multiple devices to multiple applications in a usable and efficient way [Lu08] [BBKR16].

In [SMT18], we proposed a new multi-layer framework for two-handed interaction in desktop virtual environments that we call LISU: Library for Interactive Settings of User-Modes. In this paper, we evaluated the performance of our framework with 4 interaction techniques, including the keyboard and mouse combination. The following sections describe an overview of existing systems and research ongoing in this area, the proposed system and then the implementation of the experimental test with the relative results.

2. Background

Any possible movement of a rigid body can be expressed as a combination of three translations and three rotations, the basic 6DOF [Zha95] [BKLP04]. Limitations in 2DOF devices, however, include difficult mapping, variable input rates and interaction speed [BIAI17]. To overcome these limitations, 2DOF devices can deconstruct a manipulation task into separate actions. Unfortunately, this

tends to be unnatural and unintuitive, and in the worst case, frustrating and unproductive.

Input devices for immersive visualisation of VE [San16] [DFCM11], including the Oculus Rift [CMBB19], Leap Motion [JTD*19], HTC Vive [GCA*19], eases the perception of three-dimensional content [VK18]. However, despite having promising results, the accuracy of human spatial interactions is limited [OOS16]. Users want to control multiple scientific visualisation parameters that are often on-off or pre-programmed and this would include changing or enabling clipping plane and object transparency when needed, operations that these devices often cannot provide.

Previous research has demonstrated that performing tasks with both hands can obtain higher efficiency over one-handed methods [FCW15]. When the other hand is free from keyboard use there is the option for connecting two devices. This means two hands can control multiple DOF simultaneously and potentially intuitively - with some training. Based on this approach, LISU can provide full 6DOF control, for example, camera looking direction and movement directions with one hand on one device; simultaneously while manipulating a second controller either to change the object to be viewed or the lights. This allows a single operator to be cameraman and lighting rig operator at the same time, creating a system that has potential ease of use and speed up in exploration and discovery.

3. Proposed system

3.1. Input Devices Ontology

Figure 1 shows an overview of LISU's input device ontology. This ontology was developed using Stanford's Protege tool [NSD*01] and is expressed in RDF/OWL [CLS01].

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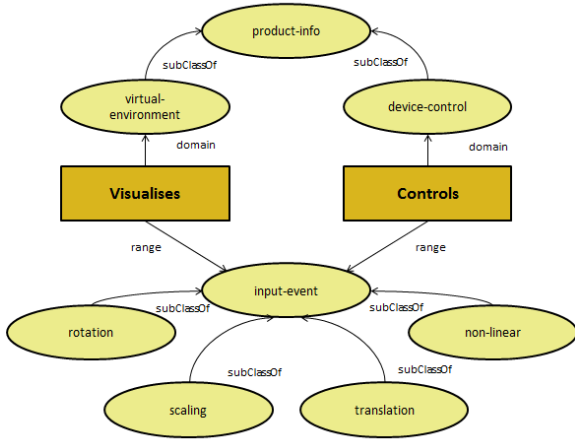


Figure 1: The LISU's input device ontology.

Table 1 describes a set of frames that represent the classes of objects in this ontology.

Class	Description
product-info	Defines the name of the controller and/or VE.
device-control	Defines the input device with its most general properties.
virtual-environment	Defines the VE with its most general properties.
input-event	Describes the change in state of the virtual object.

Table 1: The LISU's input device ontology definitions.

The *device-control* class provides users the channel to control virtual objects, with improved calibration and additional setup required by the input device. User's input is captured via control interface which can either be hardware such as a keyboard, mouse or joystick, or specialised hardware interfaces, including any controller that provide users an alternative way to input and/or be immersed in the VE. Each of the hardware interfaces has its respective *input-events*; each input event can link to one or more actions depending on the state of the virtual object, then controllers will be dynamically switched to different functions on the fly with this ontological component via LISU's Transfer Matrix.

3.2. Transfer Matrix

Our Transfer Matrix maps raw input values into input values for the application value in the affine, e.g. rotation, translation or scaling, after being processed by relevant \mathbf{F}_j algorithm, directed by the ontology component 3.1. Depending on the device technology and mapping design, LISU could allow all objects to be manipulated simultaneously or might allow only a subset of the DOF to be manipulated at a given time using different input functions.

Let \mathbf{F}_j be a set of functions at each point or cell (\mathbf{p}_j) in the system, that: $\mathbf{F}_j = f(\mathbf{p}_j)$. Let \mathbf{M} be a matrix on the fly that controls all

the states of the virtual object. LISU's Transfer Matrix \mathbf{F}_j modifies \mathbf{M} depending on the number of DOF directed from the ontology component. As a result, users can combine and integrate 2D and 3D devices simultaneously. We have that LISU's dynamic matrix \mathbf{F}_j for n components and position j is in the form:

$$\mathbf{F}_j = \mathbf{M} \prod_{i=1}^n C_n(X_j)$$

Where X_j represents the parameters of the input events, e.g. button pressed/released, joystick moved, and so on. The values of X_j correspond to the axis or button that generated the event. For an axis, input event values are signed integers between -1 and +1 representing the position of the controller along that axis. Then, X_j is of the form $X_j = (x_j, y_j, z_j, x'_j, y'_j, z'_j, \dots)$. Each component C_n is a function of \mathbf{p} at the position j , so $C_n = f(\mathbf{p}_j)$. C_n is a concatenated component of \mathbf{F}_j , and C_n in the formula can also be a matrix. Let C_1 be say a function T of translation in x , y , and z and let C_2 be say a function R of rotation in V_{x_j} , V_{y_j} , and V_{z_j} . We can expand \mathbf{F}_j as:

$$\mathbf{F}_j = \mathbf{M} T(x_j, y_j, z_j) R(V_{x_j}, V_{y_j}, V_{z_j}) \dots$$

C_1 and C_2 functions are more than just a mathematical transformation matrix. They also may include nonlinear components, e.g. noise reduction steps, smoothing filters, discretisation filter. Because \mathbf{F}_j is modifying \mathbf{M} , we have simultaneous movements or states of the virtual object. Finally, because any parameter can be mapped to the number of DOF available, the repertoire of functions is very large, and as the combination of input devices have a series of buttons, as well as a speed wheel, those can be programmed so any frequently used function or user defined keyboard macro can be integrated.

4. Experiment Overview

We conducted an experiment to evaluate the usability of LISU and the speed of mapping the input events to the graphical component. To perform the experiment, LISU was integrated into the scientific volume exploration tool, Drishti [Lim12].

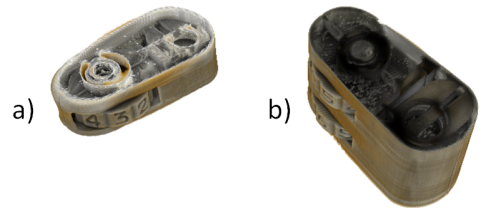


Figure 2: Images of the two volumes loaded to Drishti where (a) is the short volume and (b) the large volume.

4.1. Task

Two volume datasets of different sizes (figure 2) of an X-ray CT (Computed Tomography) metal locking mechanism were loaded to

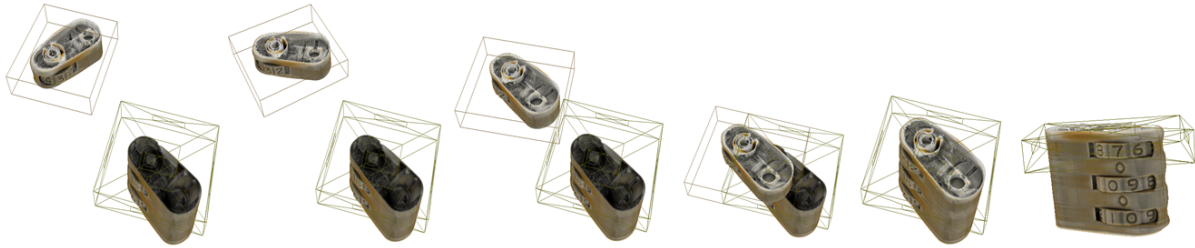


Figure 3: Screenshots of the performance of the experiment and the expected reconstructed volume.

Drishiti, and the task was to realign these components. These volumes are the bricks of the locking mechanism with the task process shown in (figure 3) to create a new volume.

The coordinates of these two volumes were normalised and the participants were asked to align the image to get the volume close to the correct orientation. For this, users were able to switch from multiple functions done via the buttons available of each combination that were previously configured, e.g. change the rotation axis, angle, pivot and translation. Figure 4 shows the combination of input devices used in this experiment and table 2 shows a brief description and abbreviation of each input devices combination.

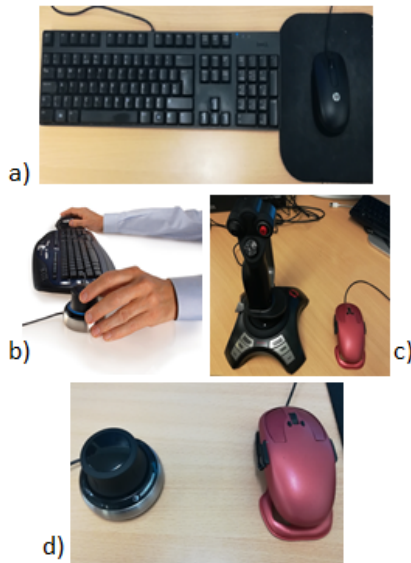


Figure 4: (a) MK setup (+3DOF), (b) SPM setup (8DOF), (c) JW setup (8DOF), (d) SPW setup (12DOF).

Setup combination	Abbreviation	DOF
Mouse + Keyboard	MK	+3DOF
Joystick + Wing	JW	8DOF
SpaceNavigator + Mouse	SPM	8DOF
SpaceNavigator + Wing	SPW	12DOF

Table 2: Combination of input devices used in the experiment.

For the keyboard and mouse device, we used a conventional optical mouse and a standard keyboard with 180 keys (figure 4-a). For the joystick device, we used the Speedlink Dark Tornado Flight (figure 4-c). For the 3D devices, we used the 3Dconnexion SpaceNavigator [3DC19], and the Worthington Sharpe’s Wing [Wor19], both commercial devices with 6DOF (figure 4-d).

4.2. Participants and Procedure

Twelve participants from the Computer Science and Computer Engineering departments with little or no experience using this 3D computer graphics applications participated in the study. Half of the participants, the expert group, consisted of those that have backgrounds in visualisation areas. The experimental test started with a training session, where experiment mentors demonstrated how each combination could be used to manipulate 3D objects in Drishiti. Once participants were familiar with all the different setups, the actual experiment was conducted. Every participant started the experiment with the **MK** in order to be used as a reference. They continued with the **JW** setup, followed by the **SPM**. Finally, the experiment ended with the **SPW** setup. We asked the participants to complete a satisfaction questionnaire after the experiment in order to analyse the results from different perspectives.

5. Results

All the participants completed the task and we formulated the following hypotheses:

H1. *The completion time for most participants will be shorter when more DOF are added.*

H2. *Once participants are familiar with the higher DOF setup (after training), we anticipate they will achieve better performance whilst engaging with the VE.*

5.1. Performance

We calculated throughput [BCV16] [Mac18] for each input device on a per-group of participants basis. The results are shown in figure 5. The average throughput of **MK** in the novice group was 0.84 bps, and in the expert group it was 1.67 bps. It is worth noting that while the throughput in the novice group for **MK** was better than the throughput for the other controllers, it is not necessarily the best choice.

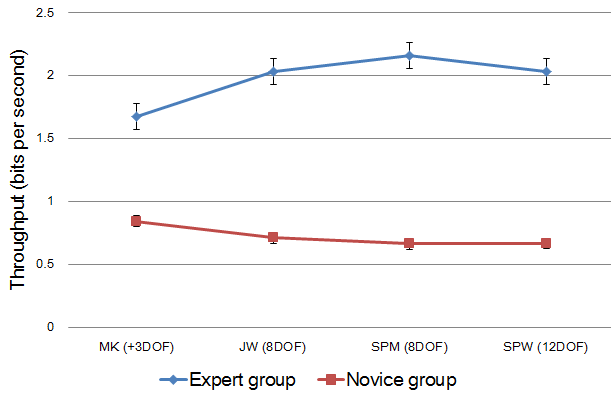


Figure 5: Throughput measured in bits per second (bps) for comparing input device performance. Error bars show ± 1 SD.

For the expert group, the results in figure 5 show an increment of 21% in the throughput for JW, 28% in the throughput for SPM, and 21% in the throughput for SPW. We can see that the throughput for the other combinations is higher than the throughput for MK. Thus, users in this group were able to have a better performance and control over the virtual object when more DOF were added to the test. For the novice group, the throughput for any other combinations with 6 or more DOF is lower than for MK: JW is 18% lower than MK, SPM is 27% lower than MK, and SPW is 26% lower than MK. We can see that experience and familiarity with the mouse and keyboard was a confounding variable for this analysis. Therefore, if our participants were as experienced with the other controllers as they were with the mouse and the keyboard, it is likely that throughput for the other controllers would have been higher.

We also examined the data collected by the task application, figure 6. We found that there is a statistically significant difference in mean time completion among the four interaction techniques ($F(3,44) = 6.15$) with a p-value of 0.002 and a significance level of 5% ($\alpha \leq 0.05$). The task was done faster with SPW (M=2.18, SD=0.41) than SPM (M=2.42, SD=0.49), JW (M=2.8, SD=0.73), and MK (M=3.13, SD=1.27) setups for the expert group; in the non-expert group, the task was done faster with SPM (M=4.84, SD=0.91) than SPW (M=5.13, SD=1.34), JW (M=5.26, SD=1.69), and MK (M=7.52, SD=2.85) setups. The results show that the expert group had 30.35% percent of improvement in its completion time, and the non-expert group had 35.64% percent of improvement. This confirms H1 because the time of task completion was shorter when multiple input devices with higher DOF were added.

When asked if they required extra training to master the controllers for a better performance in the VE, just two participants asked for this extra training. Ten participants mentioned that "after a time, it was more intuitive", so they did not need this. When asked which interaction technique was better for rotation, eight participants answered the SPW setup, three participants the SPM, and one participant preferred the JW. Six answered SPW is better for translations and six answered SPM. Regarding the question on which combination was most intuitive, six answered SPW,

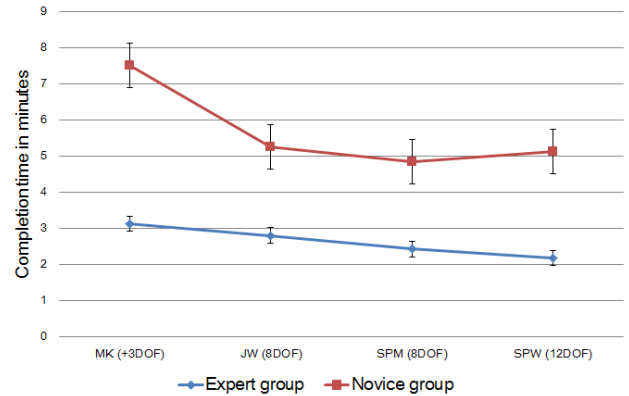


Figure 6: Comparative table of the time per participant to complete the experimental task. Error bars show ± 1 SD.

five answered SPM, one answered JW and one answered MK. Particularly, these two last participants mentioned that the highest DOF combination, SPW, "was confusing at the first time" and they "needed more training with the controller individually before trying any different combinations", showing a preference using the selected setup. Eight participants stated that "any joystick combination was less intuitive and not as responsive". Six participants commented that they felt engaged with Drishti because the experience using multiple controllers "felt part of a videogame". Overall, eleven of twelve participants preferred the combination with the highest DOF and just one participant stated that MK "was more comfortable".

6. Conclusion

This paper evaluated a new multi-layer framework for two-handed interaction to control 3D visualisations with multiple DOF called LISU. We found that, despite having experience and familiarity with MK, SPM (8DOF) in the novice group and SPW (12DOF) in the expert group offered much better performance than MK.

Half of the participants stated that they felt engaged with the VE and found it pleasant after using different combinations of controllers. Thus, we found a trend that having multiple controllers provide an immersive experience to users because the controls become mere extensions of their thoughts in the VE: the more DOF available, the more enhanced the control over the virtual object. Also, the results show that most of the participants did not require further training to master any higher DOF combination of controllers. All this information confirms H2. Thus, the two hypotheses previously formulated in section 5 are proven to be correct.

Further research is certainly needed to optimise LISU and evaluating its benefits. For this reason, we plan to develop more complex experiments where the necessity of performing multiple tasks can more clearly show the advantages of LISU. We plan to apply our framework to many different specific systems including industrial applications within the petroleum, geology and materials sciences.

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