Dynamic Decomposition and Integration of Degrees of Freedom for 3-D Positioning

Manuel Veit*
University of Strasbourg–LSIIT CNRS UMR 7005

Antonio Capobianco†
University of Strasbourg–LSIIT CNRS UMR 7005

Dominique Bechmann‡
University of Strasbourg–LSIIT CNRS UMR 7005

Abstract

In this paper we present a new interaction technique based on degrees of freedom (DoF) decomposition for accurate positioning in virtual reality environments. This technique (called DIOD for *Decomposition and Integration Of Degrees of freedom*) is based on an adaptation of the Two-Component Model. It provides two different control levels regarding DoF coordination, one integrating and one separating the manipulation of the DoF. Our hypothesis is that each control level is appropriated to a different phase of the positioning task. During the ballistic phase, users manipulate all the dimensions of the task at the same time. However, during the control phase, users try to manipulate specific dimensions individually. The results of a preliminary study we conducted seem to indicate that the DIOD technique is more efficient than existing techniques.

CR Categories: H.5.1 [INFORMATION INTERFACES AND PRESENTATION]: Artificial, augmented, and virtual realities— [H.5.2]: INFORMATION INTERFACES AND PRESENTATION—User Interfaces

Keywords: Interaction Technique, Experimental Study, Virtual Reality

1 Introduction

The recent advances of computer graphics technology allowed the emergence of high quality virtual reality (VR) environments. For some time past, 3-D visualisation spreads out from the academic and industrial fields with the democratisation of stereoscopic displays such as the NVIDIA 3-D Vision™. The possibilities offered by Virtual Environments (VE) are not limited to visualisation experiences. The use of the appropriate devices (e.g. a wand or data gloves) allows users to directly manipulate their surrounding using natural gestures such as grabbing and positioning. An example of a user manipulating a virtual object in a semi-immersive virtual environment (SIVE)–the context of our work–is given in Figure 1. Such direct interaction techniques [Sturman et al. 1989] are often considered as more intuitive [Kok and van Liere 2007].

Indeed, positioning an object in VR requires to manipulate three dimensions at the same time. Generally, when interacting on a classical desktop, the use of the mouse implicitly reduces and/or decomposes all the tasks to 2-D tasks. In VR, however, all the DoF of a task are usually manipulated simultaneously. This is generally accepted as a major asset of these environments [Chen et al. 1988].

*e-mail:mveit@unistra.fr
†e-mail:a.capobianco@unistra.fr
‡e-mail:bechmann@unistra.fr

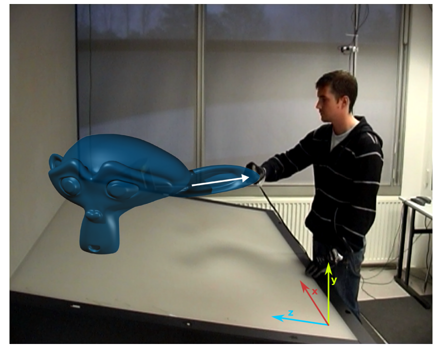

Figure 1: *On this illustration, the user sees a virtual object in three dimensions and manipulates it directly using his hands.*

Nevertheless, the level of interaction proposed by many VR applications seems disappointing [Thomson and Nichols 2009] and the main issues already identified in early studies still need to be overcome [Bryson 1996]. This is partially caused by the numerous difficulties users encounter while manipulating in immersive or semi-immersive VE. Among them, limitations in the users' precision seem to curtail the type of application developed for SIVE. These limitations may be due to the lack of manipulation restrictions existing in these environments.

While the situation of interaction in SIVEs seems closer to the situation one can experiment in the real world, the tasks users are required to perform are slightly different from what they are used to. The ecological constraints inherent to our world (such as affordances or physical constraints) limit the number of DoF simultaneously involved in the task. Such constraints are usually not present in VR worlds. As a consequence, when interacting with an object in these environments, all DoF are manipulated simultaneously, without distinctions or limitations.

This work stems from the idea that, in certain situations, especially when high accuracy is necessary, an adapted reduction of the dimensionality of the task may be beneficial. In this paper we propose a new interaction technique called *DIOD* (***D**ecomposition and **I**ntegration **O**f **D**egrees of Freedom*) implementing this idea. The DIOD technique is based on the *Two-Component Model* [Woodworth 1899]. It aims at providing different control levels during the *ballistic* and *control* phase of the positioning. During the ballistic phase, it allows to manipulate several DoF at the same time to get quickly toward the target. On the contrary, during the control phase, DIOD facilitates the separated manipulation of each DoF.

2 Related works

2.1 3-D positioning task

When interacting in VEs, the addition of the depth dimension in the interaction makes the task more complex.

To our knowledge, the most effective technique for free positioning in 3-D environment is *PRISM* [Frees and Kessler 2005]. It is based on the Two-Component Model [Woodworth 1899]. This model states that positioning gestures can be divided into two phases. The first phase, called *ballistic phase*, consists of coarsely positioning the object. The second phase, called the *control phase*, consists of small adjustments nearby the target. Each of these two phases require a specific control. When the user quickly moves the object, it means that the user does not need any precision. However, when the object is moving slowly the user is trying to be precise. The PRISM technique implements these principles. It consists in dynamically modifying the *Control:Display ratio* (noted C:D ratio) in relation to the object's velocity. If the device moves quickly, the object moves in a 1:1 mapping. As the device moves slower and slower, the C:D ratio is increased in order to provide more control to the user. Statistical evidences show that this technique is as rapid as the direct manipulation technique to position an object. The results also show that PRISM is more precise than the direct manipulation.

While this technique allows to control all the DoF of the task in a single movement, other works propose to decompose the task to improve the users' performances. The *Balloon Selection* technique proposed in [Benko and Feiner 2007] is designed to select an object in a 3-D environment. This technique is also suitable to move an object within a 3-D space. Using this technique, the selection task is decomposed into a 2-D and a 1-D subtasks which respectively consists in positioning the cursor into the horizontal plane and positioning the cursor along the height. *Benko et al.* are surprised by the performances offered by their technique regarding the direct manipulation. In addition to decreasing the error rate, their technique does not increase the achievement time (the average time difference is 0.3 s) although it compels users to decompose the task. These results are very surprising in regard to the theoretical model of *Jacob et al.* [Jacob et al. 1994] that is generally accepted to describe the manipulation of multiple DoF. The authors, however, do not propose any explanation for these results. We further discuss these notions in the next section.

2.2 Degrees of freedom

To describe the impact of the manipulation of multiple DoF during an interaction task, *Jacob et al.* [Jacob et al. 1994] introduce the notion of a *perceptual structure*. Each device and each task has its own perceptual structure that gathers all the attributes that can be modified. The perceptual structure can be *integral* when the semantic distance between the attributes is low or *separable* if the semantic distance is important. For instance, lateral and height position may have a low semantic distance. On the opposite, the grey level colour and the orientation around the horizontal axis of an object may have a high semantic distance.

Jacob et al. studied the influence of the perceptual structures on the performances users reach. They showed that to obtain the best performances, the perceptual structure of the interaction device should match the perceptual structure of the task. Because the perceptual structure of the positioning task is integral, their results suggest that the positioning techniques should integrate the manipulation of the three corresponding DoF to obtain the best performances. However, the framework ignores the users' possible inability to manipulate all the DoF simultaneously when their number increases or when the conditions of the manipulation changes.

In their work, *Casiez et al.* compared two elastic devices, the first one–the Spacemouse ©–integrating and the second one–the DigiHaptic–separating the manipulation of the three DoF. They showed that it was strenuous for the users to coordinate the manipulation of two and three DoF simultaneously during a steering task even using the SpaceMouse [Casiez et al. 2004]. Moreover, they observed a partial decomposition of the task using the Spacemouse. This may suggest that the users control the DoF separately even if they are integrated in a unique perceptual structure.

Our hypothesis is that users will adapt their strategies of integration of the DoF depending on the current objectives of the manipulation. In the *ballistic phase*, the perceptual structure may be integrated. Combining several DoF at the same time can be effective to coarsely reach the target position. However, to perform precise positioning we think users may want to adjust the position along each dimension individually by performing small directional adjustments toward the target. To that extent, the perceptual structure of the *control phase* may be separated. Thus, decomposing the 3-D positioning into three independent 1-D positioning may help the users to implement adapted strategies to preform precise positioning tasks.

The technique we propose follow this principle and provide the appropriate DoF coordination during the two phases of the positioning task.

3 The DIOD technique

The aim of our technique is to allow users to combine all the three DoF of the task when quickly moving the object. However, when the object is moving slowly users have to be able to manipulate only one DoF at a time. In its principles, this technique is similar to the *GearBox* technique proposed by *Osawa et al.* [Osawa and Ren 2007]. Users manipulate the object using a direct manipulation technique. They are also able to manipulate specific dimensions using the GearBox widget. The problem are the multiple widget selections and manipulations introduced in the positioning task. These additional tasks may introduce a significant increase in the manipulation time.

The technique we propose implicitly switches from a free to a constrained manipulation using non-isomorphic translation [Bowman and Hodges 1997]. We use the instantaneous velocity to decide whether the interaction should be free or constrained.

We consider $\vec{D_{dev}}$ as the displacement of the device. D_x, D_y and D_z are the three components of the vector in the 3-D space. V_{dev}, V_x, V_y and V_z are the instantaneous velocities associated to these components. The filtering function is defined as follow:

$$\vec{D_{obj}} = \begin{cases} \vec{D_{dev}} & \text{, if } V_{dev} > V_{max} \\ \begin{pmatrix} D'_x \\ D'_y \\ D'_z \end{pmatrix} & \text{, otherwise} \end{cases} \quad (1)$$

The displacements along each axis, D'_x, D'_y and D'_z, are defined as the effective displacement along each axis modified by the filtering function.

$$D'_i = D_i.f(V_i), \forall i \in \{x, y, z\}$$

The filtering function f varies according to the actual velocity of the object along each axis. $f(V_i) \in [0, 1]$.

$$f(V_i) = \begin{cases} 0 & \text{, if } V_i < V_{min} \\ min(1, \frac{V_i}{V_{scale}}) & \text{, otherwise} \end{cases} \quad (2)$$

The filtering method we propose is an adaptation of the filter used in PRISM. The difference is that we consider the movement as a multi-dimensional input. These dimensions can be combined or not depending on the users' need. If the movement is quick, the

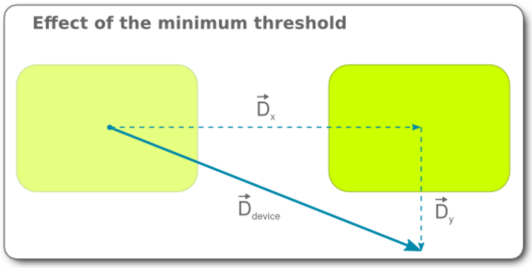

Figure 2: *On this figure, the instantaneous velocity along the y dimension is not high enough. The filter changes an* ***almost one dimensional movement*** *($\vec{D_{dev}}$) into an effective* ***one dimensional movement*** *($\vec{D_{obj}} = \vec{D_x}$).*

technique applies a one to one mapping. Therefore, it combines all the DoF exactly as they are exploited by the user. Notwithstanding, when the velocity of the displacements decreases, each dimension is filtered independently from the others. The minimum velocity threshold helps the users to manipulate the desired number of DoF: when the velocity of the displacement for a given direction is under the threshold, the movements are not taken into account. This is illustrated in Figure 2.

To avoid sudden changes in the manipulation when going from one phase to the other, the technique implements a smooth transition between the first phase (quick movements) and the second phase (slow movements). It applies independent non linear mappings along each directions. During this phase, as illustrated in Figure 3, the movement in each dimension is progressively reduced until it reaches the minimum threshold. Once the threshold is reached for a dimension and as long as the corresponding velocity is under the threshold, the movements along this dimension are ignored. Thus, the technique progressively constrains the manipulation of the object from three, to two and finally to one dimension, based on the velocity of the displacement regarding each dimension.

4 Preliminary study

To evaluation the performance of our technique we compared DIOD to PRISM during a repeated positioning task.

4.1 Apparatus

The experiment was conducted on a Workbench Barco Consul, a two screen SIVE. The images were generated using two workstations (one for each screen) fit out with a 3 Ghz Intel Quad Core and a NVIDIA Quadro FX 5600. We use an ART tracking system and optical trackers for the head and hands tracking. The users interact with the environment with two XIST Data Gloves.

4.2 3-D positioning techniques

We compare two 3-D positioning techniques. Using these techniques, users are not required to grab the object, but can grasp any part of the environment.

- **PRISM**: the displacements of the device are filtered using the function described in [Frees and Kessler 2005]. We do not use the offset recovery and we use the following thresholds : $Min_V = 0.005 m.s^{-1}$, $SC = 1 m.s^{-1}$.
- **DIOD**: the displacements of the devices are filtered using the filter described in Section 3. $V_{min} = 0.0035 m.s^{-1}$, $V_{scale} = 0.9 m.s^{-1}$, $V_{max} = 1.25 m.s^{-1}$.

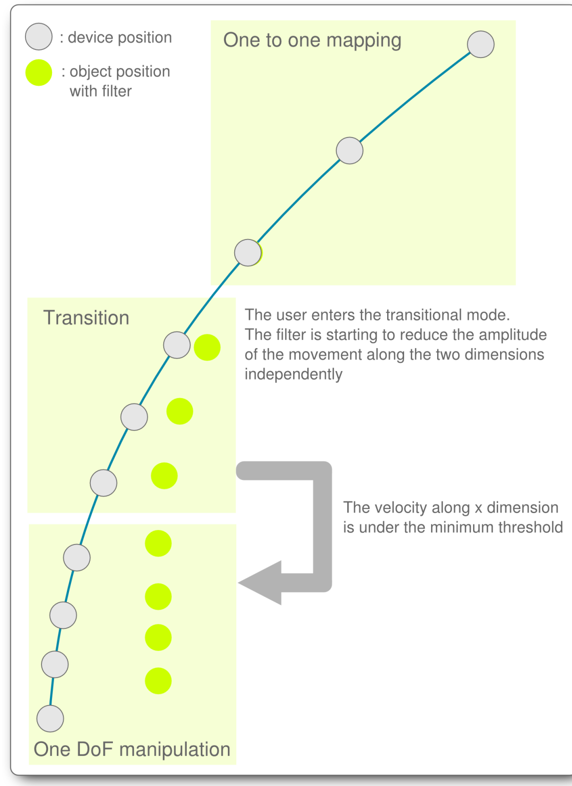

Figure 3: *The transition between the 1:1 mapping and the constrained manipulation is smooth thanks to per DoF non-linear mapping.*

4.3 Repeated positioning task

To evaluate each technique, we ran a series of tests based on a repeated positioning task (almost identical to the one used for the PRISM evaluation [Frees and Kessler 2005]). During each trial, subjects were required to repeatedly position an object to match a given target position. The precision threshold required to consider an object as positioned depends on the level of difficulty: Easy (1 cm), Medium (3.5 mm), Hard (2 mm), Very Hard (1.2 mm). To avoid unintentional positioning, we considered the object as positioned if it stayed at least 0.8 s under the precision threshold.

The object was a sphere with a radius of 7.5 cm, while the target position was represented by a semi-transparent cube of (7.5 + size of the current precision threshold) cm edge. It was chosen to ensure that the task involved a displacement along the three dimensions and was long enough to necessitate both a ballistic and a control phases. Therefore, the starting point of the manipulated object and the target did not change throughout the test. The distances along each axis are equals. The order of the task difficulty is the same for each user. The difficulty increases from Easy to Very Hard. Once the user ended the Very Hard difficulty, an identical second session followed. Each subject had to perform 8 sessions of positioning (two for each difficulty level), each one lasting one minute. Between each session, subjects could rest as long as they wanted.

4.4 Procedure

Twelve subjects with different levels of experience with SIVE participated in the study. The session began with a learning session consisting for each interaction technique in one repeated positioning task for each of the four difficulties. Afterwards, the test session began. We balanced the interaction technique to avoid ordering effect on the results. The only measurement is the **Number of positioning**, the mean number of successive positioning achieved by the subjects during a one minute session. We also asked the subjects to evaluate the techniques regarding their preference and their appropriateness to the ballistic and the control phases on a 7 Likert-Scale.

5 Analysis and discussions

We ran an ANalysis Of VAriance (ANOVA) with repeated measures. The technique has a significant influence on performances ($F(2, 22)=34.10$, $p<0.001$). The ranking of the techniques for the mean number of positioning appear to be the same for all four difficulty levels: DIOD obtain the best performances.

Therefore, we ran a post-hoc pairwise t-test with a Benjamini and Hochberg correction to check the relevancy of the differences between the techniques. The pairwise comparison shows no statistically significant difference for the Easy condition. The differences between DIOD and PRISM are significant for the Hard ($p=0.042$) and Very-Hard conditions ($p=0.001$).

	Mean	Easy	Medium	Hard	Very Hard
PRISM	11.1	17.5	13.0	9.1	5.3
DIOD	12.9	18.7	14.2	10.8	7.7

Table 1: *Mean number of successive positioning for each threshold.*

The DIOD technique appeared to be the most efficient. The results show 18.7 % and 45.3 % gains for DIOD compared to PRISM respectively for the Hard and Very-Hard threshold. Moreover, the benefit of this technique, compared to PRISM, increases with the difficulty. We think that this result might be explained by the easiness to implement decomposing strategies induced by DIOD. It seems that such strategies are needed and naturally implemented by the users. This may explain the increased performances and satisfactory for DIOD.

Indeed, the subjective preferences analyses shows a strong preference for the DIOD technique compared to PRISM (see Table 2). Concerning the appropriateness, the subjects did not rated differently the two techniques for the ballistic phase (the means ratings are 6.36). On the contrary, for the control phase, DIOD outperforms PRISM. The comments we gathered during the experiments show that *"The control provided by the technique at the end of the task is totally adapted"*.

	DIOD	PRISM
Subjective preference	6.6	4.6
Appropriateness for ballistic phase	6.4	6.4
Appropriateness for control phase	6.7	4.5

Table 2: *Mean subjective evaluations (7 levels Likert scale).*

6 Conclusions

The primary objective of this paper was to verify that in SIVE, were the simultaneous manipulation of numerous DoF is often needed, DoF decomposition could be an efficient strategy when seeking high precision. To that purpose, we presented a new interaction technique called DIOD. This technique, inspired from the *Two-Component Model*, provides two different control levels regarding DoF coordination, one integrating and one separating the DoF.

To verify our hypothesis, we compared DIOD with PRISM. The preliminary results show that the DIOD technique is more efficient. DIOD led to increased performances, suggesting that DoF decomposition facilitates small adjustments of the position of the object. We need to further analyse the data to study the coordination of the users' movements during both phases of 3-D positioning.

References

BENKO, H., AND FEINER, S. 2007. Balloon selection: A multi-finger technique for accurate low-fatigue 3d selection. In *IEEE Symp. on 3D User Interfaces*, –.

BOWMAN, D. A., AND HODGES, L. F. 1997. An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In *SI3D '97: Proceedings of the 1997 symp. on Interactive 3D graphics*, ACM, New York, NY, USA, 35–ff.

BRYSON, S. 1996. Virtual reality in scientific visualization. *Commun. ACM 39*, 5, 62–71.

CASIEZ, G., PLENACOSTE, P., AND CHAILLOU, C. 2004. Does dof separation on elastic devices improve user 3d steering task performance? In *APCHI 2004: Asia Pacific conf. on computer human interaction*, G. Springer, Berlin, Ed., vol. 3101, 70–80.

CHEN, M., MOUNTFORD, S. J., AND SELLEN, A. 1988. A study in interactive 3-d rotation using 2-d control devices. *SIGGRAPH Comput. Graph. 22*, 4, 121–129.

FREES, S., AND KESSLER, G. D. 2005. Precise and rapid interaction through scaled manipulation in immersive virtual environments. In *VR '05: Proceedings of the 2005 IEEE Conference 2005 on Virtual Reality*, IEEE Computer Society, Washington, DC, USA, 99–106.

JACOB, R. J. K., SIBERT, L. E., MCFARLANE, D. C., AND M. PRESTON MULLEN, J. 1994. Integrality and separability of input devices. *ACM Trans. Comput.-Hum. Interact. 1*, 1, 3–26.

KOK, A. J. F., AND VAN LIERE, R. 2007. A multimodal virtual reality interface for 3d interaction with vtk. *Knowl. Inf. Syst. 13*, 2, 197–219.

OSAWA, N., AND REN, X. 2007. A study on approximate and fine adjustments by hand motion in an immersive environment. *Transactions of Information Processing Society of Japan 48*, 11 (November), 3568–3576.

STURMAN, D. J., ZELTZER, D., AND PIEPER, S. 1989. Hands-on interaction with virtual environments. In *UIST '89: Proceedings of the 2nd annual ACM SIGGRAPH Symp. on User interface software and technology*, ACM, New York, NY, USA, 19–24.

THOMSON, I., AND NICHOLS, S., 2009. Top 10 disappointing technologies. Website, may.

WOODWORTH, R. 1899. The accuracy of voluntary movement. *Psychological Review 3*, 1–106.