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Manipulation of Viewpoints in 3D Environment using Interlocked Motion of Coordinate Pairs

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Abstract: This paper proposes a manipulation technique to intuitively control multiple viewpoints of cameras in a 3D environment specifically, a primary viewpoint and additional viewpoints. The first key concept is to introduce a secondary coordinate system to determine the additional viewpoints and then to interlock the motion of the additional viewpoints with the relative motion of the primary viewpoint and the secondary coordinate system. The second key concept is to control both the primary viewpoint and the secondary coordinate system by using the user's natural movements. This enables the user to intuitively control both the primary viewpoint and the additional viewpoints based on his/her proprioception.
Keywords: 3D environment, virtual reality, multimodal, viewpoint, camera, intuitive control, interlocked motion.

1 Introduction

Cameras are used in both virtual and real environments in order to observe the scene, and viewpoint determination is one of the critical issues in interactive 3D computer graphics involving virtual cameras and in awareness systems using actual cameras (Craig, 1989). Intuitive and natural control methods can provide a good user interface for effectively utilizing the resultant images (Bowman et al., 2001). In order to enable the user to intuitively understand the environment with a precise spatial sensation, the control method employed for the six degrees-of-freedom of the viewpoint must be clear to the user.

Some literature is devoted to viewpoint manipulation in the virtual environment. (Brooks, 1988) describes navigation techniques that use various input devices in a walkthrough system: the helicopter metaphor using joysticks, the eyeball metaphor using a 6D tracker, and the shopping cart metaphor using a treadmill and steers. A method that couples the user's head motion with the motion of the viewpoint in the environment is generally used (Deering, 1992). (Ware et al. 1990) described three distinct metaphors for viewpoint control using a 6D hand-held input device: eyeball-in-hand that directly controls the viewpoint, scene-in-hand that controls the position and orientation of the scene, and flying-vehicle-control that converts the user's hand motion into the velocity of the viewpoint. However, these existing viewpoint manipulation methods originally deal with a single viewpoint, and a method for effectively controlling multiple viewpoints has not yet been discussed, although chance of using multiple cameras to observe several different scenes is increasing .

In this paper, we propose the “interlocked motion of coordinate pairs” as a manipulation technique for intuitively controlling multiple viewpoints of cameras. This technique interlocks the motion of an additional viewpoint with the relative motion of the primary viewpoint and the secondary coordinate system. In addition, the primary viewpoint and the secondary coordinate system are coupled with user's natural movements. As a result, the user can control an additional viewpoint independently of or with dependence on the primary viewpoint via intuitive manipulation. Also, the user can easily understand the correspondence between an additional view and the primary view based on his/her proprioception. Experimental results show the usefulness of the proposed technique compared with other techniques used to control a global viewpoint in addition to a user’s local viewpoint in virtual environment.

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2 Manipulation of Multiple Viewpoints

Many benefits have been claimed formally or informally for making available multiple views from different positions and directions as well as in different scales. This section describes related work that uses secondary views in addition to the primary views. Then, effective manipulation methods of the additional viewpoints are considered. Please note that although there are several other parameters such as field-of-view and zoom factor, we do not discuss control of these parameters in this paper.

2.1 Related Work

There are many VR systems that present an additional view along with the user's primary view. In considering the use of additional viewpoints, it is possible to classify them into three types based on function: *fix*, the viewpoint is fixed at a certain position and orientation in the environment (Darken et al, 1993); *follow*, the viewpoint automatically changes its position and orientation according to the change in the other viewpoint (e.g. primary viewpoint) based on rules (Darken et al, 1999; Koller et al, 1995); and *free*, the user can freely control the viewpoint independent of the other viewpoint (e.g. primary viewpoint). Here, the additional viewpoint is mostly controlled with a keyboard, mouse, or joystick (Watanabe et al, 1996; Edwards et al, 1997). However, the majority of the existing VR systems provide a map-like view from a certain *fixed* viewpoint or the overview from a viewpoint that *follows* the user's primary viewpoint. A method to *freely* and intuitively control the additional viewpoints has not yet been discussed.

The world-in-miniature technique (Stoakley et al, 1995) and Voodoo Dolls (Pierce et al., 1999) also offers multiple views and scales. These techniques presents a miniature copy of the entire environment or around the object and enables the user to change the position and orientation of the miniature by using a hand-held 6D tracker. However, they must be predefined and require multiple copies of geometry corresponding to multiple different miniatures. Therefore, the order of the data size of the geometry of the environment is proportional to the number of miniatures presented.

2.2 Manipulation of Additional Viewpoints

As a method to manipulate the primary viewpoint and additional viewpoints, a combination of the existing control methods for single viewpoint is considered. For example, coupling the primary viewpoint to the user's head motion and controlling the additional viewpoint with the eyeball-in-hand, scene-in-hand, or flying-vehicle-control metaphor using a hand-held 6D tracker. Another example is controlling both the primary viewpoint and the additional viewpoint with the eyeball-in-hand, scene-in-hand, or flying-vehicle-control metaphor using two 6D trackers in both hands. These example methods enable the user to control multiple viewpoints, but there is no relation between the control of the primary viewpoint and the control of additional viewpoints because the existing methods originally only considered single-viewpoint control. Therefore, each viewpoint is controlled separately and it becomes difficult to recognize the correspondence of an additional view to the primary view because the user can only infer the correspondence only from the resultant views.

In considering the effective use of the additional view, the control method for additional viewpoints should satisfy the following two features, in addition to the features that the control method of the primary viewpoint should satisfy.

– Control of the additional viewpoint independent of the primary viewpoint.
– Easy understanding of the correspondence between the additional viewpoint and a primary viewpoint.

The second feature demands accurate recognition of the position and orientation of additional viewpoints.

3 Method of Intuitive Multiple Viewpoint Manipulation

This section describes a method that intuitively controls the position and orientation of an additional viewpoint in addition to the primary viewpoint. For this purpose, we introduce a secondary coordinate system that determines the additional viewpoint. This coordinate system differs from a world coordinate system for the environment in the geometric relationship.

3.1 Introduction of Secondary Coordinate System

Six parameters for the position and orientation of the viewpoint must be determined to generate a view. In order to intuitively control these parameters, the concept of “interlock” is introduced for the additional viewpoint and the primary viewpoint. Figure 1 shows the coordinate systems used in the proposed method. The world coordinates represent the position and orientation of all objects in the entire virtual environment, and they correspond to globally-aligned directional representations (north,

south, east, and west). Both the primary view coordinates and the additional view coordinates determine view direction and view volume of each viewpoint and correspond to the viewpoint-aligned

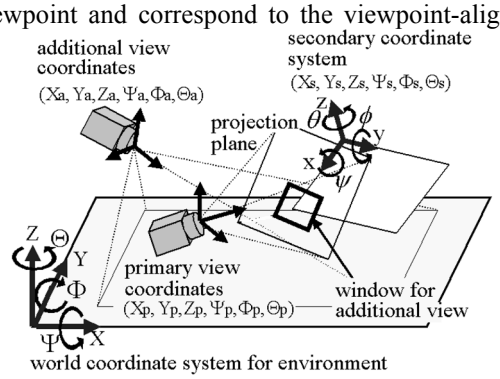


Figure 1: Coordinate systems of proposed method.

directional representations (front, rear, left, and right). Furthermore, each viewpoint is located at the origin of each coordinate system.

Besides the above three fundamental coordinate systems, a secondary coordinate system is introduced. This fourth coordinate system is used only to determine the additional viewpoint, and the user can control the position and orientation of the coordinate system in the world coordinate system. Also, the secondary coordinate system differs from a world coordinate system for the environment in its geometric relationships (scale, origin, and coordinate system axes). The additional view is generated according to its position, orientation and the geometric relationship between a world coordinate system and the secondary coordinate system. The generated additional view image is displayed in the window on the projection plane of the primary viewpoint. Therefore, the original data size of the geometry of the environment does not increase even if the number of additional view images (i.e., viewpoints) increases.

3.2 Interlocked Motion between the Viewpoints

In order to achieve effective control of the additional viewpoint, "interlocked motion" between the additional viewpoint and the primary viewpoint is proposed. This means that a pair of coordinate systems (i.e., the primary view coordinates and the secondary coordinate system) interlocks with another pair of coordinate systems (i.e., the additional view coordinates and the world coordinate system).

3.2.1 Transformation from World Coordinates to Secondary Coordinates

The position (X_p, Y_p, Z_p) and orientation (Ψ_p, Φ_p, Θ_p) of the primary viewpoint in the world coordinate system are transformed into the position (x_p, y_p, z_p) and orientation (Ψ_p, Φ_p, Θ_p) of the

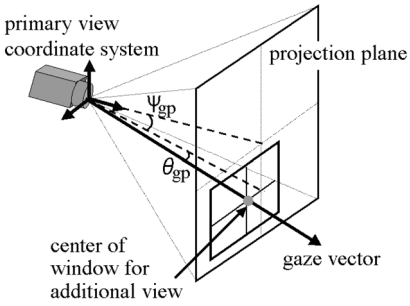


Figure 2: Gaze vector of primary viewpoint.

secondary coordinate system. Here, the angles (ψ_{gp}, ϕ_{gp}, θ_{gp}) are the orientation of the primary viewpoint's gaze vector that passes through the center of the window for the additional view in the primary view coordinate system (see Figure 2).

The rotation matrix of the primary viewpoint's gaze vector R_{pw} and the rotation matrix of the secondary coordinate system R_{sw} in the world coordinate system is represented as follows where $R_X(\Psi)$, $R_Y(\Phi)$, and $R_Z(\Theta)$ denote rotations around coordinate axes.

$$R_{pw} = R_Z(\Theta_p + \theta_{gp}) \cdot R_X(\Psi_p + \psi_{gp}) \cdot R_Y(\Phi_p + \phi_{gp}) \quad (1)$$

$$R_{sw} = R_Z(\Theta_s) \cdot R_X(\Psi_s) \cdot R_Y(\Phi_s) \quad (2)$$

The position (x_p, y_p, z_p) and rotation matrix R_{ps} of the primary viewpoint in the secondary coordinate system are obtained by the following. Here, the orientation of the primary viewpoint (ψ_p, ϕ_p, θ_p) in the secondary coordinate system is calculated by the rotation matrix R_{ps}.

$$[x_p, y_p, z_p, 1] = [X_p - X_s, Y_p - Y_s, Z_p - Z_s, 1] \cdot R_{sw}^T \quad (3)$$

$$R_{ps} = R_{pw} \cdot R_{sw}^T \quad (4)$$

3.2.2 Transformation from Secondary Coordinates to World Coordinates

The position (X_a, Y_a, Z_a) and orientation (Ψ_a, Φ_a, Θ_a) of the additional viewpoint in the world coordinate system are calculated by transforming the position (x_p, y_p, z_p) and orientation (ψ_p, ϕ_p, θ_p) of the primary viewpoint in the secondary coordinate system. Here, the geometric relationship between the secondary coordinate system and the world coordinate system is described by three parameters:

scale S_t, translation of origin (X_t, Y_t, Z_t), and rotation of coordinate system axes (Ψ_t, Φ_t, Θ_t).

The position (X_a, Y_a, Z_a) and rotation matrix R_a of the additional viewpoint in the world coordinate system is calculated by the following. Here, the rotation matrix for transformation R_t is calculated by the rotations around coordinate axes.

$$[x_a, y_a, z_a, 1] = S_t \cdot [x_p, y_p, z_p, 1] \cdot R_t^T + [X_t, Y_t, Z_t, 1] \quad (5)$$

$$R_a = R_{ps} \cdot R_t \quad (6)$$

$$R_t = R_Z(\Psi_t) \cdot R_X(\Phi_t) \cdot R_Y(\Theta_t)$$

The orientation of the additional viewpoint (Ψ_a, Φ_a, Θ_a) in the world coordinate system is calculated by the rotation matrix R_a.

$$R_a = \begin{bmatrix} R_{11} & R_{12} & R_{13} & 0 \\ R_{21} & R_{22} & R_{23} & 0 \\ R_{31} & R_{32} & R_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\Psi_a = -\arcsin(R_{23})$$

$$\Phi_a = \arctan(R_{12} / R_{33}) \quad (7)$$

$$\Theta_a = \arcsin(R_{12} / \cos(\Psi_a))$$

In this case, the geometric relationship between the secondary coordinate system and the world coordinate system can be established in various ways and also changed dynamically. This enables the user to obtain a different type of additional view. Based on this idea, sophisticated display methods using the global overview image are obtained by using constraints on the parameters of the geometric relationship.

3.3 Intuitive Control of Multiple Viewpoints by Interlocked Motion of Coordinate Pairs

There is some variation in the implementation of our proposed "interlocked motion of coordinate pairs" technique. In the proposed technique, the user controls the primary viewpoint and the secondary coordinate system. Humans intuitively perceive the position and orientation of one's own body and its several parts by the sense called proprioception (Boff et al, 1986), and exploiting proprioception is an effective approach in virtual environment interaction (Mine et al, 1997).

Therefore, we couple the primary viewpoint and the secondary coordinate system with the user's natural movements. Accordingly, the user can intuitively control both the primary viewpoint and the additional viewpoint based on his/her proprioception. Moreover, the user can easily understand the correspondence between the additional view and the primary view based on his/her proprioception, unlike the methods using the existing viewpoint control methods described in sec.2.2. For example, in one implementation the primary viewpoint is coupled with one hand and the secondary coordinate system is coupled with the other hand. In another implementation example, the primary viewpoint is coupled with the user's head motion and the secondary coordinate is coupled with the user's hand motion. In these implementation examples, the user can control the primary viewpoint and the additional viewpoint independently or with dependence. In the latter implementation example, if a user rotates his/her hand, the secondary coordinate system is rotated at the same angle and position. At the same time, the position and orientation of the additional viewpoint change due to the change in the position and orientation of the primary viewpoint relative to those of the secondary coordinate system (see Figure 3). If the user rotates his/her head, both the primary viewpoint and the additional viewpoint change the orientation of each viewpoint.

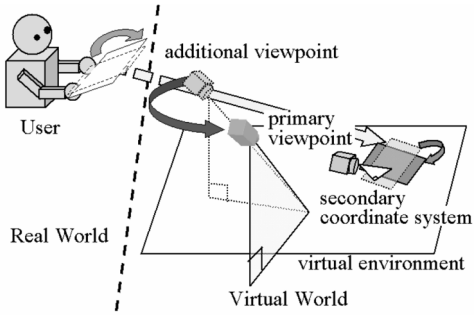


Figure 3: Interlocked motion between primary viewpoint and additional viewpoint.

Furthermore, the proposed technique can be extended to control methods for multiple viewpoints. In this case, the window and secondary coordinate system are introduced for each additional viewpoint, and the geometric relationship between a world coordinate system and the secondary coordinate system is established individually. As a result, various views from each viewpoint are displayed in the primary viewpoint's projection plane.

4 Navigation System using Additional View

We apply the proposed viewpoint manipulation technique to a navigation system that simultaneously presents a user with both a life-sized local view as a primary view and a global overview as an additional view. This section describes the system configuration and methods needed to establish such systems, alternately using the proposed method and two existing methods to control the global viewpoint.

4.1 System Description

The navigation system is implemented on an Onyx2 Infinite Reality™ workstation (Silicon Graphics Inc.) using IRIS Performer™ 2.2 (Rohlf et al, 1994). The position and orientation of the user's life-sized local viewpoint are measured by a 6D tracker attached to his/her head. The position and orientation of the user's hand are also measured by a 6D tracker attached to his/her hand, but these data are used differently for each method described in the next section. The experimental configuration is shown in Figure 4. Figure 5 shows a life-sized local image with a global overview image presented to the user. Here, parameters such as location and size of the window for the global overview image can be changed with the keyboard; however, in the experiment it is located nearly at the center of the user's view for easy explanation.

4.2 Implementation

The many viewpoint control methods are classified into two types based on the effective frame of reference: *egocentric*, which is analogous to moving a viewpoint through an environment, and *exocentric*, which allows the user to manipulate the scene in front of a static viewpoint. Therefore, we implemented a navigation system that controls the global viewpoint by three different control methods: interlocked motion of coordinate pairs, eyeball-in-hand metaphor (egocentric), and scene-in-hand metaphor (exocentric). In each navigation system, the position and orientation of the user's viewpoint is measured by a 6D tracker attached to the user's head.

4.2.1 Interlocked Motion of Coordinate Pairs (IMCP)

Figure 6(a) shows the concept of a navigation system using the interlocked motion of coordinate pairs. The user controls the position and orientation of the secondary coordinate system by using a hand-held 6D tracker. The motion of a global viewpoint against the world coordinate system (i.e., the entire virtual environment) is determined by the motion of the user's head relative to the user's hand (i.e., the secondary coordinate system). Thus, a user controls the global viewpoint with the cooperative motions of his/her head and hand.

4.2.2 Eyeball-in-Hand

Figure 6(b) shows the concept of a navigation system using the eyeball-in-hand metaphor. The virtual environment is stationary, while the motion of the global viewpoint directly corresponds to the motion of the user's hand measured by a hand-held 6-D tracker. The movement distance of the global viewpoint is obtained by magnifying the movement distance of the user's hand S_t times, and the orientation of the bird's eye viewpoint is determined by the rotation of the user's hand. Here, S_t is the scale parameter, similar to the parameter of the IMCP. Thus, a user controls the global viewpoint using only his/her hand motion and observes a non-distorted image according to his/her head motion.

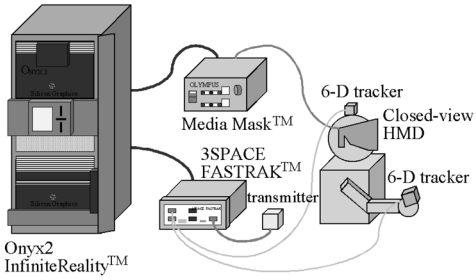


Figure 4: Experimental configuration.

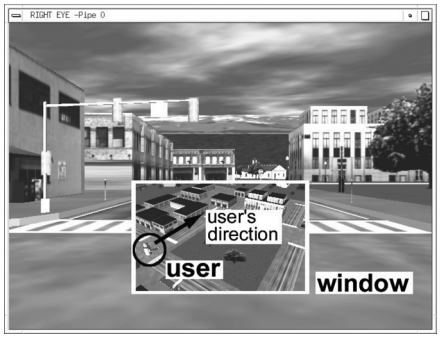


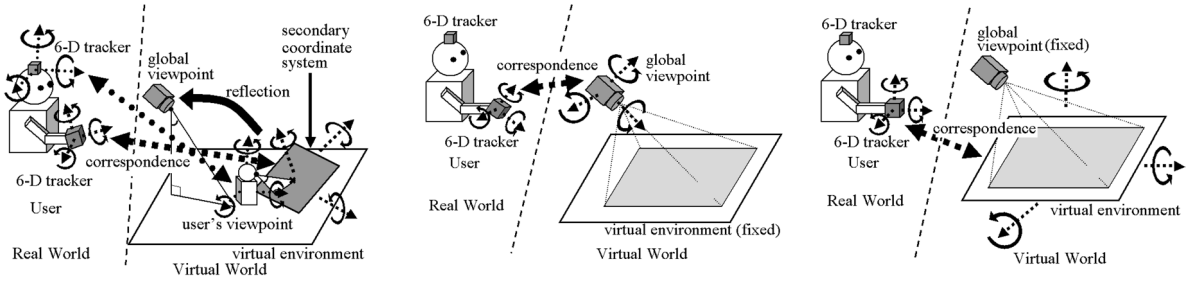
Figure 5: User's view (life-sized local view and global overview image).

4.2.3 Scene-in-Hand

Figure 6(c) shows the concept of a navigation system using the scene-in-hand metaphor. The global viewpoint is fixed at a certain point in the world coordinate system, while the motion of the virtual environment directly corresponds to the motion of the user's hand measured by a hand-held 6-D tracker. The movement distance of the virtual environment is obtained by magnifying the movement distance of the user's hand motion S_t times, and the orientation of the virtual environment is determined by the rotation of the user's hand. Here, S_t is the scale parameter, similar to the parameter of the IMCP. Thus, a user indirectly controls the global viewpoint using only his/her hand motion and observes a non-distorted image according to his/her head motion.

5 Experiments

An experiment is conducted to evaluate the usefulness of the proposed method compared with the two existing methods used to control the global viewpoint in addition to the user's local viewpoint. We particularly focus on the intuitiveness and



(a) Interlocked motion of coordinate pairs (IMCP)

(b) eyeball-in-hand

(c) scene-in-hand

Figure 6: Concept of system using each control method.

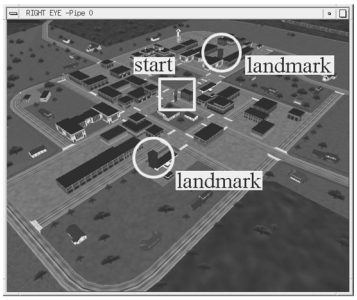


Figure 7: Landmarks in an experimental virtual environment.

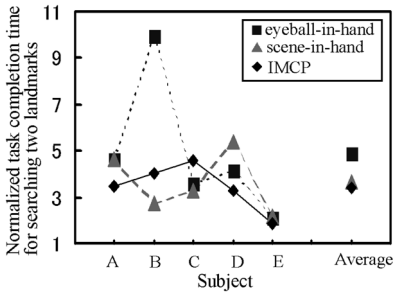


Figure 8: Normalized task completion time for searching two landmarks.

operability in the first usage of each control method in these experiments. In this case, there is little influence due to the user understanding the virtual environment by the learning effects.

5.1 Virtual Environment Design

We use a modified version of Performer Town™ (8.6km^2), which adds the two landmarks (blue and red pillar, which are each 6 meters) at random positions in the city part of the environment (700m * 500m). Figure 7 shows an experimental virtual environment and landmarks. Here, the position and orientation of the user's viewpoint is represented as a doll object in the experimental virtual environment.

5.2 Experimental Method

Subjects are asked to search for the landmarks using the global overview image and go around the two landmarks from the start position as quickly as possible. In this case, the number of landmarks is known but the location of the landmarks is not known. Also the order of visiting the landmarks is at the subject's option. The movement of the user's viewpoint in the virtual environment is controlled by the user's gestures (step forward, step backward, and stand still at initial position), and the user's viewpoint moves in the direction that the user faces at a uniform velocity (7m/sec). In the movement, a user cannot go into the buildings by detecting interference. The three different methods of controlling the global viewpoint are used in random order. Before beginning each trial, subjects are explained how to use the control method used in the trial and used the method briefly.

In the experiment, the scale parameters between the secondary coordinate system and the world coordinate system are set to 450. The correspondence of the origin and coordinate system axes between the secondary coordinate system and the world coordinate system is assumed to be established. In this case, the user can look over the entire city area where the landmarks are positioned within the physical range of the user's hand motion.

6 Results and Discussion

6.1 Task Completion Time and Trajectory

Five subjects took part in the experiment. The task completion time was defined as the ratio of the actual search time to the estimated shortest search time for reducing the influence of difference in landmark's position on the result in each trial. The shortest search time in each trial was estimated by the total distance of the recommended route that for going around the landmarks in the shortest distance and the moving velocity.

Figure 8 shows the individual task completion times for each control method within each subject. The average across subjects is shown in the last column. Results show that there are larger variations

due to individual ability with eyeball-in-hand and scene-in-hand; on the other hand, there is smaller variation due to individual ability with the interlocked motion of coordinate pairs (IMCP).

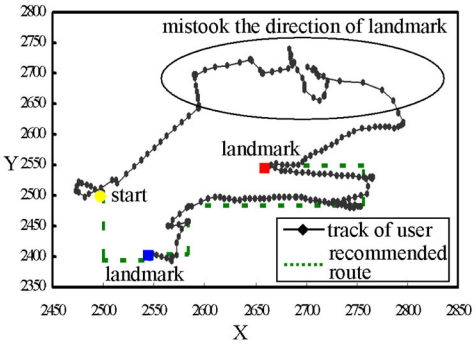
In the eyeball-in-hand and scene-in-hand, some of the subjects lost their way because they could not recognize the accurate structure of the virtual environment and misunderstood the user's own position or the landmark's position. On the other hand, in the interlocked motion of coordinate pairs, all of the subjects could search the landmarks at an appropriate route without losing one's way even when the route is different from the recommended route. Figures 9 show the trajectory of a particular subject who showed the longest task completion times. In the eyeball-in-hand, he walked wrong way around the circled area in Figure 9(a), and in the scene-in-hand, he passed a same location many times in the circled area in Figure 9(b). These are because he could not recognize the structure of the environment accurately and misunderstood his own position or the landmark's position. On the other hand, in the interlocked motion of coordinate pairs, the same subject could search the landmarks at an appropriate route without losing his way as shown in Figure 9(c).

6.2 Evaluation

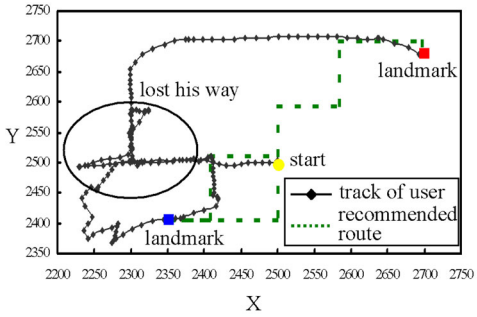
We gave the subjects questionnaires about the usefulness of the three different control methods and also asked them to rank the three different control methods: 3 when a method was judged the best, 1 when it was judged the worst, and 2 otherwise. Figure 10 shows the ranking of each control method within each subject. The average across subjects is shown in the last column. Results show that the interlocked motion of coordinate pairs (IMCP) is better than the other two in the majority of subjects' evaluations. In the following analysis, we discuss the operability and the cognitive properties of each control methods.

6.2.1 Operability

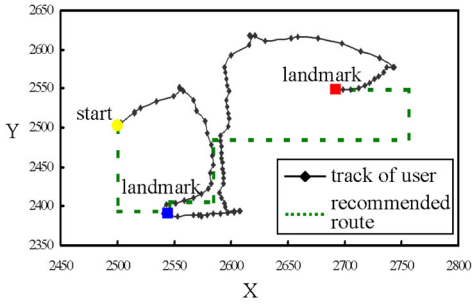
The interlocked motion of coordinate pairs enables the user to freely control the global viewpoint with both his/her hand and head motion, and it offers flexible control of the global viewpoint. On the other hand, the eyeball-in-hand and scene-in-hand methods restrict the control of the global viewpoint to his/her hand motion. Also, the motion of the global viewpoint with eyeball-in-hand was limited by the user's physical constraint because the eyeball-in-hand method directly translates the user's hand motion into the motion of the global viewpoint. It was difficult to control the global viewpoint far from the center of rotation with scene-in-hand method



(a) eyeball-in-hand



(b) scene-in-hand



(c) Interlocked motion of coordinate pairs (IMCP)

Figure 9: Trajectory in the horizontal (XY) plane for a typical subject.

because it fixed the center of rotation at the center of the virtual environment.

6.2.2 Cognitive Properties

The interlocked motion of coordinate pairs provided the user intuitive control of the global viewpoint. The user felt that he/she could hold and manipulate the secondary coordinate system and could observe it through the window of his/her life-sized local view.

On the other hand, the eyeball-in-hand method provided the user an intuitive sensation that he/she was manipulating the global viewpoint, but it was sometimes difficult to place the global viewpoint at the user's desired position. For example, a user was at a loss when the global viewpoint faced in the user's direction because the global viewpoint moved in the opposite direction of the hand-held 6D

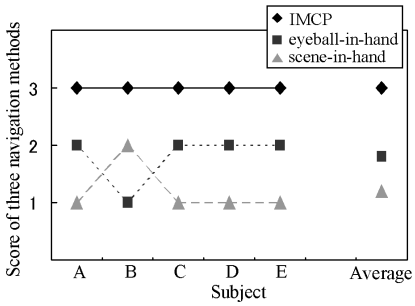


Figure 10: Result of questionnaires.

tracker's motion. It was difficult to intuitively control the global viewpoint with the scene-in-hand method because the motion of the user's head did not reflect the motion of the global viewpoint and the user had to indirectly control the global viewpoint with the direct control of the environment.

Moreover, the interlocked motion of coordinate pairs enables the user to intuitively understand the position and orientation of the global viewpoint because the relative position and orientation between the user's head and hand reflect the relative position and orientation of the global viewpoint in the virtual environment. This also enables the user to intuitively recognize the correspondence of the global overview to that of the user's life-size local view. It was difficult to understand the accurate position and orientation of the global viewpoint with the eyeball-in-hand and scene-in-hand methods because these methods did not provide any clues to recognize the position and orientation of the global viewpoint.

7 Summary and Conclusions

The "interlocked motion of coordinate pairs" technique was proposed to intuitively manipulate multiple viewpoints (a primary viewpoint and additional viewpoints). This technique interlocks the motion of an additional viewpoint with the relative motion of the primary viewpoint and the secondary coordinate system. The primary viewpoint and the secondary coordinate system are coupled with the user's natural movements. We applied the proposed technique to a navigation system that simultaneously presents a user with both a life-sized local view and a global overview image. In the system the life-size local viewpoint was coupled with the user's head motion and the secondary coordinate system was coupled with his/her hand motion. In the experiments, the proposed method was compared with two existing methods (the eyeball-in-hand and scene-in-hand methods) for controlling the global viewpoint. The experimental results showed that the proposed method enables the user to intuitively control the global viewpoint and understand the position and orientation of the global viewpoint in the virtual environment. As a result, the user intuitively understands the correspondence between the life-sized local view and the global overview.

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