Registration

SIGGRAPH '97 Course Notes #30: Making Direct Manipulation Work in Virtual Reality
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Abstract

Accurate registration is required to maximize the performance of direct manipulation interfaces, because much of the power of direct manipulation comes from leveraging the user's previous experience with the real world. Registration refers to the proper alignment and synchronization of virtual cues (visual, auditory, haptic) with corresponding real world events. Poor registration means the virtual environment system is not synchronized with the user's real-world actions, reducing the effectiveness of direct manipulation. Registration errors are difficult to avoid and come from many sources. The tolerable amount of error depends on the sensory modes involved. Approaches that have been taken to reduce registration error are briefly described and referenced, along with some topics for future research.

1. Motivation

Most systems today that use direct manipulation interfaces in Virtual Environments are not as effective as they could be. A significant limiting factor is the lack of good registration. Registration refers to the precise alignment and synchronization of two or more sensory elements. For example, a user wearing a Head-Mounted Display (HMD) may move his real hand around and see a virtual representation of that hand. The virtual hand model should be drawn to occupy exactly the same location as the real hand, precisely following the motion of the real hand. Any errors cause discrepancies between what the user sees (his virtual hand) and what he feels (where his proprioceptive sensors tell him his real hand is). Registration can involve synchronization between cues in one sensory mode (e.g., two visual events that occur simultaneously) or involving two or more senses (e.g., playing a sound at the exact moment a real baseball bat hits a virtual baseball).

Why is accurate registration a necessary component of effective direct manipulation interfaces? Direct manipulation interfaces gain much of their power from leveraging the user's experience with the real world. Proponents argue that these interfaces are more "intuitive" because they use actions that human beings have spent a lifetime practicing -- grabbing, twisting, pushing, bending, etc. But to most effectively make use of this experience, the virtual environment must accurately mimic the behavior of the real world. The response of the virtual objects should be accurately registered with the user's real-world actions.

Let me give an example. When I gave a demonstration of a HMD-based kitchen walkthrough, a user told me that he felt as if he was under water. I found the analogy quite accurate. The HMD fit over his face like a scuba mask. The optics in the displays distorted his view of the virtual environment. Because of the system delays, the system felt "sluggish," with all the virtual objects lagging behind the user's head motion, which is analogous to the increased resistance to motion experienced underwater. The user's comment revealed that the virtual environment was doing a better job matching real-world scuba diving than the desired goal of walking inside a kitchen.

If being in a virtual environment is like being underwater, then we are not getting the full benefit of direct manipulation interfaces. I can perform tasks (such as building a table) faster on land than underwater. Why? Being underwater hinders my performance by slowing down my motions, much as system delays in virtual environments force users to slow down their actions. Furthermore, some objects behave differently underwater (e.g., some float). Therefore, I would require time to practice and adapt to the different behaviors. Peak performance requires accurate registration to mimic the real-world situations that match the user's past experience.

The lack of accurate registration also raises the potential problem of negative training transfer. If a virtual environment is used to train users on a real world task, it may teach the users the wrong lessons. They may develop skills appropriate for how the virtual environment responds, but not for how the real world behaves. In extreme cases, breakdowns may occur in the form of pilot-induced oscillation or motion sickness.

Does this mean that registration errors prevent the use of direct manipulation interfaces? Of course not. Most direct manipulation interfaces have been developed on systems with such errors. However, if virtual environments are to become more widely accepted, more attention will have to be paid on how to improve user performance, and registration is an important factor in achieving that.

2. Difficulties

Registration errors are difficult to avoid. For example, errors in the reported tracker measurements may cause virtual objects to be drawn in the wrong locations. In a head-tracked stereo display using a large CRT, it may be difficult to directly manipulate objects if a magnetic tracker is used, due to the jitter and distortion caused by the proximity to the CRT. Temporal synchronization can be tricky. For example, in a virtual putt-putt game, a user may swing a putter and expect to hear a sound and feel a haptic pulse at the instant that the putter contacts a virtual golf ball. System delays are ubiquitous and cause all the virtual objects to be drawn later in time than they should be, making the entire environment appear to lag behind the user's head motions. With existing virtual environment technologies and systems, registration errors are almost certain to exist unless special efforts are made to remove them.

How small must registration errors become until they are not noticed or do not affect performance? That is a research topic, but it is known that the answers depend on the senses involved. The most common conflict in a virtual environment system is between the visual and kinesthetic or proprioceptive senses, such as drawing a virtual hand model at the same location as the user's real hand. The proprioceptive sense is relatively inaccurate compared to the visual sense. A phenomenon called *visual capture* describes the tendency of the brain to believe the visual sense over other senses; in this case, the user thinks that his hand is where he sees it, rather than where he feels it [Welch78]. Visual capture is why ventriloquism works. While I have argued that large registration errors will cause performance problems, because of visual capture I doubt that the errors need to be kept under one millimeter -- the tolerance is probably significantly larger. However, visual - visual conflicts are much more noticeable. In Augmented Reality, the user can see the real world around her, with virtual objects superimposed and composited with the real world [Azuma97]. If the user holds up her hand and the display draws a virtual outline around her hand, even small registration errors will be easily detected. The ultimate bound comes from the resolution of the fovea, which is about 0.5 minutes of arc. (In comparison, the diameter of the full moon covers 0.5 degrees, or 30 minutes, of arc.) Visual - auditory and visual - haptic conflicts are ones that should be explored in future research, but they probably fall somewhere in between visual - proprioceptive and visual - visual conflicts in terms of how noticeable they are. For example, stationary listeners can detect the position of sound sources along the front horizon to within one degree, but the accuracy grows considerably worse as the sound source moves away from the front horizon (e.g., behind the head) [Holman97].

Eliminating registration errors is difficult because of the many sources of error. Registration errors can be divided into two categories: static and dynamic. Static errors are ones that occur even when nothing moves. Dynamic errors only occur when either the head moves or the virtual objects move. Static errors are caused by static tracker errors, mechanical misalignments in the HMD, incorrect viewing parameters used to render the images, and distortions in the display, such as optical distortions introduced by the lenses in an HMD. Dynamic errors can be caused by the tracker as well, but usually most of these come from system delays. In today's systems, dynamic errors tend to dominate [Holloway95], although static errors are also significant.

3. Approaches

This section briefly summarizes and references the approaches that have been attempted to reduce registration errors. For more details, see [Azuma97]. Because registration errors are most noticeable and annoying when they are visual - visual conflicts, most of the work in this area has been done in the area of Augmented Reality.

Static errors: Sometimes, the best approach is to "build it right in the first place" to avoid having problems. This is often the case for mechanical misalignments. Other static errors are amenable to measurement and calibration. In some cases, it has been possible to reduce the static errors in the head tracker [Bryson92] [Ghazisaedy95] [Livingston98]. The distortions introduced by the Leep HMD optics have been measured and compensated for by predistorting the image [Robinett92] [Rolland93] [Edwards93]. Viewing parameters have been measured by asking the user to perform view-based tasks that set up constraints, allowing the parameters to be calculated [Azuma94] [Caudell92] [Oishi96]. Direct measurements of the viewing parameters have also been taken [Janin93]. Some systems incorporate a video camera onto the HMD to record what the user sees. If this provides the real-world background in an Augmented Reality system, camera calibration techniques can be used to extract the viewing parameters [ARGOS94] [Bajura93] [Tuceryan95]. Alternatively, a few recent works take "calibration-free" approaches that achieve good registration without the need for computing any viewing parameters [Kutukalos96] [Iu96]. Calibrating static tracker error is discussed further in another talk in this course.

Dynamic errors: Compensating for dynamic tracker errors has rarely been done; see [Welch97] for an example with an optical tracker. Most of the work here focuses on compensating for system delay. Ideally, one would like to eliminate delay, and some efforts have been made to greatly reduce the delay in the rendering pipeline [Olano95] [Wloka95]. However, reducing delay to the point where it is of no consequence is not currently possible. At a moderate head rotation rate of 50 degrees per second, total system delay must be less than 10 ms to keep angular errors below 0.5 degrees. The scanout of one frame at 60 Hz consumes 16.67 ms by itself. Therefore, the next best goal is to reduce the effective delay. Image deflection is a technique that can greatly reduce the effects of delay due to orientation changes [Burbidge89] [Regan94] [Riner92] [So92]. While image deflection does not work on translation, image warping is an active area of computer graphics research and may eventually be applied here to solve that problem. Systems that use a head-mounted camera to provide the user's view of the real world have been able to show impressive registration results by tracking image features and using those to enforce registration; examples include [Mellor95] [State96]. Finally, predicting future head locations can eliminate the effects of delay if the prediction is accurate. Predicting user head motion is described in more detail by another talk in this course.

What is the current status of registration? Good registration has been achieved by a few systems. However, the problem is far from solved. These systems severely constrain the environment, only working with a specific set of objects or sometimes only in a static environment. Research needs to be done to increase the domains under which accurate registration is possible. Duplicating these results is a nontrivial task, due to the complexity of the methods and the equipment required. Achieving good registration with less effort is a particularly desirable result.

4. Future work

Future developments in the following areas will help improve registration in future virtual environment systems:

Time-critical rendering and operation: The real world operates in "real time," and if a virtual environment system is to attain accurate registration with the user's real world actions, then it too must operate in real time. UNIX and other complex multiuser operating systems are not built for real-time operation. Time must become a first-class citizen. We need lightweight or real-time operating systems that also provide a good environment for building complex virtual environment applications [van Dam96]. Time-critical rendering is becoming a more popular research topic. The flight simulation community historically has paid more attention to guaranteed performance than others have [Krueger92]; that will have to change to improve direct manipulation performance.

Latency reduction or control: Decoupling the act of rendering from the actual display has the potential to remove a large amount of latency from the system. Developments in image-based rendering will make this possible. The Talisman architecture uses this approach to minimize rerendering "sprite" objects [Torborg96].

Hybrid trackers and sensors: A wider variety of input sensors will be needed, such as those measuring velocities and accelerations rather than just positions and orientations. Since each tracking technology has weaknesses, hybrid trackers will be developed that combine multiple technologies that cover each other's weaknesses for improved tracking performance.

Methods to ease implementation: As previously stated, implementing techniques that improve registration requires a significant effort, preventing their common use. Finding ways to reduce the investment required would do much to make accurate registration more common. Note that this is a *system* issue, not just one of improving individual components. For example, effective prediction requires tight integration of the predictor with the renderer, real-time operating system, and tracker.

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