High-Performance Wide-Area Optical Tracking
The HiBall Tracking System

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ABSTRACT

Since the early 1980's the Tracker Project at the University of North Carolina at Chapel Hill has been working on wide-area head tracking for Virtual and Augmented Environments. Our long-term goal has been to achieve the high performance required for accurate visual simulation throughout our entire laboratory, beyond into the hallways, and eventually even outdoors.

In this article we present results and a complete description of our most recent electro-optical system, the *HiBall Tracking System*. In particular we discuss motivation for the geometric configuration, and describe the novel optical, mechanical, electronic, and algorithmic aspects that enable unprecedented speed, resolution, accuracy, robustness, and flexibility.

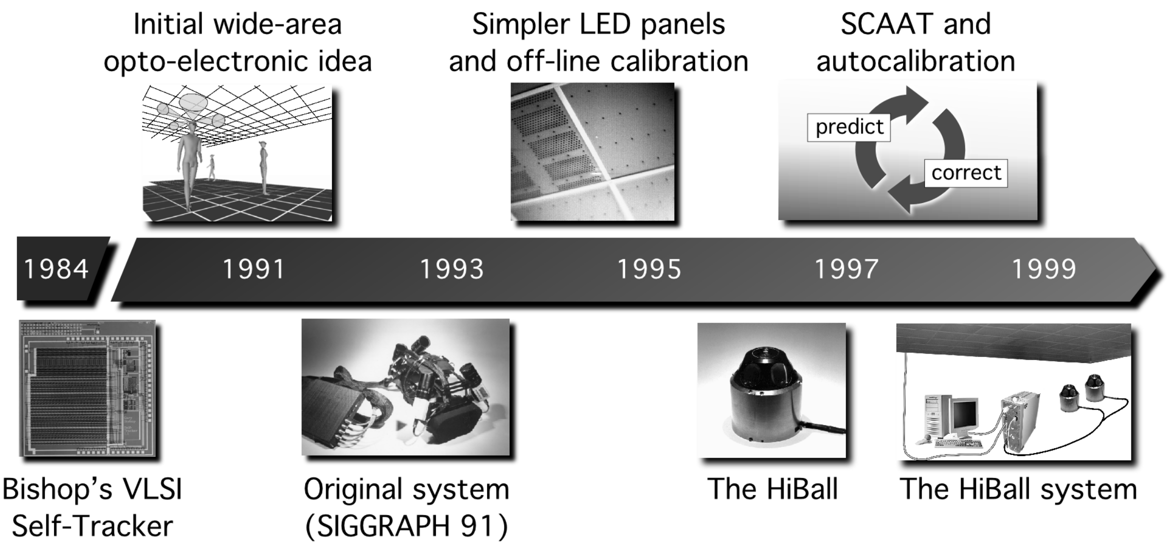

Figure 1

1. INTRODUCTION

Systems for *head tracking* for interactive computer graphics have been explored for over 30 years (Sutherland, 1968). As illustrated in Figure 1, the authors have been working on the problem for over twenty years (Azuma, 1993, 1995; Azuma & Bishop, 1994a, 1994b; Azuma & Ward, 1991; Bishop, 1984; Gottschalk & Hughes, 1993; UNC Tracker Project, 2000; Wang, 1990; J.-F. Wang et al., 1990; Ward, Azuma, Bennett, Gottschalk, & Fuchs, 1992; Welch, 1995, 1996; Welch & Bishop, 1997; Welch et al., 1999). From the beginning our efforts have been targeted at *wide-area* applications in particular. This focus was originally motivated by applications for which we believed that actually walking around the environment would be superior to virtually "flying." For example, we wanted to interact with room-filling virtual molecular models, and to naturally explore life-sized virtual architectural models. Today we believe that a wide-area system with high performance everywhere in our laboratory provides increased flexibility for all of our graphics, vision, and interaction research.

1.1 Previous Work

In the early 1960's Ivan Sutherland implemented both mechanical and ultrasonic (carrier phase) head tracking systems as part of his pioneering work in virtual environments. He describes these systems in his seminal paper "A Head-Mounted Three Dimensional Display" (Sutherland, 1968). In the ensuing years, commercial and research teams have explored mechanical, magnetic, acoustic, inertial, and optical technologies. Complete surveys include (Bhatnagar, 1993; Burdea & Coiffet, 1994; Meyer, Applewhite, & Biocca, 1992; Mulder, 1994a, 1994b, 1998). Commercial magnetic tracking systems for example (Ascension, 2000; Polhemus, 2000) have enjoyed popularity as a result of a small user-worn component and relative ease of use. Recently inertial hybrid systems (Foxlin, Harrington, & Pfeifer, 1998; Intersense, 2000) have been gaining popularity for similar reasons, with the added benefit of reduced high-frequency noise and direct measurements of derivatives.

An early example of an optical system for tracking or motion capture is the *Twinkle Box* by Burton (Burton, 1973; Burton & Sutherland, 1974). This system measured the positions of user-worn flashing lights with optical sensors mounted in the environment behind rotating slotted disks. The *Selspot* system (Woltring, 1974) used fixed camera-like photo-diode sensors and target-mounted infrared light-emitting diodes that could be tracked in a one-cubic-meter volume. Beyond the HiBall Tracking System, examples of current optical tracking and motion capture systems include the *FlashPoint*© and *Pixsys*™ systems by Image Guided Technologies (IGT, 2000), the *laserBIRD*™ system by Ascension Technology (Ascension, 2000), and the *CODA Motion Capture System* by B & L Engineering (BL, 2000). These systems employ analog optical sensor systems to achieve relatively high sample rates for a moderate number of targets. Digital cameras (two-dimensional image-forming optical devices) are used in motion capture systems such as the *HiRes 3D Motion Capture System* by the Motion Analysis Corporation (Kadaba & Stine, 2000; MAC, 2000) to track a relatively large number of targets, albeit at a relatively low rate because of the need for 2D image processing.

1.2 Previous Work at UNC-Chapel Hill

As part of his 1984 dissertation on *Self-Tracker*, Bishop put forward the idea of outward looking tracking systems based on user-mounted sensors that estimate user *pose*[1] by observing landmarks in the environment (Bishop, 1984). He described two kinds of landmarks: high signal-to-noise-ratio beacons such as LEDs (light emitting diodes) and low signal-to-noise-ratio landmarks such as naturally occurring features. Bishop designed and demonstrated custom VLSI chips (Figure 2) that combined image sensing and processing on a single chip (Bishop & Fuchs, 1984). The idea was to combine multiple instances of these chips into an outward-looking cluster that estimated cluster motion by observing natural features in the un-modified environment. Integrating the resulting motion to estimate pose is prone to accumulating error, so further development required a complementary system based on easily detectable landmarks (LEDs) at known locations. This LED-based system was the subject of a 1990 dissertation by Jih-Fang Wang (Wang, 1990).

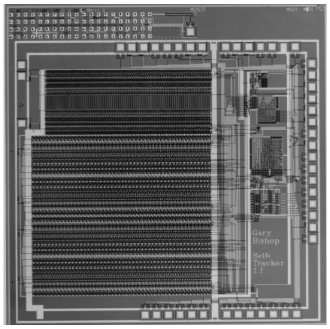

Figure 2

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[1] We use the word *pose* to indicate both position and orientation (six degrees of freedom).

Figure 3

In 1991 we demonstrated a working scalable electro-optical head-tracking system in the *Tomorrow's Realities* gallery at that year's ACM SIGGRAPH conference (J.-F. Wang et al., 1990; Wang, Chi, & Fuchs, 1990; Ward et al., 1992). The system (Figure 3) used four head-worn lateral effect photo-diodes that looked upward at a regular array of infrared LEDs installed in precisely machined ceiling panels. A user-worn backpack contained electronics that digitized and communicated the photo-coordinates of the sighted LEDs. Photogrammetric techniques were used to compute a user's head pose using the known LED positions and the corresponding measured photo-coordinates from each LEPD sensor (Azuma & Ward, 1991). The system was ground-breaking in that it was unaffected by ferromagnetic and conductive materials in the environment, and the working volume of the system was determined solely by the number of ceiling panels. (See Figure 3, top.)

1.3 The HiBall Tracking System

In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system.

As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy-chained together for head or hand tracking, pose-aware input devices, or precise 3D point digitization throughout the entire working volume.

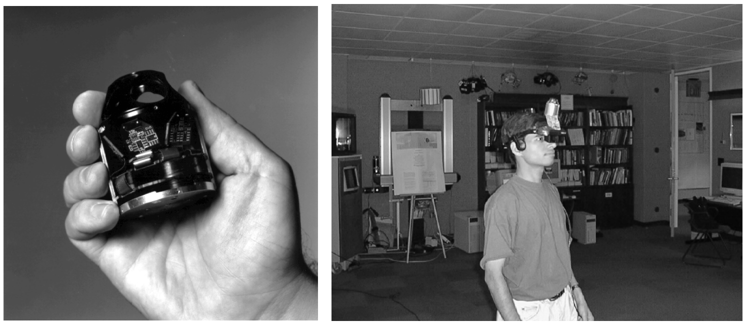
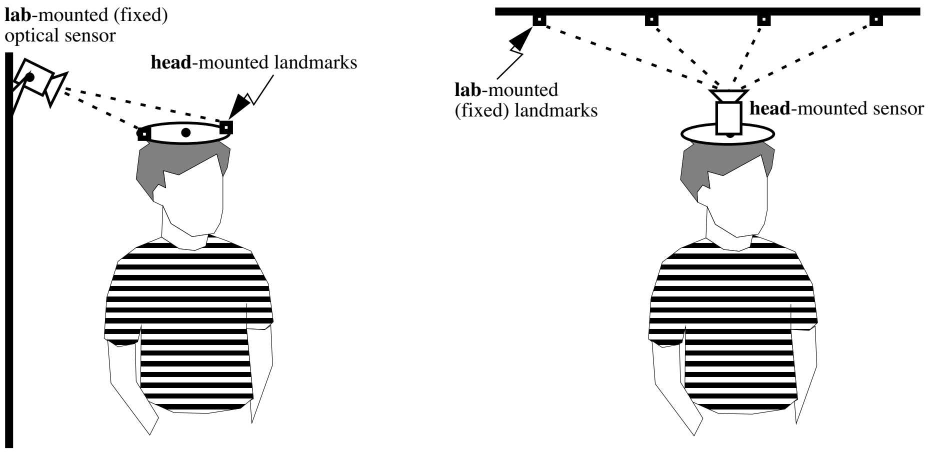


Figure 4

2. DESIGN CONSIDERATIONS

In all of the optical systems we have developed (see Section 1.2) we have chosen what we call an *inside-looking-out* configuration, where the optical sensors are on the (moving) user and the *landmarks* (e.g., LEDs) are fixed in the laboratory. The corresponding *outside-looking-in* alternative would be to place the landmarks on the user, and to fix the optical sensors in the laboratory. (One can think about similar outside-in and inside-out distinctions for acoustic and magnetic technologies.) The two configurations are depicted in Figure 5.



Outside-Looking-In Inside-Looking-Out

Figure 5

There are some disadvantages to the inside-looking-out approach. For small or medium-sized working volumes, mounting the sensors on the user is more challenging than mounting them in the environment. It is difficult to make user-worn sensor packaging small, and communication from the moving sensors to the rest of the system is more complex. In contrast, there are fewer mechanical considerations when mounting sensors in the environment for an *outside-looking-in* configuration. Because landmarks can be relatively simple, small, and cheap, they can often be located in numerous places on the user, and communication from the user to the rest of the system can be relatively simple or even unnecessary. This is particularly attractive for full-body motion capture (BL, 2000; MAC, 2000).

However there are some significant advantages to the inside-looking-out approach for head tracking. By operating with sensors on the user rather than in the environment, the system can be scaled indefinitely. The system can evolve from using dense active landmarks to fewer, lower signal-to-noise ratio, passive, and some day natural features for a Self-Tracker that operates entirely without landmark infrastructure (Bishop, 1984; Bishop & Fuchs, 1984; Welch, 1995).

The inside-looking-out configuration is also motivated by a desire to maximize sensitivity to changes in user pose. In particular, a significant problem with an outside-looking-in configuration is that only position estimates can be made directly, and so orientation must be inferred from position estimates of multiple fixed landmarks. The result is that orientation sensitivity is a function of both the *distance to the landmarks* from the sensor and the *baseline between the landmarks* on the user. In particular, as the distance to the user increases or the baseline between the landmarks decreases the sensitivity goes down. For sufficient orientation sensitivity one would likely need a baseline that is considerably larger than the user's head. This would be undesirable from an ergonomic standpoint and could actually restrict the user's motion.

With respect to translation, the change in measured photo-coordinates is the same for an environment-mounted (fixed) sensor and user-mounted (moving) landmark as it is for a user-mounted sensor and an environment-mounted landmark. In other words, the translation and corresponding sensitivity are the same for either case.

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