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8. “*An Open Software Architecture for Virtual Reality Interaction*” by Gerhard Reitmayr and Dieter Schmalstieg on March 25, 2002, in Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST '01). Association for Computing Machinery, New York, NY, USA, 47-54. DOI:<https://doi.org/10.1145/505008.505018>. Exhibit 1 is a true and correct copy of this paper.



9. The conference started on November 15, 2001, and the paper would have been available to the conference attendees on this date.

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I declare under penalty of perjury that the foregoing statements are true and correct.

Executed on: January 28, 2022



Scott Delman, Director of Publications

Exhibit 1

An Open Software Architecture for Virtual Reality Interaction

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ABSTRACT

This article describes OpenTracker, an open software architecture that provides a framework for the different tasks involved in tracking input devices and processing multi-modal input data in virtual environments and augmented reality application. The OpenTracker framework eases the development and maintenance of hardware setups in a more flexible manner than what is typically offered by virtual reality development packages. This goal is achieved by using an object-oriented design based on XML, taking full advantage of this new technology by allowing to use standard XML tools for development, configuration and documentation. The OpenTracker engine is based on a data flow concept for multi-modal events. A multi-threaded execution model takes care of tunable performance. Transparent network access allows easy development of decoupled simulation models. Finally, the application developer's interface features both a time-based and an event based model, that can be used simultaneously, to serve a large range of applications. OpenTracker is a first attempt towards a "write once, input anywhere" approach to virtual reality application development. To support these claims, integration into an existing augmented reality system is demonstrated. We also show how a prototype tracking equipment for mobile augmented reality can be assembled from consumer input devices with the aid of OpenTracker. Once development is sufficiently mature, it is planned to make OpenTracker available to the public under an open source software license.

Keywords

Tracking, Mobile Augmented Reality, Virtual Reality, XML

1. INTRODUCTION

Tracking is an indispensable part of any Virtual Reality (VR) and Augmented Reality (AR) application. While the need for quality of tracking, in particular for high perfor-

mance and fidelity, have led to a large body of past and current research, little attention is typically paid to software engineering aspects of tracking software. Some current systems have a modular approach that allows to substitute one type of tracking device for another. Typically, this is the approach taken by commercial VR products that offer turn-key support for many popular tracking and input devices, but at the cost of a limited amount of extensibility and configuration options. In particular, they make it hard to combine existing features in novel ways.

In contrast, research systems may offer features not found in commercial systems, such as prediction or sensor fusion, but are usually limited to their particular research domain and not intended for the end user. In such systems, replacing a piece of hardware or changing its configuration usually leads to rewriting a significant portion of the tracker software.

In the middle(-ware), there is a lack of tools that allow for a high degree of customization, yet are easy to use and to extend. One notable exception is the MR toolkit [21] of the University of Alberta, which still serves as a starting point for many VR research projects despite its aged architecture and lack of active development. What is needed is a system that allows mixing and matching of different features, as well as simple creation and maintainance of possibly complex tracker configurations.

In this article, we describe a tracking software system called *OpenTracker* with the following characteristics:

- An object-oriented approach to an extensive set of sensor access, filtering, fusion, and state transformation operations
- Behavior specification by constructing graphs of tracking objects (similar in spirit to scene graphs or event cascades) from user defined tracker configuration files
- Distributed simulation by network transfer of events at any point in the graph structure
- Decoupled simulation by transparent multi-threading and networking
- A software engineering approach based on XML [4], which allows to use many generic tools such as [2, 11, 10] for development, documentation, integration and configuration
- An application independent library to be integrated into software projects

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VRST'01, November 15-17, 2001, Banff, Alberta, Canada.
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Through its scripting capability (tracker configuration files) as well as easy integration of new tracking features, *OpenTracker* encourages exploratory construction of complex tracking setups. It is equally useful for end users, which can fully exploit their hardware without any custom programming, as well as developers, who can easily build test environments. The modular approach gives instant access to wide range of tracking related functionality for any application. Through the release under the LGPL Open Source license [7], *OpenTracker* is available to a larger audience.

2. RELATED WORK

Ideas implemented in *OpenTracker* were drawn from several areas:

Device abstraction is a standard requirement for 2D graphical user interfaces, (e. g. GKS [12]), and sometimes incorporated into 3D applications [9]. There is a number of libraries such as VRPN [15], MRTToolkit [21] implementing device abstraction for input devices typically found in VR and AR systems. Their main goal is to provide a fixed interface to the application for different devices and provide simple services for relaying the data over the network between several hosts. However, these libraries mostly lack any further means to process the data. Device abstraction is also an important goal of *OpenTracker*. However, it goes beyond pure abstraction using a static interface in that the data can be re-combined in novel ways.

Many interactive systems employ sophisticated event handling schemes. State changes to attributes of scene objects are either propagated through functional dependencies (e. g. routes in VRML [5], engines in Open Inventor [22]), or may be handled by user supplied callback functions (e. g. script nodes in VRML [5]). These approaches inspire the architecture of *OpenTracker*, although none of them deals specifically with tracker configurations.

Finally, an important requirement for virtual environments is support for distributed simulation, partly to support simultaneous users, partly to better exploit available hardware. Decoupled simulation was first introduced in MR [21], and later used in almost any major VR software system. Decoupled simulation can either be implemented by multithreading and/or symmetric multiprocessing on one host, or by configuring a small set of hosts to work as an ensemble. The latter approach may be inferior performance-wise because of network lag, but it is inexpensive and flexible, and thus favored by many researchers - for example, Rekimoto's "hyperdragging" system [19] uses a distributed architecture very much like our own.

3. DATA FLOW OF TRACKING DATA

In a typical VR or AR application tracking data passes through a series of steps. It is generated by tracking hardware, read by device drivers, transformed to fit the requirements of the application and send over network connections to other hosts. Different setups and applications may require different subsets and combinations of the steps described but the individual steps are common among a wide range of applications. Examples of such invariant steps are geometric transformations, Kalman filters and data fusion of two data sources.

The main concept behind *OpenTracker* is to break up the whole data manipulation into these individual steps and

build a data flow network of the transformations. To describe the details of this concept, we will need some theoretical definitions which are discussed in section 3.1. Details of an actual implementation are described in section 3.2.

3.1 Data Flow Concept

Each transformation is represented by a node in a data flow graph. Nodes are connected by directed edges to describe the direction of flow. The originating node of a directed edge is called the child whereas the receiving node is called the parent. To allow more than simple linear graphs, we introduce the following concepts.

Multiple Input Ports and References

Each node has one or more input ports and a single output port. A port is a distinguished connection point for an edge, i.e. the node can distinguish between events passing through different node ports. The output port of one node is connected to any of the input ports of another node. This establishes the flow by defining directed edges in the graph. A node receiving a new data event via one of its inputs computes a new update for itself and sends the new data event out via its output port.

Multiple input ports are desirable because computations typically have more than one parameter. Dynamic transformations, for example, are parameterized by the value of another node and thus use the data value received by a child to be transformed differently from the data of the parameterizing child. Merge nodes may select part of the data of an event based on the input port the event used. This allows more complex computational structures.

Additionally, an input port can be connected to several output ports. This enables several children nodes connected to the same input port of a node. Upon receiving an event, the parent node can only distinguish between the input ports, not between the actual children.

Conversely, an output port can also be connected to other nodes by using references within the graph. This establishes new edges between a nodes output port and other nodes input ports. However this is transparent to the child node. It cannot selectively send events to only one parent, but all events are distributed equally to all parents.

Edge types

The basic mechanism behind the data flow concept is event passing. Data events are passed from the children nodes upward to their parents. However, not all computations fit well into this model: Algorithms that operate on a vector of tracker measurements or that require or compute the tracker state at an arbitrary point in time require different types of input or output interfaces. Examples are smoothing algorithms that take a history of events into account, or prediction algorithms that compute an expected measurement for a given point in time.

Therefore, we also distinguish between different edge types. Edges are typed by typing the ports of the nodes they connect. We establish the rule that only two ports of the same type can be connected and this type is then the type of the edge. There are three edge types: *event*, which is implemented by event passing, *event queue* and *time dependent*. The latter two are implemented as interfaces that are polled by the parent node, because the data returned is parameterized. In the case of the *event queue* interface, it is possible to query the number of stored events and retrieve them by index. The *time dependent* interface can be queried by spe-

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