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8. *"SCAAT: incremental tracking with incomplete information"* by Greg Welch and Gary Bishop on August 3, 1997, in Proceedings of the 24th annual conference on Computer graphics and interactive techniques, (SIGGRAPH '97). ACM Press/Addison-Wesley Publishing Co., USA, 333–344. DOI:https://doi.org/10.1145/258734.258876. Exhibit 1 is a true and correct copy of this paper.

9. The conference started on August 3, 1997, and the paper would have been available to the conference attendees on this date.

10. I hereby declare that all statements made herein of my own knowledge are true and that allstatements made on information and belief, are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under 18 U.S.C. § 1001.

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

Executed on: December 20, 2021

Scott Delman, Director of Publications

Exhibit 1

SCAAT: Incremental Tracking with Incomplete Information

Greg Welch and Gary Bishop

University of North Carolina at Chapel Hill[†]

Abstract

We present a promising new mathematical method for tracking a user's pose (position and orientation) for interactive computer graphics. The method, which is applicable to a wide variety of both commercial and experimental systems, improves accuracy by properly assimilating sequential observations, filtering sensor measurements, and by concurrently autocalibrating source and sensor devices. It facilitates user motion prediction, multisensor data fusion, and higher report rates with lower latency than previous methods.

Tracking systems determine the user's pose by measuring signals from low-level hardware sensors. For reasons of physics and economics, most systems make multiple sequential measurements which are then combined to produce a single tracker report. For example, commercial magnetic trackers using the SPASYN (*Space Synchro*) system sequentially measure three magnetic vectors and then combine them mathematically to produce a report of the sensor pose.

Our new approach produces tracker reports as each new low-level sensor measurement is made rather than waiting to form a complete collection of observations. Because single observations under-constrain the mathematical solution, we refer to our approach as single-constraint-at-a-time or SCAAT tracking. The key is that the single observations provide some information about the user's state, and thus can be used to incrementally improve a previous estimate. We recursively apply this principle, incorporating new sensor data as soon as it is measured. With this approach we are able to generate estimates more frequently, with less latency, and with improved accuracy. We present results from both an actual implementation, and from extensive simulations.

CR Categories and Subject Descriptors: I.3.7 [Computer Graphics] Three-Dimensional Graphics and Realism—Virtual reality; I.4.4 [Image Processing] Restoration—Kalman filtering; I.4.8 [Image Processing] Scene Analysis—Sensor fusion; G.0 [Mathematics of Computing] General—Numerical Analysis, Probability and Statistics, Mathematical Software.

Additional Key Words and Phrases: virtual environments tracking, feature tracking, calibration, autocalibration, delay, latency, sensor fusion, Kalman filter.

1 INTRODUCTION

The method we present requires, we believe, a fundamental change in the way people think about estimating a set of unknowns in general, and tracking for virtual environments in particular. Most of us have the preconceived notion that to estimate a set of unknowns we need as many constraints as there are degrees of freedom at any particular instant in time. What we present instead is a method to constrain the unknowns *over time*, continually refining an estimate for the solution, a *single constraint at a time*.

For applications in which the constraints are provided by real-time observations of physical devices, e.g. through measurements of sensors or visual sightings of landmarks, the SCAAT method isolates the effects of error in individual measurements. This isolation can provide improved filtering as well as the ability to individually calibrate the respective devices or landmarks concurrently and continually while tracking. The method facilitates user motion prediction, multisensor or multiple modality data fusion, and in systems where the constraints can only be determined sequentially, it provides estimates at a higher rate and with lower latency than multiple-constraint (batch) approaches.

With respect to tracking for virtual environments, we are currently using the SCAAT method with a new version of the UNC wide-area optoelectronic tracking system (section 4). The method could also be used by developers of commercial tracking systems to improve their existing systems or it could be employed by end-users to improve custom multiple modality hybrid systems. With respect to the more general problem of estimating a set of unknowns that are related by some set of mathematical constraints, one could use the method to trade estimate quality for computation time. For example one could incorporate individual constraints, one at a time, stopping when the uncertainty in the solution reached an acceptable level.

1.1 Incomplete Information

The idea that one might build a tracking system that generates a new estimate with each individual sensor measurement or *observation* is a very interesting one. After all, individual observations usually provide only partial information about a user's complete state (pose), i.e. they are "incomplete" observations. For example, for a camera observing landmarks in a scene, only limited information is obtained from observations of any single landmark. In terms of control theory, a system designed to operate with only such incomplete measurements is characterized as *unobservable* because the user state cannot be observed (determined) from the measurements.

The notion of observability can also be described in terms of constraints on the unknown parameters of the system being estimated, e.g. constraints on the unknown elements of the system state. Given a particular system, and the corresponding set of unknowns that are to be estimated, let C be defined as the minimal number of independent simultaneous constraints necessary to uniquely determine a solution, let N be the number actually used to generate a new estimate, and let N_{ind} be the number of *independent* constraints that can be formed from the N constraints. For any $N \geq N_{\text{ind}}$ constraints, if $N_{\text{ind}} = C$ the problem is *well constrained*, if $N_{\text{ind}} > C$ it is *over constrained*, and if $N_{\text{ind}} < C$ it is *under-constrained*. (See Figure 1.)

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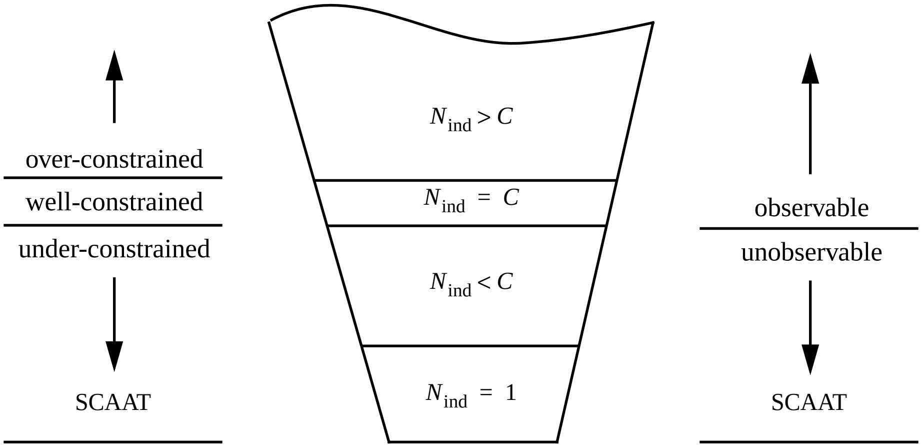

Figure 1: SCAAT and constraints on a system of simultaneous equations. C is the minimal number of independent simultaneous constraints necessary to uniquely determine a solution, N is the number of given constraints, and N_{ind} is the number of *independent* constraints that can be formed from the N. (For most systems of interest $C > 1$). The conventional approach is to ensure $N \geq N_{\mathrm{ind}}$ and $N_{\mathrm{ind}} \geq C$, i.e. to use enough measurements to well-constrain or even over-constrain the estimate. The SCAAT approach is to employ the smallest number of constraints available at any one time, generally $N = N_{\mathrm{ind}} = 1$ constraint. From this viewpoint, each SCAAT estimate is severely under-constrained.

1.2 Landmark Tracking

Consider for example a system in which a single camera is used to observe known scene points to determine the camera position and orientation. In this case, the constraints provided by the observations are multi-dimensional: 2D image coordinates of 3D scene points. Given the internal camera parameters, a set of four known coplanar scene points, and the corresponding image coordinates, the camera position and orientation can be uniquely determined in closed-form [16]. In other words if $N = C = 4$ constraints (2D image points) are used to estimate the camera position and orientation, the system is completely observable. On the other hand, if $N < C$ then there are multiple solutions. For example with only $N = 3$ non-collinear points, there are up to 4 solutions. Even worse, with $N = 2$ or $N = 1$ points, there are infinite combinations of position and orientation that could result in the same camera images.

In general, for closed-form tracking approaches, a well or over-constrained system with $N \geq C$ is observable, an under-constrained system with $N < C$ is not. Therefore, if the individual observations provide only partial information, i.e. the measurements provide insufficient constraints, then multiple devices or landmarks must be excited and (or) sensed prior to estimating a solution. Sometimes the necessary observations can be obtained simultaneously, and sometimes they can not. Magnetic trackers such as those made by Polhemus and Ascension perform three *sequential* source excitations, each in conjunction with a complete sensor unit observation. And while a camera can indeed observe multiple landmarks simultaneously in a single image, the image processing to identify and locate the individual landmarks must be done sequentially for a single CPU system. If the landmarks can move independently over time, for example if they are artificial marks placed on the skin of an ultrasound patient for the purpose of landmark-based tracking [41], batch processing of the landmarks can reduce the effectiveness of the system. A SCAAT implementation might grab an image, extract a *single* landmark, update the estimates of both the camera *and* landmark positions, and then throw-away the image. In this way estimates are generated faster and with the most recent landmark configurations.

1.3 Putting the Pieces Together

Given a tracker that uses multiple constraints that are each individually incomplete, a *measurement model* for any one of incomplete constraints would be characterized as *locally unobservable*. Such a system must incorporate a sufficient set of these incomplete constraints so that the resulting overall system is observable. The corresponding aggregate measurement model can then be characterized as *globally observable*. Global observability can be obtained over *space* or over *time*. The SCAAT method adopts the latter scheme, even in some cases where the former is possible.

2 MOTIVATION

2.1 The Simultaneity Assumption

Several well-known virtual environment tracking systems collect position and orientation constraints (sensor measurements) sequentially. For example, tracking systems developed by Polhemus and Ascension depend on sensing a sequence of variously polarized electromagnetic waves or fields. A system that facilitated simultaneous polarized excitations would be very difficult if not impossible to implement. Similarly both the original UNC optoelectronic tracking system and the newer HiBall version are designed to observe only one ceiling-mounted LED at a time. Based on the available literature [25,27,37] these systems currently assume (mathematically) that their sequential observations were collected simultaneously. We refer to this as the *simultaneity assumption*. If the target remains motionless this assumption introduces no error. However if the target is moving, the violation of the assumption introduces error.

To put things into perspective, consider that typical arm and wrist motion can occur in as little as 1/2 second, with typical “fast” wrist tangential motion occurring at 3 meters/second [1]. For the current versions of the above systems such motion corresponds to approximately 2 to 6 centimeters of translation *throughout* the sequence of measurements required for a single estimate. For systems that attempt sub-millimeter accuracies, even slow motion occurring during a sequence of sequential measurements impacts the accuracy of the estimates.

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