Extended-Range Hybrid Tracker and Applications to Motion and Camera Tracking in Manufacturing Systems

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***Abstract*—Extended- or long-range tracking effectiveness is crucial for the automation of manufacturing systems. In this paper, we conceptualize and develop a prototype long-range hybrid tracker based on a combination of a laser tracker and a magnetic tracker and apply the concept to the following two applications: 1) extended-range human motion tracking on factory floors and 2) factory floor object reconstruction from camera images. The easily portable system not only utilizes the strengths of a laser tracker in tracking mobile objects over long ranges in large environments, such as a manufacturing shop floor and the strength of a magnetic tracker to compensate for violation of line-of-sight constraint, but it also reduces the overall cost by reducing the number of expensive beacons required by the laser tracker. The hybrid tracker assists in the development of two concepts: 1) real-time synchronization of human head and hand motion in a manufacturing environment with those of an avatar in a virtual manufacturing environment and 2) a mathematically simpler and practical camera self-calibration technique for the creation of three-dimensional objects in a virtual environment from camera images.**

***Index Terms*—Hybrid tracker, laser tracking, magnetic tracking, stereo reconstruction, virtual reality applications.**

I. INTRODUCTION

AUTONOMOUS navigation of mobile robots and material handling equipment (such as automated guided vehicles or forklifts) is often a prerequisite for automation of manufacturing systems. In order to achieve autonomous navigation of such components of manufacturing systems, they need to know at any time where they are located within the environment, with respect to a global coordinate system [20]. Similarly, in virtual reality (VR)-aided manufacturing systems design and maintenance applications, it is necessary to capture the motion of human participants in order to replicate it on avatars within virtual environments (VE's) representing specific manufacturing systems. This motion has to be often captured over a longer range than the ranges of current tracking systems for VR applications. A survey of the existing position trackers used in VR can be found in [12] and [25].

Currently, extended-range trackers are employed for tracking mobile robots [7], [23], [13]. The most widely used long-range tracking systems in robotics are active beacon systems. The biggest disadvantage of active beacon navigation systems is the line-of-sight constraint (LOS) [7]. There may be instances when tracking a certain part (such as the end-effector) of a robot is necessary, and this part cannot be visible to the tracking system, unless multiple beacons are placed within the motion environment, thus increasing substantially the cost of the tracking system.

In VR applications, the task of a tracker is to report the position and orientation of a user's head and hand. Accordingly, the VR system updates the perspective display to make it consistent with the user's viewpoint. There are multiple types of tracking systems used in VR: magnetic, optical, mechanical, acoustic, and inertial. Each of these trackers has advantages and disadvantages. For example, magnetic trackers have no LOS constraints, but their accuracy decreases dramatically with increase in distance from transmitter and is also influenced by metallic objects in the neighborhood. Optical trackers are very fast and accurate, and they are also immune to magnetic interference, but their use is restricted by the LOS constraint. Mechanical trackers, based on linkages, are very accurate, but their work is severely restricted within a small-range volume (determined by the geometry of linkages). Acoustic (ultrasonic) trackers are relatively cheap and accurate, but they also have limited range and LOS restriction.

The above considerations suggest combining some of the advantages offered by individual tracking systems to design a hybrid tracker for autonomous navigation in real manufacturing environments and human motion in VE's. In this paper, a hybrid tracker, based on a combination between a laser tracker and a magnetic tracker, is described. The laser tracker used is an active beacon system[1] [36], and the magnetic tracker employed is called MotionStar[2] [37]. The laser tracker has the advantage of enabling accurate tracking of position and orientation over long ranges (the system we use has a maximum range of 100 m, but through serialization of multiple such systems, unlimited range can be obtained). The magnetic tracker enables tracking of multiple parts of an object without problems due to occlusion. Moreover, when the LOS constraint for the laser tracker is temporarily violated, the magnetic tracker can compensate for it. This is an important advantage since it reduces the number of beacons or landmarks that have to be placed within the environment, thus reducing substantially the cost of tracking systems.

This paper is organized as follows. Related work in hybrid tracking is discussed in Section II. Section III describes the geometry of the hybrid (laser and magnetic) tracking system.

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[1] CONAC by MTI Research, Westford, MA 01886 USA.

[2] Manufactured by Ascension Technologies Corporation, Burlington, VT 05402 USA.

Section IV describes the application of the proposed hybrid tracker to motion tracking during real-time synchronization of real environments and VE's. Section V covers three-dimensional (3-D) object reconstruction from camera images and describes our camera self-calibration procedure using extended-range tracking. Section VI is devoted to conclusions and future directions.

II. RELATED WORK

Due to their contribution to the end-to-end latency of VR systems, tracking systems have received a great deal of attention among VR research community. Hybrid tracking has been explored mostly in the area of augmented reality (AR), where accurate registration between real environment and virtual objects superimposed on it is critical. In [2], the need for hybrid tracking in AR is stressed, especially for outdoors applications. Most of the tracking in AR is being performed with the aid of video cameras, by tracking fiducial marks (placed at known locations in the environment) using computer vision techniques. Despite the accuracy of these techniques, they are slow (due to the necessity of searching the marks by scanning the image pixel by pixel), their range is limited by the placement of the fiducial marks and are not robust to occlusions of the fiducial marks. In [26], a hybrid tracker is described, which combines computer vision-based tracking with inertial tracking. Since it is well known that inertial trackers exhibit drift with time (their errors increase over time [3]), their output is corrected by using vision-based tracking. Another hybrid system has been proposed in [17], where it has been proven that by combining two types of vision-based tracking, called "inside-out" (camera(s) mounted on the head of the user and fiducials mounted at known locations in the environment) and "outside-in" (cameras mounted at known locations in the environment and fiducials mounted on the user's head), the uncertainty in head pose (position and orientation) estimation is considerably decreased. In [28], the accuracy of a magnetic tracker is improved by augmenting it with a passive image-based system that observes known fiduciary marks in the real world. At the same time, the magnetic tracker measurements help in reducing the search area of the fiducials in two-dimensional (2-D) images captured by head-mounted cameras, thus reducing the latency of the hybrid tracker. Other hybrid systems have been previously proposed in [5], [9], and [14]. For example, in [5] and [9], combinations between inertial and optical technologies are described in terms of accuracy and end-to-end latency. In [14], an inertial system is aided by angular position sensors. None of these applications address the problem of tracking motion in large environments, such as a factory floor. For this kind of application, active beacon systems are very suitable, due to their accuracy and extended range but, due to the LOS constraint, usually a large number of beacons has to be mounted on the factory floor. We overcome this disadvantage by using a magnetic tracker in combination with a laser tracker.

III. DESCRIPTION OF THE HYBRID TRACKING SYSTEM AND GENERIC METHODOLOGY FOR MOTION TRACKING

As mentioned in Sections I and II, our hybrid tracker for motion tracking is a combination of a laser tracker and a magnetic one. The laser tracker provides high accuracy and update rate for high ranges (0–100 m), but its use is restricted by the LOS constraint. On the other hand, the magnetic tracker does not require LOS, but it is accurate only within small working volumes. The laser tracker is based on triangulation of laser signals emitted by two beacons and received by one or more position transponders (PT's), attached to the moving object. One PT can report only the position with respect to one beacon so, in order to retrieve the orientation, one has to employ three PT's rigidly mounted on a special fixture. The advantage of using a magnetic tracker is its suitability to applications with frequent occlusions between transmitter and receiver. The magnetic tracker employed in our tracker uses pulsed direct current (dc) magnetic fields instead of alternate current (ac) magnetic fields (which are being used by Polhemus, Inc. magnetic trackers and older versions of Ascension Technologies trackers). DC fields are significantly less susceptible to metallic distortion than ac fields. However, dc-based magnetic trackers are susceptible to interference with magnetic fields generated by ferromagnetic objects (such as computer monitors or dc motors, see [27]). Even though it is hard to estimate up front the probability of encountering such objects during a motion sequence, it is reasonable to assume that in most cases the wearer of a magnetic tracker will not be in the immediate proximity of ferromagnetic objects that would catastrophically affect the tracker's output. Overall, by weighing its advantages, the dc-based magnetic tracker remains a reliable magnetic tracker for motion capture in manufacturing environments. By using a Kalman filter [19] to minimize the external effects on its performance, reasonable results can be obtained, as will be seen later in this paper. The advantages of incorporating a magnetic tracker into our hybrid tracker are as follows.

It can track multiple targets without worrying about occlusions between transmitter and receivers.

Since its behavior is not influenced by an LOS constraint, the magnetic tracker can be used as a backup, when the LOS between laser tracker's beacons and PT's is temporarily occluded. This enables reduction in the number of beacons (landmarks) used for motion tracking, thus reducing the cost of the tracking system. Details are provided below.

Typically, magnetic tracker's receivers are placed on components whose motion trajectories have to be captured and cannot be "seen" all the time by beacons of the laser tracker. The PT's of the laser tracker are mounted on the moving objects, in a location that is always visible to the transmitting beacons. The positions of the tracked components (i.e., the components equipped with a magnetic receiver) are reported either with respect to a beacon's coordinate system or to a coordinate system attached to the motion environment, termed world coordinate system (WCS) (in this case, the transformation between the WCS and beacon coordinate systems is known *a priori*). For this purpose, one of the magnetic receivers is rigidly attached to the PT's, so the transformation between this receiver and PT's is invariant as the tracked object moves. The magnetic transmitter is also placed on the moving object.

The described hybrid tracker has the advantage of being easily portable, unlike other trackers currently in use, such as UNC HiBall [31], which requires a large number of beacons (LED's) mounted on the ceiling and whose range is limited

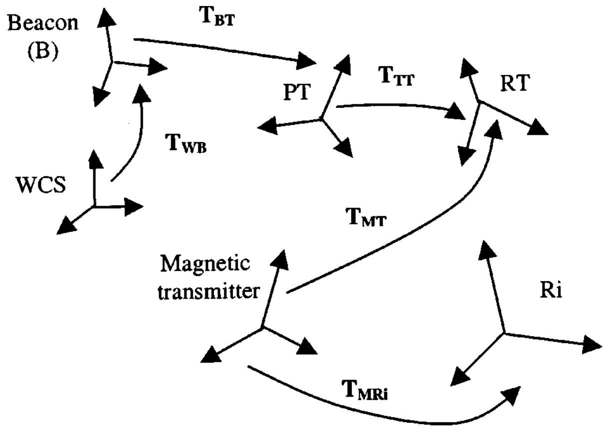

Fig. 1. Geometry of the hybrid tracker.

by the number of such beacons. The tracker described in [31] has the advantage that, by mounting a large number of closely located LED's on the ceiling, one will have less problems with LOS but, in order to increase the tracking range, the cost of the system rises significantly, and the system becomes less portable. By being equipped with only two stationary beacons (at least for now), our tracking system is expected to be more susceptible to LOS problems. By mounting the beacons in optimal locations (to minimize the likelihood of violating the LOS constraint) and by using also the magnetic tracker to aid the laser tracker temporarily (when the LOS constraint is violated), we expect the impact of LOS problems to be minimal. The following two questions arise. 1) How accurate are the tracker outputs when the magnetic tracker aids in circumventing LOS problems? 2) For how long can the violation of the LOS constraint be tolerated so that the position estimates fall within acceptable accuracy limits? These questions will be addressed through an example in Section IV.

The generic geometry of our hybrid tracker is depicted in Fig. 1. In this figure, the case when the positions of the tracked components are reported with respect to a WCS is illustrated. Note that in Fig. 1, only one beacon (B) of the laser tracking system is shown. In reality, the laser tracker has two beacons, but the position is reported with respect to a coordinate system associated with one of the beacons, so in order to simplify the figure, only this beacon is shown. The notations employed in Fig. 1 are summarized in Table I.

In Fig. 1, only one tracked component (denoted Ri) is shown, for the purpose of clarity. Our hybrid tracker can track as many components as the magnetic tracker allows (up to 40 targets).

The position of the tracked component Ri, w.r.t. WCS, is represented by the vector $\mathbf{x} = (x, y, z)^T$, and w.r.t. the magnetic transmitter is given by $\mathbf{x_m} = (x_m, y_m, z_m)^T$. As can be seen from Fig. 1, $\mathbf{x}$ and $\mathbf{x_m}$ can be related by the following equation:

$$\mathbf{x} = \mathbf{T_{MT}}^{-1}\mathbf{T_{TT}}\mathbf{T_{BT}}\mathbf{T_{WB}}\mathbf{x_m}. \tag{1}$$

The vector $\mathbf{x_m}$ is measured by the receiver Ri w.r.t. the magnetic transmitter. So (1) is the basic equation for tracking a component within WCS. For tracking the object globally (as a whole), only PT is used, therefore the magnetic tracker is not needed (unless the LOS constraint is violated). The hybrid tracker described here can track an unlimited number of moving objects. For each object, a distinct set of PT's and a separate magnetic tracker is needed. The examples provided in this paper consider only a single tracked object, without loss of any generality.

TABLE I
EXPLANATION OF NOTATIONS IN FIG. 1

Notation	Meaning
$\mathbf{T_{WB}}$	Transformation matrix from WCS to the coordinate system associated with the laser tracker (attached to one of the beacons); it is known a priori;
PT	Position transponders coordinate system; it is coincident with the center of the circle circumscribing the three PTs (hereafter, when we mention position transponders, we refer to this particular point associated with them);
$\mathbf{T_{BT}}$	Coordinate transformation matrix between beacon(B) and PT
RT	Magnetic receiver rigidly attached to PTs
$\mathbf{T_{TT}}$	Invariant transformation matrix between PT coordinate system and magnetic receiver rigidly attached to PTs (RT)
$\mathbf{T_{MT}}$	Coordinate transformation matrix between the magnetic transmitter and RT
Ri	Magnetic receiver mounted on a tracked component
$\mathbf{T_{MRi}}$	Coordinate transformation matrix between the magnetic transmitter and Ri (not used, but defined for the purpose of clarity)

A. *Hybrid Tracker Precalibration*

In order to compute the position of a tracked component with respect to WCS, one needs the transformation between PT coordinate system and the coordinate system associated with the magnetic receiver that is rigidly attached to the PT's (labeled RT in Fig. 1). This transformation is labeled $\mathbf{T_{TT}}$ in Fig. 1 and is invariant as the PT-RT ensemble moves. In order to compute $\mathbf{T_{TT}}$, precalibration of the hybrid tracker is performed before starting the motion tracking process. The geometry associated with precalibration is depicted in Fig. 2.

The notations used in Fig. 2 are summarized in Table II, for a generic case, as well as for two applications that demonstrate the use of our hybrid tracker (human motion capture and camera tracking for object reconstruction—applications described in Sections IV and V, respectively). In Fig. 2, the coordinate transformations and coordinate systems specific only to (or at least closely related to) camera tracking are written with a different font and are represented by dashed lines.

Hybrid tracker precalibration is performed as follows. The tracked object is placed in two arbitrary locations within the environment (care must be taken so that no ferromagnetic objects are located in the neighborhood to ensure that magnetic readings are not distorted), from where readings from PT's and RT are collected with the object stationary. The two consecutive positions are denoted by indices a and b in Fig. 2. The relative transformations between positions a and b can be written as in (2) and (3) below (for both PT and RT).

Let

$$\mathbf{T_{Pab}} = \mathbf{T_{BTb}}\mathbf{T_{BTa}^{-1}} \tag{2}$$

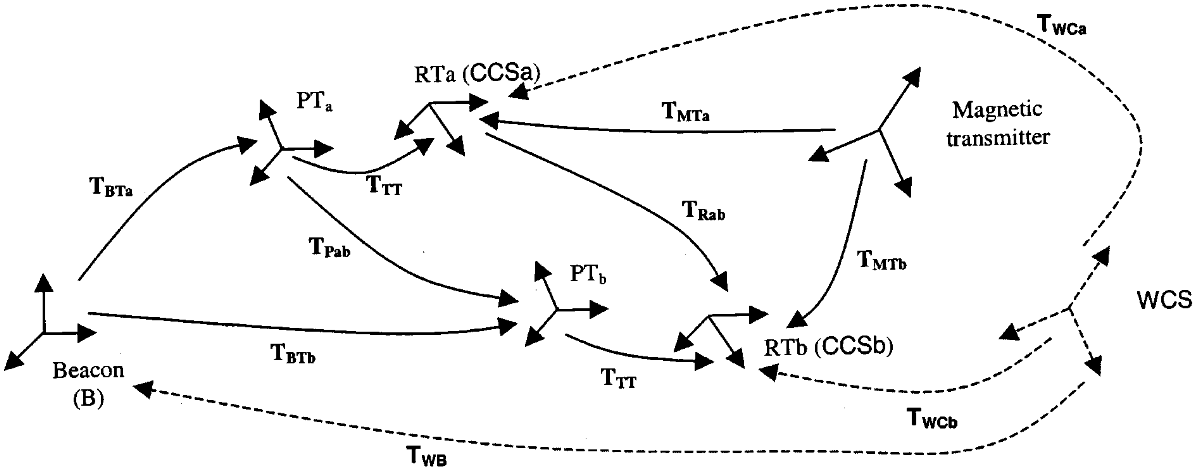

Fig. 2. Hybrid tracker precalibration setup.

and let

$$\mathbf{T_{Rab}} = \mathbf{T_{MTb}}\mathbf{T_{MTa}^{-1}}. \tag{3}$$

From Fig. 2, the following equation can be written:

$$\mathbf{T_{Rab}} = \mathbf{T_{TT}}\mathbf{T_{Pab}}\mathbf{T_{TT}^{-1}}. \tag{4}$$

Equation (4) follows from the fact that the transformations involved form a closed loop. From (4), it follows that

$$\mathbf{T_{Rab}}\mathbf{T_{TT}} = \mathbf{T_{TT}}\mathbf{T_{Pab}} \tag{5}$$

from which $\mathbf{T_{TT}}$ is computed. Equation (5) is an equation of the form AX = XB, typically encountered in hand-eye calibration in robotics applications. To solve (5), we use the method proposed in [29].

B. Violation of the LOS Constraint

In order to track all components with respect to WCS, the transformation between beacon (B) and PT coordinate system has to be known and is given by the laser tracker. In order to recover this transformation, all three PT's have to be visible at any time by both beacons of the laser tracker. In tracking mobile robots on the factory floor by using active beacon systems, usually beacons are placed at optimal locations throughout the environment [7]. This can be easily done when the paths are predefined or are expected to take place in well-known areas, but also increases the cost of tracking systems.

When a tracker is used to capture unpredictable motion (such as human motion), one cannot design *a priori* an optimal configuration of beacons to prevent violation of the LOS constraint. To get around this problem, we can use the magnetic tracker (specifically the receiver attached to PT's - RT in Fig. 1) to back-up the system when the LOS of the laser tracker is temporarily occluded. Consider again Fig. 2. Let us assume that the tracked component moves from position a to position b. In position a, all three PT's are visible, and therefore the transformation $\mathbf{T_{BTa}}$ is correctly reported. In position b, at least one PT is occluded. In this case, the transformation $\mathbf{T_{BTb}}$ can be recovered from the previous estimate of the PT's position and orientation $(\mathbf{T_{BTa}})$ and the relative motion undertaken by magnetic receiver RT (denoted as $\mathbf{T_{Rab}}$), by the following equation:

$$\mathbf{T_{BTb}} = \mathbf{T_{TT}^{-1}}\mathbf{T_{Rab}}\mathbf{T_{TT}}\mathbf{T_{BTa}}. \tag{6}$$

In (6), $\mathbf{T_{Rab}}$ is measured w.r.t. the magnetic transmitter. Equation (6) is valid when the magnetic transmitter remains fixed relative to WCS or its motion w.r.t. WCS is negligible by comparison of RT motion w.r.t. WCS. For example, when tracking human motion, the magnetic transmitter is placed on the back of the human and RT on the user's head. When the human operator bends (and thus PT's are not visible from the beacons), the magnetic transmitter remains relatively fixed. The potential violation of this assumption is considered while designing the Kalman filter that deals with LOS constraint violations (described in Section IV), by scaling up the measurement noise uncertainty.

C. Operating the Hybrid Tracker

When retrieving position and orientation information by fusing data provided by two or more sensors, typically the assumption that measurements are available simultaneously from all sensors is made. In reality, this is almost never the case, due to different update rates of the various sensors. In our case, measurements from the laser and magnetic trackers are fed to a 300-MHz Pentium PC via serial cables and from there to an SGI workstation that performs all the calculations for position and orientation estimates. Since tracking is initiated only when the first data packet arrives from both sensors, communication overhead is not relevant for the time increment between two consecutive measurements. The interval between two measurements of the laser tracker is 22 ms. When using a single receiver, the update rate of the magnetic tracker is 5 [ms] and increases by the same amount as a new receiver is added. The temporal diagram shown in Fig. 3 depicts the succession of measurement packets as those arrive to the SGI workstation when using three receivers of the magnetic tracker (in this case the update rate is 15 [ms]).

As can be seen from Fig. 3, the measurements arriving from the laser and the magnetic trackers are not synchronous. This introduces an error in estimating the true position of a tracked

TABLE II
EXPLANATION OF NOTATIONS IN FIG. 2

Notation	Meaning		
	Generic	***Human motion***	***Camera tracking***
$\mathbf{PT_{a,b}}$	PT coordinate system in positions labeled *a* and *b*, respectively	Same (PTs are head-mounted)	Same
$\mathbf{T_{BTa,b}}$	Coordinate transformation matrix between beacon coordinate system (B) and PT coordinate system in positions labeled *a* and *b*, respectively	Same	Same
$\mathbf{T_{Pab}}$	Transformation undertaken by PTs from position *a* to position *b* (w.r.t. B)	Same	Same
$\mathbf{T_{Rab}}$	Transformation undertaken by receiver RT from position *a* to position *b* (w.r.t. the magnetic transmitter)	Same	Transformation undertaken by camera from position *a* to position *b*
WCS/ $\mathbf{T_{WB}}$	World Coordinate System/ Transformation between WCS and beacon (B) – used for the purpose of registering real environments with virtual environments		
CCS	Camera Coordinate System		
$\mathbf{T_{TT}}$	Invariant transformation between PT and RT (parameter to be calibrated)	Same	Invariant transformation between PT and CCS
CCSa,b	N/A	N/A	CCS in positions labeled *a* and *b*
$\mathbf{T_{Wca,b}}$	N/A	N/A	Transformation between WCS and CCSa,b
RTa,b	RT in positions labeled *a* and *b*, respectively	Head-mounted magnetic receiver in positions labeled *a* and *b*	RT in positions labeled *a* and *b*, respectively
$\mathbf{T_{MTa,b}}$	Coordinate transformation matrix between the magnetic transmitter and RT in positions labeled *a* and *b*, respectively	Same	Same

Note: In the case of camera tracking, RTa,b and CCSa,b are distinct coordinate systems. For reasons of compactness, this fact is omitted in fig. 2.

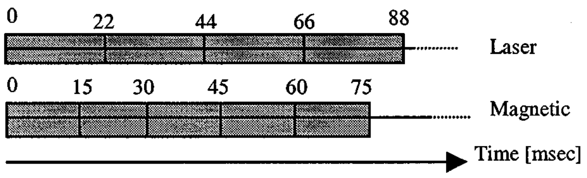

Fig. 3. Temporal diagram of the hybrid tracker measurements.

component, since it is not possible to collect a measurement from both trackers at exactly the same moment in time. The fact that there is no constant offset between readings complicates the problem. Due to the small temporal difference between measurements collected from the two sensors and due to the fact that the expected number of magnetic sensors typically used in our applications is between 2–6, the errors are not expected to be significant in comparison to the errors inflicted by the noise in the measurements. Consider the case shown in Fig. 3. In the current stage of our hybrid tracker, if in between two successive readings from the laser tracker there is only one reading from the magnetic tracker, this one is considered in the calculations. If two or more readings appear, these are first averaged to obtain a more realistic estimate.

The position of a tracked component is estimated through a Kalman filter [19]. When using Kalman filters in tracking applications, the following steps have to be performed before process initiation [8], [24]:

- identification of state variables and measurement parameters;

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