

Preface

This book had its genesis in 2003, when Dr. Lixu Gu of Shanghai Jiatong University asked whether we would consider organizing a workshop on image-guided interventions at the 2005 International Symposium on Engineering in Medicine and Biology in Shanghai, China. We agreed and our subsequent workshop included five individual speakers and covered neurological, orthopedic, and abdominal applications of image-guided interventions, with the inclusion of issues on visualization and image processing. After the symposium, Springer-Verlag approached us about editing a book on the basis of the workshop, and we decided that such a book would indeed fill a niche in the literature, but to do its justice, it would need to cover more than the original five topics.

We asked Jackie Williams to take on the role of Executive Editor, and over the next six months, we received agreement from the authors represented in this book, which includes 18 chapters divided between principles and applications. The title, “Image-Guided Interventions” was deliberately chosen over “Image-Guided Surgery” or “Minimally-Invasive Surgery and Therapy,” as it covers the widest range of both therapeutic and surgical procedures, and reflects the recognition that the basic principles covered in the first part of the book are applicable to all such procedures. In addition, the inclusion of two chapters dealing with radiation-based therapies recognizes the convergence between surgery and radiation therapy in terms of the guidance technologies.

This book is aimed at both the graduate student embarking on a career in medical imaging, and the practicing researcher or clinician who needs a snapshot of the state-of-the-art in both the principles and practice of this discipline. Accordingly, the book begins with a historical overview of the development of image guidance for medical procedures, and follows with discussions of the critical components of tracking technologies, visualization, augmented reality, image registration (both rigid and nonrigid) image segmentation, and image acquisition. A chapter on the important issue of software development for image-guided systems is also included, as is one on the equally important issue of validation.

In the application section, examples are presented on the use of image guidance for focused ultrasound therapy, neurosurgery, orthopedics, abdominal surgery, prostate therapy, and cardiac applications. Finally, the linkages between image-guided surgery and radiation therapy are highlighted in chapters on the clinical application of radiosurgery and radiation oncology.

We sincerely thank our colleagues for agreeing to assist us in this endeavor, and for putting up with our incessant demands over the past year.

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Chapter 2

Tracking Devices

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Abstract

Tracking devices are an essential component of an image-guided surgery system. These devices are used to track the position of instruments relative to the patient anatomy. Although early tracking systems were essentially mechanical digitizers, the field quickly adopted optical tracking systems because of their high accuracy and relatively large workspace. However, optical tracking systems require that a line-of-sight be maintained between the tracking device and the instrument to be tracked, which is not always convenient and precludes tracking of flexible instruments inside the body. Therefore, electromagnetic tracking systems were developed that had no line-of-sight requirement and could track instruments such as catheters and the tips of needles inside the body. The choice of tracking system is highly application dependent and requires an understanding of the desired working volume and accuracy requirements. To meet these needs, a variety of tracking devices and techniques have been introduced as described in this chapter.

2.1 Introduction

The advent of x-rays as a medical imaging modality at the turn of the last century brought about clinical interest in the 3D localization of internal anatomical structures. This was first realized with the invention of the stereotactic frame in the late 1920s, and its first use in humans for neurosurgical applications in the early 1940s. Targets within the cranium are relatively easy to localize because of visible landmarks such as the exterior auditory canals and inferior orbital rims, onto which the early stereotactic frames were fixed. The improved accuracy and benefits of this technique to existing surgery techniques led to the emergence of framed stereotactic approaches as standard practice by the early 1960s, with devices such as the Leksell frame and Mayfield clamp being widely used.

Advances in computed tomography (CT) and magnetic resonance imaging (MRI) by the mid-1980s led to the development of frameless

stereotaxy. Neurosurgical applications pioneered the early advances with this technique, but its use quickly spread to ENT and spine procedures. Frameless stereotaxy allowed for smaller incisions, less patient discomfort, shorter patient preparation times, and fewer restrictions on surgical access. Perhaps the single most crucial benefit was the capability for real-time overlay of CT and MRI images that facilitated a more exact roadmap of the patient anatomy and thereby more accurate surgical outcome.

The emergence of frameless stereotaxy was facilitated by position trackers, which can track surgical tools and enable the physician to register external landmarks to pre-operative images of the patient anatomy. Over the past 20 years, frameless stereotaxy has become the predominant influence on image-guided interventions. Techniques that were pioneered for neurosurgical applications have been used in orthopedic, endoscopic, and, more recently, abdominal surgical procedures. The wide-ranging applications of image-guided surgery place differing emphasis on requirements. In addition, novel position tracking techniques and devices have also been introduced.

2.2 Tracking: A Brief History

The introduction and successful outcome of computer-aided surgery (CAS), or frameless stereotaxy in neurosurgery in the 1980s, relied heavily on position tracking devices. A well-established technology at the time that could provide accurate position information was a mechanical digitizer, consisting of a robotic arm with rotary encoders at the various linkage nodes. Position and orientation information of the robotic end effector is resolved using forward kinematics.

The use of mechanical digitizers facilitated frameless stereotaxy by localizing either an operating microscope's focus, or a surgical probe inside the patient's cranium [Reinhardt and Landolt 1989; Watanabe et al. 1987]. Early CAS systems used mechanical digitizers to replace the need for the Mayfield clamp, a staple of framed stereotaxy procedures. Due to the cumbersome nature of mechanical digitizers of the time, interest in alternative tracking methods led to the introduction of ultrasonic transducers for localization [Hata et al. 1997; Reinhardt and Zweifel 1990; Roberts et al. 1986]. However, ultrasonic solutions rely on the speed of sound, which is dependent on relative air moisture and surrounding temperature and is prone to obstruction; thereby lacking the robustness of mechanical digitizers.

The reliability of mechanical digitizers, such as the Faro arm [Zamorano et al. 1994], helped spearhead the development of a commercial product, the ISG Viewing Wand [Doshi et al. 1995; Sandeman et al. 1994]. The ISG Viewing Wand was used for a number of non-neurosurgical interventions in cranio- and maxillofacial surgery [Dyer et al. 1995; Hassfeld et al. 1995] and in ENT surgery [Carney et al. 1996; Freysinger et al. 1997; Nishizaki et al. 1996]. During early trials, a localization accuracy of approximately 2–3 mm [Sipos et al. 1996] was reported. Although the system served the

purpose of localizing a probe relative to the fixed coordinate system of the Mayfield clamp, this approach posed several limitations in a clinical setting. A primary limitation of this approach was the inability to track multiple devices. In addition, sterilization issues and relatively cumbersome handling in the operating theater led researchers to move toward alternate tracking techniques.

Optical trackers proved to be an early answer to clinically feasible tracking systems. Systems such as the Optotrak 3020 (Northern Digital Inc., Waterloo, Ontario, Canada) [Nolte et al. 1995; Rohling et al. 1995], the Flashpoint 5000 (Boulder Innovation Group Inc., Boulder, Colorado, USA) [Anon 1998; Eljamel 1997; Li et al. 1999; Smith et al. 1994; Watzinger et al. 1999], and the Polaris (Northern Digital) [Khadem et al. 2000; Schmerber and Chassat 2001] were adopted. Figure 2.1 shows some of the commonly used optical tracking systems (OTS). Optical trackers evolved into the most reliable and accurate tracking solution. The early systems usually consisted of charge-coupled device (CCD) cameras and sequentially illuminated infrared (IR) light-emitting diodes (LED), and were integrated into image-guided systems such as the Neurostation, which finally evolved into the well-known StealthStation (Medtronic, Minneapolis, Minnesota, USA).

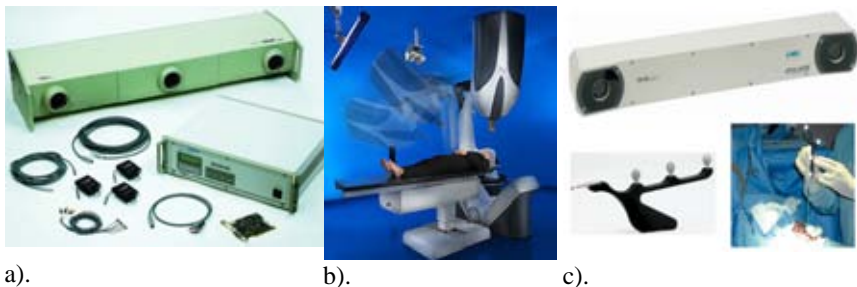


Fig. 2.1. Examples of optical trackers: (a) Optotrak 3020 camera, control unit, and active markers (courtesy of Northern Digital), (b) Flashpoint active optical camera from Boulder Innovation Group used in the CyberKnife suite (courtesy of Accuray), (c) Polaris camera shown with passive marker tool and use in surgery (courtesy of Northern Digital)

Most OTS in use are wired devices that lead to increased clutter in the OR. A few wireless systems have been developed. VISLAN, an experimental system for neurosurgery [Colchester et al. 1996] shown in Fig. 2.2a, was one of the earliest efforts to use a videometric system to estimate patient pose and instrument orientation by identification of passive markers in video-image sequences. Another early effort was the use of the Qualisys tracking system [Gumprecht et al. 1999; Josefsson et al. 1996] in the VectorVision system by BrainLAB (Heimstetten, Germany) shown in Fig. 2.2b, now distributed by Advanced Realtime Tracking GmbH, Munich,

Germany. The de-facto standard at the time of writing is the Polaris tracking system with its variants, which provides both the option of wireless and wired tracking.

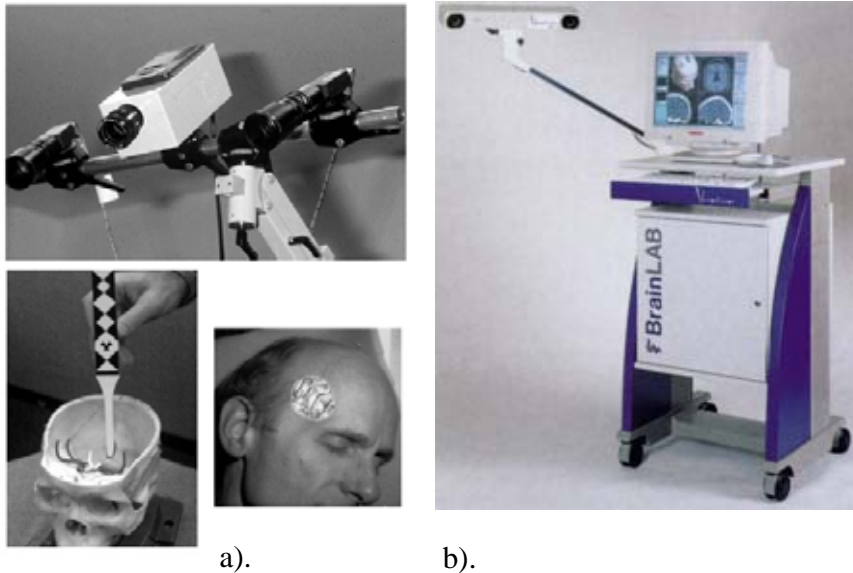


Fig. 2.2. Examples of IGS systems: (a) VISLAN system with pattern marked tool and image overlay (reprinted from Colchester 1996 with permission from Elsevier), (b) Brainlab VectorVision system (reprinted from Gumprecht 1999 with permission from the Congress of Neurological Surgeons)

The key limitation with the use of an OTS in a crowded operating theater is the line-of-sight requirement between the optical markers and the tracker camera, which led to the development of alternative tracking methods that avoided line-of-sight limitations. In particular, electromagnetic tracking systems (EMTS),¹ a technology well known from motion analysis [Meskers et al. 1999; Milne et al. 1996; van Ruijven et al. 2000; Wagner et al. 1996], helmet-mounted displays, and the animation industry, was proposed as a possible alternative. EMTS incorporating small coils or similar electromagnetic field sensors and multiple position measurement devices can easily be used in a clinical setting. Therefore, electromagnetic trackers

¹The term “electromagnetic” tracking has historically been used to describe systems that are based on magnetic fields. Some researchers may argue that these systems should be called “magnetic” spatial measurement systems since they do not depend on the electric field component of the electromagnetic wave. However, we will use the term electromagnetic here to reflect common usage and the fact that a varying magnetic field has an associated electric component.

that were developed for military applications as well as motion capture solutions in general, were employed within CAS [Bottlang et al. 1998; Fried et al. 1997; Goerss et al. 1994, Javer et al. 2000; Reittner et al. 2002; Sagi et al. 2003; Suess et al. 2001; Wagner et al. 1995] motion detection in radiation oncology [Kirsch et al. 1997; Litzenberg et al. 2006; Seiler et al. 2000; Watanabe and Anderson 1997], image-guided radiological interventions [Wood et al. 2005; Khan et al. 2005; Zhang et al. 2006], endoscopic procedures [Deguchi et al. 2006; Hautmann et al. 2005; Solomon et al. 2000], and 3D B-mode ultrasound imaging [Barratt et al. 2001; Fristrup et al. 2004; Sumiyama et al. 2002].

2.3 Principles of Optical Tracking Systems

The broad use of OTS in industry has introduced many manufacturers and system variants with wide-ranging specifications. Clinical systems are a niche sector and the technology used for their operation has not changed significantly in recent years. Optical systems can be characterized as follows:

1. *Videometric tracking systems.* These systems identify marker patterns on video image sequences, usually taken using one or more calibrated video cameras. The well-known marker patterns on crash-test dummies as well as the videometric solutions implemented in the VISLAN system and the freely available AR Toolkit [Kato and Billingham 1999] fall into this category. Systems commercially available today, such as the Claron tracker (Claron Technology Inc., Toronto, Ontario, Canada), are provided in small form factors.
2. *IR-based tracking systems.* An optical band-pass filter eliminates all ambient light of other wavelengths, making the identification of optical markers a comparatively simple and reliable task. Two types of IR trackers exist, both used widely in clinical applications:
 1. *Active optical trackers.* Sterilizable LEDs operating in the near-IR range (approximately 900 nm wavelength) are used as markers, tracked by either two planar or three linear CCD units that form the camera module. The LEDs are fired sequentially and detected by each CCD unit. The central unit uses a process of triangulation based on the known geometric configuration and firing sequence of each LED and the known, fixed distance between the CCD elements. A minimum of three non-collinear LEDs are necessary for determining six degrees-of-freedom (DOF) pose information. Since the LEDs must be powered, traditionally active systems were also wired systems.

2. *Passive optical trackers.* These systems work in the near IR range. Instead of active markers, retroreflective spheres are illuminated by the camera in the near-IR spectrum. The pattern of the reflective markers, which has to be unique for each tracking probe so that unambiguous assignment of each probe is feasible, is identified on a 2D image. For this reason, these systems are always equipped with 2D CCD cameras. One big advantage of these systems is that no wires are needed between the tracking system and the tracked probes.
3. *Laser tracking systems.* Rather than localizing a set of LEDs, an array of photosensors is mounted to a rigid carrier. Two or three fans of coherent laser light emitted by conventional semiconductor lasers are reflected by rotating mirrors. The fan-shaped laser beam sweeps the digitizer volume. The position of the rigid body is estimated by simultaneously sampling the position of the sweep fan and the signal from the photosensor [Cash et al. 2007]. An example of such a tracker is the laserBIRD2 by Ascension Technology (Burlington, Vermont, USA). However, these systems have not found widespread use in medical applications.

A key reason for the success of optical tracking technology in the clinical environment has been its high accuracy and reliability. There have been a few scattered instances in clinical practice where the use of high-intensity IR from the emitter LEDs of passive IR trackers interferes with other IR devices in the operating room, but this is a rare occurrence. Despite their line-of-sight limitation, OTS are the standard in clinical applications at this time. Other examples of applications include high-precision radiation therapy of retinal diseases, where the beam is controlled by detection of eye motion [Petersch et al. 2004], or for motion correction in tomographic reconstruction [Buhler et al. 2004; Feng et al. 2006].

2.4 Principles of Electromagnetic Tracking

EMTS are a relatively new tracking technology in medical applications. Their main advantage is that they have no line-of-sight limitation, but their disadvantages include susceptibility to distortion from nearby metal sources and limited accuracy compared to optical tracking. These systems localize small electromagnetic field sensors in an electromagnetic field of known geometry. The EMTS used in medical imaging can be divided into three categories as described below. Figure 2.3 shows an example system from each category.

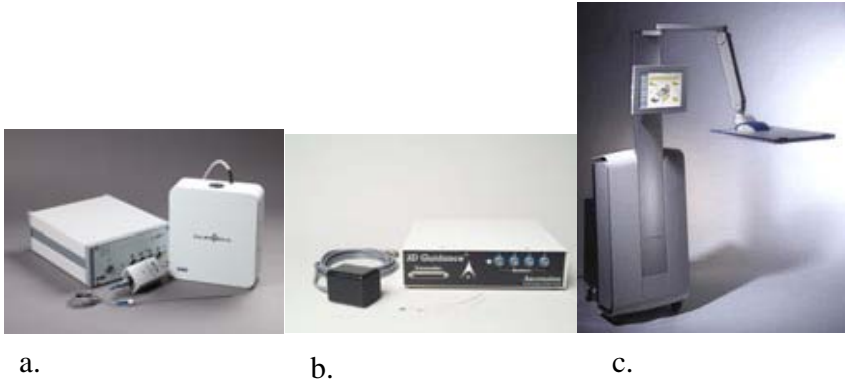


Fig. 2.3. (a) Aurora AC-based system (courtesy of Northern Digital), (b) 3D Guidance pulsed-DC system (courtesy of Ascension), (c) transponder-based system (courtesy of Calypso Medical Systems)

1. *AC-driven tracking.* The earliest developed “classical” EMTS are driven by alternating current (AC). One of the earliest systems is from Polhemus Inc. (Colchester, Vermont, USA). This system consists of three coils arranged in a Cartesian coordinate system that emits an electromagnetic field composed of three dipole fields. Typical operating frequencies for the AC-driven magnetic trackers lie in the range of 8–14 kHz. Small search coils measure the induced voltage, which is proportional to the flux of the magnetic field. A thorough description of the principles of operation of AC-driven tracking systems can be found in Kuipers [1980]. As systems have evolved, manufacturers have employed different approaches to generate the electromagnetic field [Raab 1979]. An early iteration of the Northern Digital Aurora system used six coils in a tetrahedral arrangement [Seiler et al. 2000, 2007].
2. *DC-driven tracking.* As the name would suggest, rather than using an AC-driven magnetic field, these systems are driven by quasistatic direct current (DC). DC trackers are available from Ascension Technology. The magnetic induction within miniature active (fluxgate) sensors was originally measured after establishment of a stationary magnetic field, but current models employ passive microminiaturized sensors [Blood 1989].
3. *Passive or transponder systems.* These systems track position by localization of permanent magnets or implanted transponders. One such system in use for medical application is to assess the placement of nasogastric feeding tubes [Bercik et al. 2005]). Another system introduced recently for tumor position tracking during radiation therapy is the Calypso 4D system (Calypso Inc., Seattle, Washington, USA)

[Willoughby et al. 2006]. Since these systems are relatively new, they have not been widely used yet in image-guided interventions.

The main difference between AC and DC systems lies in their behavior when metallic objects are in close proximity to either the field emitter or the sensor. With an AC-based system, eddy currents are induced in conductive materials, which can then interfere with the continuously generated (i.e., never turned off) magnetic fields and distort the sensor readings. DC-based tracking systems can circumvent this problem by using static magnetic field measurements. With a DC-based system, the magnetic field is turned on and off at a certain frequency, allowing eddy currents to decay sufficiently to mitigate distortions caused by common conductive metals such as stainless steel (300 series), titanium, and aluminium.

A second issue is that ferromagnetic materials such as iron, nickel, cobalt, and some steels become strongly magnetic in the presence of an electromagnetic field. This phenomenon can also distort the reference magnetic field and thereby affect the measurement accuracy of the EMTS [Birkfellner et al. 1998a; Hastenteufel et al. 2006; King 2002; LaScalza et al. 2003; Milne et al. 1999; Poulin and Amiot 2002]. Another source of reference field distortion is magnetic stray fields from drives or other computer equipment and peripheral devices. Therefore, EMTS can be susceptible to measurement errors. To mitigate ferromagnetic errors, Ascension has recently introduced a planar (flat) transmitter with a built-in shield that negates metal distortions emanating from OR and procedural tables [Ashe 2003]. Both radio-translucent and radio-opaque models are available.

From the early days of application of EMTS in the virtual reality/augmented reality (AR) community to more recent applications in the medical field, methods to differentiate the systematic error or compensate for it have been studied extensively. For medical applications, methods to calibrate the work environment for changes in the magnetic field by interpolation or lookup table-based approaches have been proposed for EMTS [Birkfellner et al. 1998b; Meskers et al. 1999]. A more promising approach might lie in systems that can inherently detect field distortions.

The adoption of this technology for biomechanical applications has been slow, in part due to the aforementioned distortion factors. In fact, it was not until the introduction of miniature electromagnetic tracking sensors (small enough to embed in surgical instruments such as needles or catheters, as shown in Fig. 2.4) by companies such as Northern Digital in the last 5 years, and more recently by Ascension, that the use of EMTS provided a clear advantage not offered by any other existing tracking technology; the ability to track flexible instruments and to track instruments inside the body. Thus applications aimed at tracking inner organs using flexible instruments such as catheters and endoscopes were made possible, and more sophisticated algorithms capable of error detection have been developed recently [Ellsmere

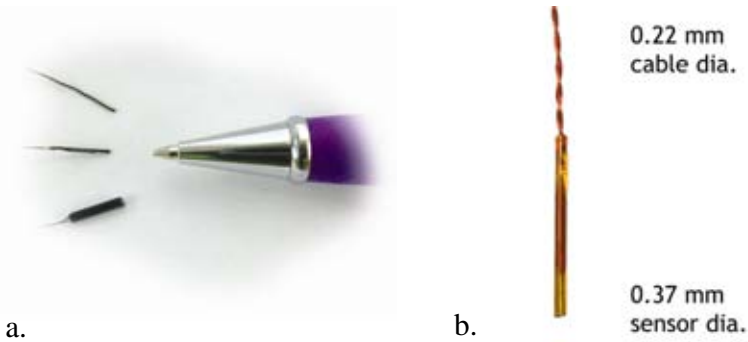


Fig. 2.4 With growing interest in clinical applications of electromagnetic tracking, more companies have begun to produce miniaturized sensors: (a) 0.5 mm and 0.8 mm five DOF sensors and 1.8 mm six DOF sensor (courtesy of Northern Digital), (b) 0.37 mm five DOF sensor (courtesy of Ascension)

et al. 2004; Gepstein et al. 1997; Seiler et al. 2000; Solomon et al. 2000, 2003; Zaaroor et al. 2001].

Despite recent improvements in the technology, it should be noted that EMTS do not, in the general sense, compete with OTS in terms of tracking accuracy. From the application accuracy point of view, the difference between EMTS and OTS becomes smaller, since EMTS sensors tend to be closer to the point of interest. Therefore, extrapolation errors are less important. The lack of any line-of-sight limitation and the ability to track flexible endoscopes and catheters are the main advantage of EMTS. Several studies on the robustness and accuracy of the newer medical EMTS have been performed [Hummel et al. 2002, 2005, 2006; Schicho et al. 2005; Wagner et al. 2002] with reported accuracy in the range of a millimeter for a $0.5 \text{ m} \times 0.5 \text{ m} \times 0.5 \text{ m}$ volume workspace. Due to the dependence of device accuracy on environment, which makes comparison of distortion effects a delicate matter, several groups have proposed standardized assessment protocols [Frantz et al. 2003; Hummel et al. 2005, 2006; Wilson et al. 2007].

2.5 Other Technologies

While this chapter has covered the most commonly used tracking systems in medical applications, other technologies exist that either have great potential for IGI applications in their current state, or which could be used for specific clinical procedures more efficiently than the present systems. An example of such a device is the “ShapeTape” (Measurand Inc, Fredericton, New Brunswick, Canada) [Koizumi et al. 2003] shown in Fig. 2.5. ShapeTape uses optical sensor linkages to measure torsion and flexion of fiber optic cables to determine position and pose along the entire length of the device.

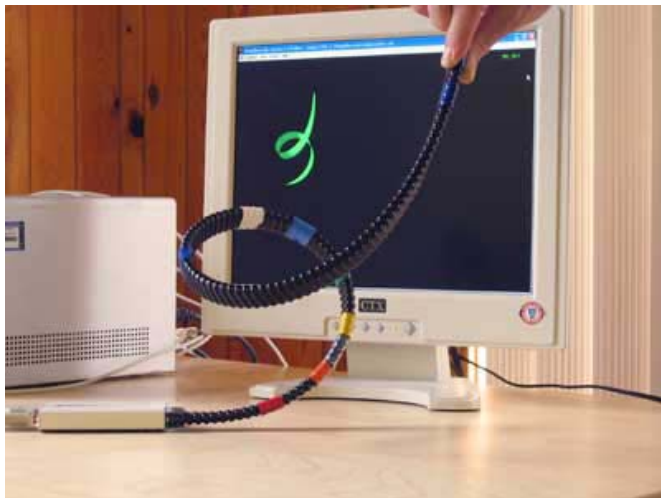


Fig. 2.5 Although the ShapeTape device shows potential, it has not yet seen any application in IGI systems (courtesy of Measurand)

This device has been used predominantly for reverse engineering and animation in the entertainment industry.

Another potential technology is the use of accelerometers and gyroscopes to measure acceleration and angular velocity, respectively, to determine tool pose. A sensor assembly with a pair of three such sensors aligned in the main coordinate axes is usually referred to as an inertial tracking system. Since acceleration is the second derivative of position with respect to time, and angular velocity is the first derivative, angular changes integrated over time from a known starting position yield translation and rotation. Inevitably, small measurement errors, either systematic or statistical (those caused by jitter), lead to increased error over time. Since error of this type is intrinsic, it cannot be tolerated for medical interventions. Despite these limitations, inertial sensors have found application in some biomechanical setups for measurement of joint motion [Zhou et al. 2006; Zhu and Zhou 2004] and as auxiliary sensing devices in hybrid motion tracking systems.

In both instances, the setup can be realized by a Kalman filtering algorithm [Kalman 1960] that uses a predictor-corrector structure to estimate the state of a dynamic system characterized by noisy or incomplete measurements. The expected position in the near future is predicted using the measurements from the inertial system. Such solutions were first presented in the AR community [Azuma and Bishop 1994], but they may not be applicable to image-guided surgery, as high update rates are not a necessity at present. The continuing efforts of the community of researchers to bring

AR to the operating theater [Birkfellner et al. 2002; Das et al. 2006; Edwards et al. 2000; Shahidi et al. 2002; Wacker et al. 2006] might render these approaches an important technology in the near future, especially since some of these visualization devices feature considerable optical magnification that complicates latency issues even further [Figl et al. 2005].

Another approach is to use hybrid navigation systems that combine two or more tracking technologies, such as EMTS and OTS, to provide continuous position data in case of obstruction or failure of any one tracking system. Hybrid systems of this nature have been proposed by several authors [Birkfellner et al. 1998b, Khan et al. 2006; Muench et al. 2004], sometimes in combination with calibration efforts for compensation of distortion in the EMTS. Since tracking systems are moderately expensive (in the \$10,000 to \$25,000 price range at the time of writing), using two tracking systems increases the cost of the image-guided system, while adding more equipment to an already congested clinical environment. For these reasons, interest in such systems to date has been largely academic.

Finally, medical imaging modalities can be used for tracking instruments during procedures. A simple example is tumor motion detection by identification of marker motion in electronic portal images (EPI) acquired during radiation therapy. In this case, the treatment beam is used as an imaging modality where the resulting absorption images resemble conventional x-ray imaging. One drawback of this technique is that the high-energy photons emitted by the accelerator provide rather poor image contrast. However, external or internal markers are easily detected in those perspective images [Aubin et al. 2003; Harada et al. 2002; Nederveen et al. 2001; Pang et al. 2002; Shimizu et al. 2000; Vetterli et al. 2006]. Another closely related technique is the tracking of guidewires or similar structures in fluoroscopic x-ray images during radiological interventions [Baert et al. 2003; van Walsum et al. 2005], and the localization of bronchoscopes from a comparison of virtual endoscopy images and actual bronchoscopy images [Mori et al. 2002], or angiography images and 3D rotational angiography data [van de Kraats et al. 2006]. A key methodology for these three examples is the use of 2D/3D registration techniques [Birkfellner et al. 2003; Hipwell et al. 2003; Lemieux et al. 1994; Livyatan et al. 2003; Penney et al. 1998; Skerl et al. 2006; Turgeon et al. 2005]. As these registration applications become faster with the advent of more rapid rendering techniques and computing capabilities [Birkfellner et al. 2005; Russakoff et al. 2005], improved image-based tracking may become the technology of choice for a variety of applications in interventional radiology and image-guided radiation therapy. Related work in this direction has been proposed that retrieves a starting point for an iterative registration process [Deguchi et al. 2006; Krueger et al. 2005].

2.6 Data Transmission and Representation

The protocol and interface used to transfer data from the tracker to the control computer and the representation of the transmitted data are important practical concerns for any researcher wishing to develop an IGS system. Historically, the most commonly used interface for tracking systems was the serial RS 232 interface and this is still the standard for many current systems. However, newer systems are transitioning to a USB interface as this is more standard with modern computers and can provide faster data rates. This interface is available for the newer Northern Digital systems such as the Polaris Spectra and Polaris Vicra as well as the 3D Guidance system from Ascension.

Equally relevant is the parameterization and representation of the data to be transmitted. It should be noted that some EMTS are ambiguous on data representation, as their digitizer volume is only defined as a hemisphere around the field emitter. The data representation is particularly confusing for rotations and orientation measures. From a mathematical perspective the rotation transformation forms a group named $SO(3)$. These rotations are given as 3×3 matrices with two special properties:

1. the determinant of a rotation matrix is 1.
2. the inverse is formed by transposition of the matrix.

Providing a full rotation matrix would give an unambiguous representation of rigid body rotation, but suffers two drawbacks. First, transmission of nine matrix components requires bandwidth and takes time, especially when using slow serial communication lines. Second, interpolation and other non-trivial computations such as filtering algorithms are not easily accomplished using matrices.

The most straightforward parameterization of the rotation group is the use of three rotation angles around a Cartesian coordinate system, which are sometimes denoted as roll, pitch, and yaw. Unfortunately, this parameterization suffers from the non-commutativity of rotations given as rotation matrices. Providing three rotation angles, therefore, also requires directions on how to combine them to obtain a single rotation. As a result, the quaternion representation has become the generally accepted standard for parameterization of the rotation group. Quaternions are a quadruple of numbers consisting of a scalar component q_0 and a vector component $(q_1, q_2, q_3)^T$ associated to three complex units i , j , and k . They were first introduced to theoretical mechanics by Hamilton in the nineteenth century. Quaternions, while not commutative, provide a non-singular representation of the rotation group (thereby avoiding the so-called gimbal lock problem). Most modern tracking systems like the Northern Digital products and several trackers from Ascension use this representation. A compact description of quaternion kinematics can be

found in Chou [1992]. The derivation of the quaternion representation from a conventional rotation matrix representation is given in Shepperd [1978].

2.7 Accuracy

Accuracy in image-guided surgery is a critical issue, and the aspect of validation in image-guided surgery systems is discussed in Chapter 18. There have been many papers describing accuracy evaluations of the tracker component on the overall outcome of image-guided surgery procedures. We can make the following general statements concerning accuracy:

1. Tracker accuracy is a crucial component of the overall target registration error (TRE) in image-guided surgery systems [Fitzpatrick et al. 1998].
2. Evaluation of image-guided surgery systems, including tracker performance, should take place with the specific intended clinical application in mind. The crucial questions are
 - a. Can therapeutic outcome be improved by deploying an image-guided surgery system?
 - b. Can this improvement be optimized by applying other (more accurate or more convenient) tracking technologies?

If trackers of different technologies or from different vendors are to be compared, one should aim at providing an experimental framework that makes comparison of measurements feasible for other groups. The principle of experiment repeatability is important and should be taken into account.

2.8 Conclusions

Position tracking is an essential component in image-guided surgery. Many different types and styles of tracking devices have been introduced and perhaps the ideal solution does not exist yet. The best choice of tracking device is highly application dependent.

Although the first image-guided system incorporated mechanical digitizers, these were replaced as more compact and less intrusive optical tracking devices emerged. In some sense, it would be appropriate to say that optical tracking is the standard benchmark with sufficient accuracy in applications where it is viable.

Over the last decade, companies have taken note of the growing prominence of image-guided interventions and developed systems targeted toward medical applications. This has resulted in EMTS with smaller profile sensors that facilitate the tracking of flexible instruments. Continual refinement and sophistication in measurement error detection and distortion

correction could in time replace the use of optical trackers altogether in general surgery, interventional radiology, and image-guided radiation therapy. We also could expect to see optimized solutions for application groups (like miniature EMTS for endoscopy and catheterization and OTS for high-precision localization of rigid bodies). Simple-to-use interfaces and sufficient data update rates would greatly stimulate uptake of new devices for the development of image-guided intervention systems.

As intra-operative imaging becomes a more integral part of surgical and interventional routine, we assume that some applications for external tracking might be replaced by image processing methods rather than external position sensing. In addition, tracking does not need to be confined to instrument localization alone. Examples mentioned in this chapter on the use of tracking within biomechanics, radiation therapy, motion correction, and instrument position surveillance illustrate the myriad avenues in which tracking exhibits clear potential. To facilitate the research and development of interventional systems that serve the vast patient community is indeed a noble goal for researchers in the fields of clinical research, biomedical engineering, and medical physics.

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