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# Electromagnetic Tracking in Medicine – a Review of Technology, Validation and Applications

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***Abstract*—Object tracking is a key enabling technology in the context of computer-assisted medical interventions. Allowing the continuous localization of medical instruments and patient anatomy, it is a prerequisite for providing instrument guidance to subsurface anatomical structures. The only widely used technique that enables real-time tracking of small objects without line-of-sight restrictions is electromagnetic (EM) tracking. While EM tracking has been the subject of many research efforts, clinical applications have been slow to emerge. The aim of this review paper is therefore to provide insight into the future potential and limitations of EM tracking for medical use. We describe the basic working principles of EM tracking systems, list the main sources of error, and summarize the published studies on tracking accuracy, precision and robustness along with the corresponding validation protocols proposed. State-of-the-art approaches to error compensation are also reviewed in depth. Finally, an overview of the clinical applications addressed with EM tracking is given. Throughout the paper, we report not only on scientific progress, but also provide a review on commercial systems. Given the continuous debate on the applicability of EM tracking in medicine, this paper provides a timely overview of the state-of-the-art in the field.**

***Index Terms*—Electromagnetic tracking (EMT), magnetic tracking, computer-assisted interventions (CAI), intraoperative surgical navigation, image-guided therapy (IGT)**

## 1. Introduction

Computer-Assisted Interventions (CAI) are becoming an integral part of modern patient care [137]. This is attributed to a number of expected benefits compared to conventional approaches, including increased accuracy, reduction of complications and decreased intervention time. These benefits of CAI have been shown in various studies, particularly for neurosurgical and orthopedic applications [49, 137]. Within the field of CAI, image-guided therapy (IGT) is based on the registration of pre-operative (e.g., computed tomography (CT)) or intra-operative (e.g., ultrasound (US)) patient data to the actual operative field. In this manner, IGT can provide freehand navigation or guidance for mechatronic positioning of medical instruments [137, Chap. 9]. Therefore, these methods commonly rely on the localization of the equipment with respect to the patient. This localization in 3D space is referred to as tracking, and is a key enabling technology for CAI. Optical tracking uses cameras to localize visual markers and is the most established tracking modality [137, Chap. 2]. Its main drawback is the requirement for a free line-of-sight to the markers, which is not feasible for many applications. Especially for minimally invasive surgical procedures, instruments such as flexible endoscopes, catheters and needle tips must be tracked inside the human body. For such applications, electromagnetic (EM) tracking has emerged as the method of choice that enables localization of small EM sensors in a given EM field without the requirement for line-of-sight.

It is pertinent to comment on the terminology employed in this paper. The term ”Electromagnetic” to describe the tracking phenomenon arises from the fact that electromagnets are responsible for producing changing (AC) or quasi-static (DC) magnetic fields, which induce currents in solenoids or fluxgate sensors embedded in the detectors. The phenomenon responsible for the operation of these tracking systems relies solely on magnetic induction rather than any strict electromagnetic effect. Nevertheless, while this technology is referred to by both the terms ”Magnetic Tracking” (MT) and ”Electromagnetic Tracking” (EMT), the latter has become the more common, having been adopted by the manufacturers of these devices, and so we retain this terminology throughout the paper.

Unfortunately, EMT technology has some drawbacks regarding clinical application. EM tracking accuracy can be compromised by magnetic field distortion due to nearby medical diagnostic devices such as CT or MRI scanners [206], or other ferromagnetic objects [141]. Furthermore, additional hardware components of the tracking system, such as the EM field generator, must be placed close to the patients or be attached to them, as in the case of a patient-mounted receiver unit (e.g., *CORTRAK*®system, CORPAK Medsystems, see Sec. 6-B). Medical equipment such as instruments and imaging devices must be equipped with fragile EM sensors, which in most cases must be tethered by a cable to system hardware. However, different EM tracking systems on the market have been customized for specific applications, and can minimize



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Manuscript received January 21, 2014; revised April 15, 2014; accepted April 27, 2014

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMI.2014.2321777, IEEE Transactions on Medical Imaging



such drawbacks for specific procedures.

Various publications focus on *EM tracking in medicine* by describing the validation, integration, or usage of these systems in a medical context. The content of the papers range from technical technology descriptions and accuracy assessments to clinical applications, including patient studies. While this literature includes many important findings relating to the use of EM tracking in medicine, the picture provided of the field is far from unified. To the authors' knowledge, there has been no general review published that summarizes the domain. To rectify this, this paper tries to present a complete review of the literature, and give an analytical overview on the state-of-the-art, highlighting future research directions.

## 2. Methods of literature research

Due to the diversity of the field described above, *EM tracking in medicine* was divided into the four main topical areas *I. Fundamentals*, *II. System Assessment*, *III. Distortion Compensation*, and *IV. Clinical Applications*. Using these titles, a systematic search of relevant literature was performed in the period from December 2012 to June 2013, using the scientific search engines *PubMed*[1], *IEEE Xplore*[2] and *Google Scholar*[3]. We extended the search by a manual screening of the most important conference proceedings, namely SPIE[4] Medical Imaging, CARS[5], MICCAI[6] and several IEEE[7] conferences. Additionally, the literature repositories (including online library access and conference proceedings) of the authors and other experts were screened for further important papers. Then, the abstracts of all findings were scanned to exclude clearly irrelevant papers that did not cover EM tracking at all. In the next step, all remaining papers were briefly summarized and rated by the authors (from 0:"clearly irrelevant" to 10:"clearly relevant"). In this step, journal papers were preferred in the cases when multiple similar papers were published by the same authors. Based on the resulting arranged prioritized list, the papers were reviewed in depth and finally the sections were written. These methods were refined for each topical area as described below.

**I. Fundamentals:** Papers on EM tracking fundamentals rarely can be found in *PubMed*, because the topic is too technical. Thus, we also performed a *IEEE Xplore* search using the search terms "Magnetic Positioning", "Electromagnetic Tracking" and "Electromagnetic Localization". The systematic search resulted in 84 papers, which were reduced to 14 by removing duplicates and clearly irrelevant papers. This was extended by a manual search, resulting in 44 additional papers, 11 patents and a patent review, as well as 3 theses. After reviewing the total number of 73 documents, we decided to cite 26.

[1]http://www.ncbi.nlm.nih.gov/pubmed
[2]http://ieeexplore.ieee.org
[3]http://scholar.google.de/
[4]Society of Photo-Optical Instrumentation Engineers (SPIE), http://spie.org
[5]Computer Assisted Radiology and Surgery (CARS), http://www.cars-int.org
[6]Medical Image Computing and Computer Assisted Intervention (MICCAI), http://www.miccai.org
[7]Institute of Electrical and Electronics Engineers (IEEE), http://www.ieee.org

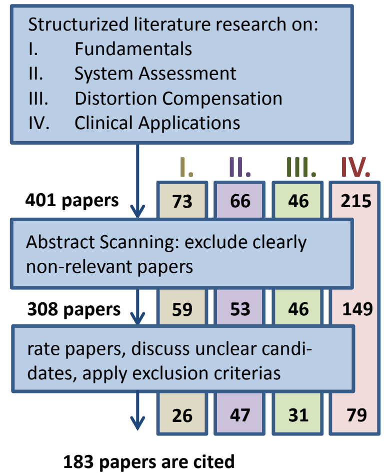


Fig. 1. Flow diagram of the literature research process, broken down along the topical areas presented in this paper.

**II. System Assessment:** A *PubMed* search was performed with the search terms "Accuracy" and "Assessment" that were combined with each of the terms "EM/Electromagnetic/Magnetic Tracking", "NDI Aurora", "Ascension Microbird/Trakstar/Fastrak/Isotrak", "Polhemus" and "Calypso" using *AND*. The search was extended by a manual scanning of the proceedings of conferences which are not listed in *PubMed*. These included conferences as described above, and was completed by a free manual search employing *Google Scholar*. This led to 163 results that were reduced to 66 after removing duplicates and clearly non-relevant titles (see Fig. 1). Nine of the papers were moved to the other topical areas after processing the abstract, and another 10 were dropped as non-relevant. Having read these papers, we decided to include 47 publications.

**III. Distortion Compensation:** *PubMed* does not provide relevant publications for the search terms that were applied in this area. The screening was extended to *IEEE Xplore*, using the search terms *"Document Title":Electromagnetic Tracking* and *"Document Title":Calibration* combined with *AND*, which resulted in 5 possible relevant findings and to *Google Scholar* using the search term *"Calibration electromagnetic tracking"*, leading to 7 findings. This systematic research was completed by a manual search resulting in an overall number of 46 papers, theses and patents. After screening these documents, we decided to discuss 22 papers, 3 theses and 6 patents.

**IV. Clinical Applications:** Using *PubMed*, the publication titles were searched for the term "Electromagnetic" in combination with "Guidance", "Tracking Navigation" and "Navigation". Additionally, a search for "Magnetic Navigation" was limited by adding NOT ("Magnetic Resonance" OR "Remote Magnetic Navigation") to avoid too many false positive results. A manual search also was performed, leading to 276 results, later reduced to 215 by removing clearly non-relevant titles

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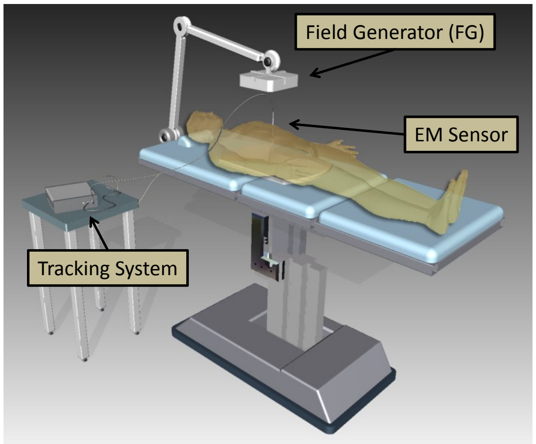


Fig. 2. Principle of intra-operative EM tracking.

and duplicates (see Fig.1). During abstract scanning, five of these results were moved to other topics and 61 were considered as non-relevant. After scanning of the remaining 149 full papers, we decided to cite 79 aiming to cover all clinical applications, but preferentially citing the most relevant publications.

Overall, the literature research led to a list of 398 potentially relevant papers on EM tracking, as shown in Fig. 1. A few citations that were not part of the literature research were added for discussion, which resulted in some additional references to those included in Fig. 1. The following sections present the relevant literature for each of the four areas, and major findings are discussed in depth at the end of each section. The last two sections present a summary and outlook to future R&D directions, followed by a conclusion.

## 3. Fundamentals

As shown in Fig. 2, EM tracking localizes small sensors inside a magnetic field of known geometry, which is created by a field generator (FG). The idea of sensor localization by means of magnetic positioning first emerged in the 1970s, when Wynn *et al.* presented a method for 2D tracking [204]. Based on this work, Kuipers [87] and Raab *et al.* [148] described the first tracking methods for positioning and orientation of a magnetic sensor. Besides these early works that presented the principles of EM tracking, a plethora of papers, patents and books were subsequently published. Manufacturers introduced commercial EM tracking systems [121] that were then used for further studies by many authors, e.g., [19, 41, 61, 134, 194]. This section gives an overview of the fundamentals of EM tracking based on 26 papers, theses, books and patents found during the literature search as described in Sec. 2. Information is given on the *physical background* of tracking and the *magnetic sensors* it employs, and the basic principles of *EM tracking techniques* plus the technology of *field generators* are summarized. Another important issue in this context is the identification of possible *sources of errors*. The end of this section describes commercially available EM tracking systems.

### A. Physical Background

Physically, EM tracking utilizes magnetic fields of known geometry to determine the pose of sensors for measuring magnetic flux or magnetic fields. The magnetic reference field either can be produced by permanent magnets or by electromagnetism [180, p.885]; in the latter case, the structure of the magnetic reference field is governed by the law of Biot-Savart. The geometry of the emitting coil assembly and the type of current sent through the coils determines the shape and the geometric properties of the aforementioned field. As it is possible to control the dynamic behavior of the reference field, it is possible to encode both spatial position and orientation relative to the reference field. For actual measurements inside a magnetic field, special sensors are needed. These are described in the following section.

### B. Magnetic Sensors

A basic component of EM tracking systems is the magnetic sensor. Since the magnetic flux density $\vec{B}$ [$_{\text{Weber(Wb)}} = \frac{kg \cdot m^2}{A \cdot s^2}$] cannot be determined directly, magnetic sensors measure the magnetic flux $\Phi$ [$_{\text{Tesla(T)}} = \frac{kg}{A \cdot s^2}$], which is defined as the component of $\vec{B}$ that passes through a specific point/surface. Note that a sensor only measures the gradient of a magnetic field that represents the difference in the magnetic field intensity between different positions inside the field [46]. Thus, inhomogeneous magnetic fields, such as those created by magnetic dipoles are needed for measurement. Within such a known inhomogeneous magnetic field, there is a correlation between $\Phi$ and the distance to the source of the field, which is the starting point for magnetic positioning methods as described in Sec. 3-C. In the context of EM tracking, different types of sensors are used to measure $\Phi$:

- **Search coils** use inductors to measure the magnetic flux as a function of the time $t$. Thus, an alternating magnetic field is needed for these sensors to measure a voltage $e$, given by:

$$e = -N \frac{d\mathbf{\Phi}}{dt} \tag{1}$$

| | |
|---|---|
| $e$ | voltage |
| $N$ | number of coil turns |
| $\mathbf{\Phi}$ | magnetic flux |
| $t$ | time |

- **Fluxgate sensors** use two inversely arranged inductors to measure the second harmonic Fourier component of the magnetic field. Thus, a fluxgate can vectorially measure magnetic fields that are static or alternating with a low frequency.
- **Other magnetic sensors** including Hall Effect and superconducting quantum interference devices (SQUIDs) currently are not in use for medical EM tracking. However, SQUIDs already have been described in a patent for possible use in EM tracking [20].

Different manufacturers sell magnetic sensors for EM tracking, as shown in Fig. 3. While it is feasible to miniaturize these sensors to a diameter smaller than 1 mm, a cable is still required to connect a sensor to the control unit. Although Polhemus (Polhemus Inc., Colchester, Vermont, USA) offers

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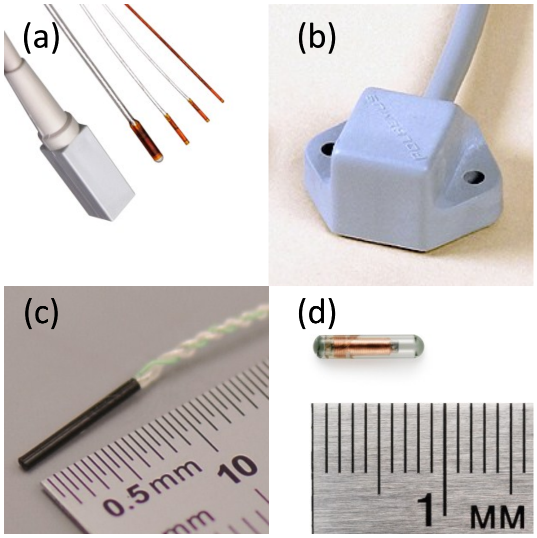


Fig. 3. Examples of magnetic sensors for EM tracking. (a) Different sensors for the Ascension DC tracking system. Photo courtesy of Ascension Technology Corporation. (b) Sensor for the Polhemus AC tracking system. Photo courtesy of Polhemus Inc.. (c) 6 DoF Sensor for the NDI *Aurora*® AC tracking system. Photo courtesy of Northern Digital Inc.. (d) Passive EM transponder of the Calypso *GPS for the Body*® system, referred to as a *beacon*. Photo courtesy of Varian Medical Systems Inc..

wireless sensors, the requirement to use an active transmitter together with an energy supply to the sensor makes them more complex and much larger. Some manufacturers also sell ready-to-use medical instruments equipped with EM sensors. Examples include catheters and needles from NDI or *eTRAX*™ needles from CIVCO (CIVCO Medical Solutions, Kalona, Iowa, USA).

Some authors proposed combining EM sensors with other technologies to improve the accuracy of tracking. Whenever line-of-sight is available, it is possible to use optical tracking systems to fuse the data (for example, [60, 62, 88, 117, 151]). A method not requiring line-of-sight was proposed by Liu *et al.*, who used an accelerometer [101], and a wireless solution was developed by Ren *et al.* [150]. Since such sensors currently are not available on the market, they are not widely used.

Some systems localize passive transponders (Fig. 3d) instead of magnetic sensors. Passive transponders do not measure the magnetic field, but use it for energy supply and emit a radiofrequency signal for localization. This technology is addressed separately at the end of the next subsection.

### C. EM Tracking Techniques

Different authors describe techniques to localize magnetic sensors inside a magnetic field [73, 164, 204]. When acquiring at least three measurements, e.g., by sequentially activating different magnetic fields, a non-linear system of equations is derived, which can be solved by using Newton's method [164]. To explain the basic concept of EM tracking, some authors use spherical coordinates introduced in Fig. 4 [87, 148]. The distance $R$ from the source of the magnetic field to the sensor can be determined by exploiting the inverse-cube attenuation in near-field applications, or the signal propagation delay in far-field applications [87]. If using several sources in a known setup, the position of the sensor can be determined by triangulation [140]. Another possibility is the determination of the angles $\alpha$ and $\beta$ (Fig. 4) by sequential source excitations along the standard basis vectors, or some linear combination of these [87], [117, p.2]. In practice, this means there are multiple differently aligned inductors. These inductors are commonly combined into one device called the Field Generator (FG), see Sec. 3-D.

The methods mentioned above only allow for the determination of the sensor's position, but not its orientation (Fig. 4). One way to obtain sensor orientation is to combine multiple sensors on a tracking tool in a known position and then to use this information to determine the orientation. However, it also is feasible to gain information about the orientation from a single magnetic sensor. A magnetic dipole, such as the sensor's inductor, is axially symmetric, which limits this information to 2 degrees of orientation. Thus 5 degrees of freedom (DoF), 3 for the position and 2 for the orientation, can be determined by these sensors. 5 DoF sensors are quite common for EM tracking devices. For 6 DoF tracking, two inductors can be combined. Although manufacturers offer small 6 DoF sensors, they are bigger than their 5 DoF counterparts. In practice, EM tracking systems allow for tracking of a few of these sensors with update rates of 40–250 Hz [121]. Note that most systems, e.g. the NDI *Aurora*® system (see Sec. 3-F), are able to read out their sensors in parallel, thus the number of connected sensors does not affect the update rate of one single sensor.

It is important to note that some systems use quasi-static direct current (DC) magnetic fields, while others use alternating current (AC) magnetic fields. The main difference between these systems is the employed sensor technique. While search coils need AC fields for magnetic flux measurements, fluxgate sensors are used in pulsed DC fields (see Sec. 3-B) [137, Chap. 2].

Another point is that the principle of tracking the sensor can be reversed and the source can be tracked relative to the sensor. This was proposed for tracking a feeding tube [12], and for instrument tracking in general [11]. However, tracking of more than one object at the same time is not possible using this approach.

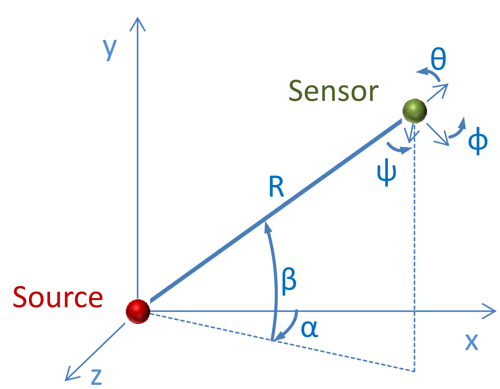


Fig. 4. The magnetic dipoles of the source and the sensor in polar coordinates of the source. The position of the sensor is represented by the triplet POS [R,$\alpha$,$\beta$], the orientation by the triplet ROT [$\psi$,$\theta$,$\phi$].

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There are some other tracking techniques that also are referred to as *EM tracking* or *magnetic tracking*, yet, the underlying principle is fundamentally different. One such technique is the tracking of small permanent magnets. In this case, magnetic sensors are part of the tracking system and the magnetic field of the tracked object is measured. A serious limitation is that only one magnet can be tracked, but this approach does not require wiring. This technique has been used in research studies [138], but the existing systems are experimental and only play a minor role in the field of CAI.

Another tracking technique uses passive transponders [137, Chap. 2], [138]. These transponders use a magnetic field for energy supply to emit a location signal to external sensors/antennas in a known arrangement. The position can be determined by signal intensity, delay or angular phase shift. Such a system, referred to as Calypso *GPS for the Body*® was presented by Varian Medical Systems Inc. (Palo Alto, California, USA). The system supports three trackable transponders, referred to as *beacons*, with resonance frequencies of 300, 400 and 500 kHz [201]. These *beacons* are excited by the system in a sequential manner and the position of each is determined by a sensor array that measures the emitted location signal [6, 104]. Note that the Calypso system is an example of true electromagnetic technology being used in a tracking system, as discussed in Sec. 1. Another tracking method based on passive transponders has recently been proposed for radio frequency identification (RFID) chips [55, 158, 191]. However, within passive transponder technologies, only the Calypso system plays an important role in clinical practice.

### D. *Field Generators*

To create the magnetic fields needed for EM tracking, field generators are used. As mentioned before, an FG needs to sequentially generate at least three different magnetic fields of known geometry. Inside the FG, inductors are used, as shown for the NDI Tetrahedron FG in Fig. 5. In this early FG, the inductors are aligned in a tetrahedron shape to generate magnetic fields as proposed by Kirsch *et al.* [73]. An important property of each field generator is the tracking volume, which describes the area around the generator where sensors can be tracked. For the Tetrahedron FG, the tracking volume covers up to 0.5 meters around the FG, which is a typical scale for such a system [34, p.8].

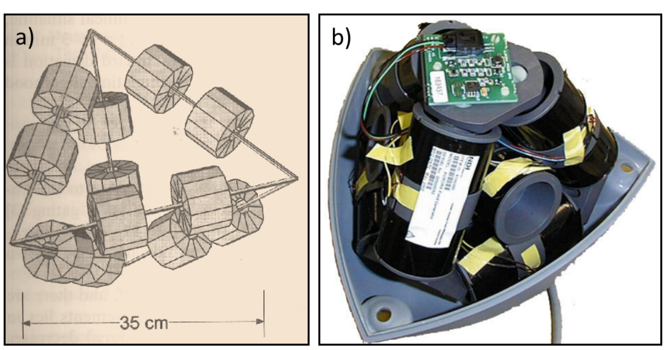


Fig. 5. Example of a first generation EM field generator: the NDI Tetrahedron FG. (a) Sketch from Kirsch *et al.*, similar to [73]. Photo courtesy of Northern Digital Inc.. (b) Photograph of the corresponding coils in an open FG. Reprinted with permission from [34].

TABLE I
TYPES OF FIELD GENERATORS

| Type | Typical Properties | Examples |
|---|---|---|
| Standard | Range: ca. 1 m, Size: cube-shaped, ca. 10–30 cm | NDI Tetrahedon FG [34], NDI Planar FG [117, p.6], Ascension Mid Range [117], Polhemus Standard FG [34], Medtronic AxiEM FG [146] |
| Flat | Range: ca. 1 m, Size: flat, ca. 50×40 cm | NDI Tabletop FG [102], NDI Window FG [207], Ascension Flat FG [117, p.5], SuperDimension location board [145], Biosense Webster location pad [144] |
| Mobile | Range: ca. 0.2 m, Size: small, $<$ ca. 10 cm | NDI Compact FG [39], NDI Handheld FG [142], Ascension Short Range FG [143], Polhemus Short Ranger [147], Smith&Nephew Donut FG [58], Cortrak Receiver Unit [81] |
| Long Range | Range: ca. 5 m, Size: ca. 50×50 cm | Polhemus Long Ranger [147] |

In many cases, customized field generators offer advantages such as better possibilities of placement, or more robustness against distortions in a particular environment. Thus, manufacturers have presented different types of stand-alone FGs, while others were specially developed for medical products. Table I gives an overview of the types with their typical properties, and Fig. 6 shows example images.

*Standard* FGs are available from various manufacturers and so are the most widespread. *Flat* field generators were developed for direct placement under the reclining patient, offering the capability to shield the magnetic field against distortions from below, and even to hide them inside the patient table. This type is used by some commercial products, as in the *CARTO XP* (Biosense Webster Inc., Diamond Bar, CA, USA) or the *iLogic*™ (superDimension Inc., Minneapolis, MN, USA) system. *Mobile* FGs are small and can be placed directly at the area of interest, which is a benefit because tracking accuracy is high near the FG [102], but also is a necessity because the tracking volume is quite small. *Long range* FGs that cover areas up to a couple of meters are available from Polhemus.

All these FGs contain a set of inductors arranged in a particular pattern (Fig. 5). One possibility to generate differently aligned magnetic fields is to rotate one inductor, as proposed by Ge *et al.* [43]. The Calypso system contains a FG for energy supply for the transponders [201], but in contrast to other FGs, this example is not involved in localization [201]. However, the tracking volume of the Calypso system covering 14 cm $\times$ 14 cm $\times$ 27 cm is smaller than that of others [6, 104].

### E. *Sources of Error*

There are different sources of error for EM tracking systems. Laws of physics, limitations of design, and imperfection in manufacturing or environmental noise can all lead to erroneous localization. While some errors can be dealt with only at the system developer/manufacturer side, many others can be

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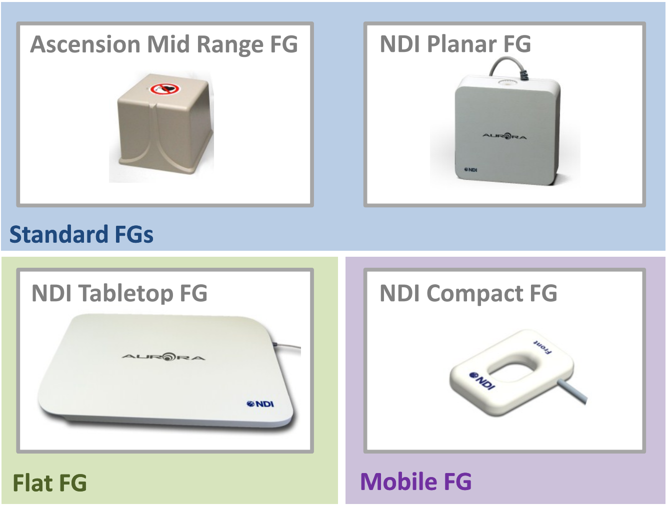


Fig. 6. Examples of field generators for EM tracking. Photo courtesy of Northern Digital Inc. and Ascension Technology Corporation.

handled with careful experimental design and execution [170]. Different forms can be used to express errors and noise, however, for Gaussian noise, mean ± standard deviation (STD) is most commonly employed. In the following, classification of these errors is discussed, and *Inherent System Errors*, *Field Distortion Errors* and *Motion-Induced Errors* then are introduced in detail.

*Error Classification:* In general, errors describe the deviation of the measurement and a known reference value. Like every observation, magnetic field measurements are typically affected by systematic errors and random noise. The latter is sometimes referred to as jitter and appears during the measurements of a fixed sensor over a period of time [117]. However, to further complicate the analysis, another possible reason for random noise might be dynamic errors at a high frequency. In addition, there is a possible error caused by the manufacturing inaccuracies.

Traditionally, EMT errors are classified as *static*, when a sensor stays in a fixed position and *dynamic*, which typically arises due to sensor movement. Static errors might be subdivided into systematic errors (*static distortions*) and a random noise (*jitter*), while dynamic errors include *dynamic distortions* and the *sensor velocity error* [117]. However, this classification might be misleading, since a constantly moving sensor in a homogeneous field will show both systematic and random error components that are difficult to distinguish or handle separately. Fig. 7 shows the errors discussed in this paragraph.

From the application point of view, the overall effect of errors is important, and the proportion of the systematic part that can be handled with calibration. Random errors only can be handled using filtering. It often happens that only 3 translational components are used by a specific CAI system. In such cases, typically only the 3 DoFs of the position are of interest, but for a complete error classification all possible DoFs should be taken into account.

*Inherent System Errors:* Fundamentally, the FG has technical limits in accuracy and reproducibility of the generated magnetic field. These problems were reported thoroughly in the case of custom made FGs [65]. Calibration can deal with systematic errors, while filtering may be useful to tackle random errors. The first publications on EM tracking already purposed random noise reduction methods by using previous measurements, moving average or Kalman filters [87, 148]. It is typically assumed that all system noises are symmetric and follow a Gaussian distribution. However, more precise measurements do not support that theory with evidence [170]. Since position values are calculated from current measurements, these derivations also introduce some error in localization. Factory calibration of FGs and sensors plays an immense role in performance improvement. The quality of a tracking system regarding noise is referred to as inherent accuracy. The overall inherent precision might depend on the environment, but the noise cannot be reduced beyond a certain level. When performing system assessment trials, it is important to replicate measurements under very similar environmental conditions.

*Field Distortion Errors:* Magnetic fields interfere with ferromagnetic materials and/or other fields in the surrounding area [128], which is represented in the measurements as additive noise. Naturally, also expressed by the *Biot–Savart law*, magnetic fields are generated by every electric current [180]. As EM tracking relies on the known geometry of the magnetic field, its accuracy is susceptible to these distortions. Furthermore, the changing of magnetic fields induces eddy currents in conductors that also can cause secondary magnetic fields, and this also may disturb the measurements. In summary, there are four major sources of magnetic field distortions (excluding the error originating from the imperfect modeling of the field under standard conditions):

- Ferromagnetic materials,
- Eddy currents in other conductive materials, induced by the magnetic field itself,
- External currents inside the magnetic field, e.g. caused by other electronic devices,
- Inhomogeneous wave transportation medium, such as air or the human body, because all theoretical EM equations refer to a vacuum.

Some EM tracking systems, such as the Ascension systems (see 3-F) use pulsed quasi static DC fields to avoid eddy currents [138]. However, these systems are still affected by the other types of errors. In principle, it is possible to compensate for systematic field distortions by calibration on the

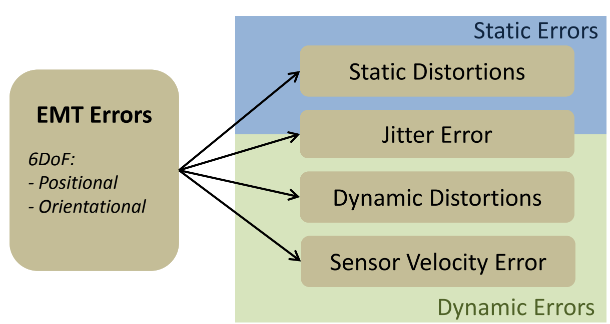


Fig. 7. Classification of EM tracking errors.

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Fig. 8. The image shows current example systems of the three manufacturers of stand-alone EM tracking systems (a,b,c). The Calypso *GPS for the Body*®system, shown on the bottom right (d) includes the passive transponder tracking technology, which is not available as stand-alone product. Photo courtesy of Northern Digital Inc. (a), Polhemus Inc. (b), Ascension Technology Corporation (c), and Varian Medical Systems Inc. (d).

system level [72]. These techniques are described in detail in Section 5.

*Motion-Induced Errors:* Besides distortions, dynamic effects, including the sensor velocity that can affect the tracking accuracy and distortions caused by external moving materials such as a changing environment also can cause EM tracking errors [60, 117].

### F. Commercial Systems

As a consequence of the geographically scattered development and continuous publishing and patenting on EM tracking, several manufacturers developed different stand-alone EM tracking systems for medical applications. The earliest, based on AC magnetic fields (Sec. 3-C) was presented by Polhemus Inc. (Colchester, VT, USA) [121], [137, Chap. 2], and other companies soon entered the market. An overview of the current manufacturers is given in Fig. 8.

Ascension Technology (Burlington, VT, USA) developed an EM tracking system based on a DC-driven magnetic field. Different models of the system as well as customized field generators and miniaturized sensors designed for medical purposes are available (Fig. 3). Northern Digital (NDI) Inc. (Waterloo, ON, Canada) presented a AC-driven EM tracking device, *Aurora*®, with customized FGs and sensors. In July 2012, NDI acquired Ascension and decided to maintain both product lines. AC-driven EM tracking devices also are available from Polhemus, although they are not focused on medical products, but rather on other applications such as motion tracking. Thus, Polhemus offers long range FGs and wireless solutions.

The stand-alone EM tracking systems mentioned above have been integrated into various medical devices. For example, the Ascension system is used in the *Virtual Navigator* system (Esaote Group, Genova, Italy), while the NDI *Aurora*®is part of the *Veran ig4*™system (Veran Medical Technologies Inc., St. Louis, USA). However, some manufacturers of medical products also developed their own EM tracking systems that are available as part of their products, but not as stand-alone EM tracking systems. Example systems are *iLogic*™(superDimension Inc., Minneapolis, Minnesota, USA), *CARTO XP* (Biosense Webster Inc., Diamond Bar, CA, USA), *StealthStation*®*AxiEM*™(Medtronic Inc., Minneapolis, MN, USA), *ScopeGuide* (Olympus Corporation, Tokyo, Japan) and *CORTRAK*®(CORPAK MedSystems Inc., Buffalo Grove, IL, USA). Another example is the Calypso *GPS for the Body*®system for radiation therapy, which includes a unique tracking technology described in Section 3-C. All these commercial integrated medical products are discussed in detail in Section 6-B. There is also a controller for video games, referred to as *Hydra* (Razer Inc., San Diego, CA, USA), which uses EM tracking for controller tracking and has already been used in a scientific context [8].

## 4. System Assessment

In accordance with the laws of physics, the accuracy of EM tracking is vulnerable to distortions in the magnetic field, originating from any sources, such as metals or magnetic fields of other devices [206]. Since this is the major limiting factor of the technology, assessment of EM tracking devices has been the focus of research for many years. This is represented by 47 findings on this topic during the literature research described in Sec. 2. Based on this literature, an overview of assessment protocols is presented in this section. In subsection 4-B, results of assessment studies are summarized, and then all protocols and results are discussed.

### A. Assessment Protocols

While early studies mostly used their own assessment protocols and comparability of these studies is poor, standardized protocols also have been proposed, and were used in many of the following projects [51]. In general, a protocol should include (1) a phantom or measurement setup and (2) a measurement process with evaluation methods. Furthermore, a good protocol [117, p.13] should provide evaluation and analysis of:

- the basic quality criteria of tracking methods:
  - *Precision:* Deviation of measurements over a period of time while the sensor is fixed, also called jitter.
  - *Accuracy:* Exactness of relative measurements, e.g. the distance between two measured positions.
- as well as extension to:
  - *Dynamic effects:* Impact on measurements when the sensor is moving during the measurement or when the environment is changing.
  - *Magnetic field distortions:* Effect of potential disturbing environments, e.g., ferromagnetic materials

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMI.2014.2321777, IEEE Transactions on Medical Imaging



or electronic devices on the magnetic field possibly resulting in tracking errors.

These characteristics of a tracking system should be assessed at different positions inside its tracking volume for all degrees of freedom of a specific system, which typically include:

- *Position (3 DoF):* location in 3D space, e.g., [x,y,z],
- *Rotation (3 DoF):* orientation in 3D space, different representations possible, e.g., yaw-pitch-roll, quaternions or Euler angles.

Unbiased representation of measurement data is another major challenge in the domain. For representation of precision, the Root Mean Square (RMS) error is typically used [117, p.14]. For accuracy, usually statistical values such as mean error, standard deviation, median, minimum, maximum and confidence intervals are quoted. To represent these values, some authors used boxplots (e.g., [39, 102]) others listed them in tables (e.g., [61, 196]). 3D representations of errors also have been employed by simply plotting the measured points in a 3D scene [102] or by more complex methods such as plotting of fitted polynomials [62]. While 3D representation can be very helpful to overview the results, acquiring quantitative feedback is not easy. If the complete 6 DoF data is truly represented, it becomes too complex to perceive and understand, motivating the use of tables or diagrams in addition to 3D figures.

Table II provides an overview of the distinctly different types of protocols. The most common approach is to use an accuracy board with drilled holes as a phantom. As ground truth, the distance between the holes is given from the construction data or from accurate a priori measurements. “Scribbling” approaches are similarly popular. These employ a rigid body—containing typically two sensors—that can move freely on a plane board. The ground truth is the fact that all measurement values (should) lie in the same plane, and the changing measurement of the displacement between the fixed sensors provides an estimation of the errors. All these planar measurements should be repeated at various elevations within the working volume. Another possibility to cover a 3D volume is to create a cube where a sensor can be placed in known 3D positions inside. Most of the phantoms do not allow for assessment of dynamic aspects, but some proposed moving phantoms: a pendulum [60] and a turning plate [120]. More complex constructions were also used as phantoms for different reasons, a few examples are given in Table II.

Besides employing phantoms, some groups chose simpler methods, such as fixing the sensor on a ruler [83] or simply moving the sensor along straight lines on a sheet of paper [152]. While these approaches are simple and fast, their comparability and accuracy are very limited.

In addition to the relatively simple phantom-based approaches, some robots have also been included in studies. Automatic data collection for assessment allows for higher numbers of measurement points, and also potentially enables dynamic experiments. However, robots are problematic, because they typically present disturbing components to the workspace, and are more complex/expensive than conventional phantoms.

TABLE II
ASSESSMENT PROCOLS

| Phantom type | Examples | Comments |
|---|---|---|
| **Board phantoms** | Hummel *et al.* [61] | Standardized, position and rotation |
| *- Drilled holes:* | More: [3, 89] [25, 66] | Only position |
| *- LEGO®:* | Haidegger *et al.* [51] | Common LEGO® plate |
| *- Scribbling:* | Nafis *et al.* [122], Fontanelle *et al.* [36] | Random manual movement on the plate |
| **Cube phantoms** | Wilson *et al.* [196] | Standardized |
| | Calypso QA fixture [159] | |
| **Moving phantoms** | Hummel *et al.* [60] | Pendulum |
| | Murphy *et al.* [120] | Turning plate |
| **Robots** | Shen *et al.* [169] | Most studies |
| | Gergel *et al.* [45] | Custum-build tripod |
| | Frantz *et al.* [38] | Collects random data |
| | Risholm *et al.* [154] | Commercial tobot |
| | Wu *et al.* [203] | LEGO® robot |
| **Other phantoms** | Barratt *et al.* [7] | Position and rotation |
| | Yoo *et al.* [207] | Custom-build for C-arm |
| | Kirsch *et al.* [74] | Distortion of metals |
| | Birkfellner *et al.* [16] | 6 DoF Phantom, distortion assessment |

There are at least two protocols that were intended as “standardized protocol” to enable comparability between different assessment studies. Both protocols have been used for several studies and allow for a comprehensive presentation of their results (see Sec. 4-B).

1. **Hummel *et al.*** [61] introduced a board phantom (50 cm × 50 cm) with drilled holes at 90 possible sensor positions. The 5 cm distance between the positions is used as ground truth. On this board, only two of the three DoF for positional measurements are possible to be executed. Sirokai *et al.* [170] and Maier-Hein *et al.* [102] proposed an extension of the protocol by performing measurements on multiple elevations that extend the protocol to the missing DoF. The protocol also allows for rotational measurements for all three orientational DoF in the middle of the board and distortion assessment with metal probes. The proposed evaluation includes the precision as RMS error, averaged over all 90 positions as well as the evaluation of mean positional and rotational errors.
2. **Wilson *et al.*** [196, 206] introduced a cube phantom (18 cm × 18 cm × 18 cm) with 225 holes at different depths from 10 mm to 150 mm. The known positions inside the phantom which include variations in all three positional DoF are registered to the measured positions, and the error for each point is calculated. Statistical values, such as the RMS error, are then determined to evaluate the accuracy. For the evaluation of precision, a maximal sample variability of the distance from the tracking system to the sensor is calculated.

### *B. Study Results*

Many studies assessing EM tracking systems for CAI can be found in the literature, e.g., [3, 6, 7, 15, 19, 25, 36, 39, 45, 51, 59, 60, 61, 66, 74, 82, 83, 86, 89, 102, 120, 122, 152, 154, 159, 165, 169, 170, 172, 196, 202, 206, 207]. However, in many cases, the results of these studies are not comparable because different measurement protocols and evaluation methods were used. Thus, some groups pushed forward standardized assessment and several studies have been performed using these standardized protocols.

An overview of the study results of EM tracking assessment is given in Table III. The majority of the standardized studies used one of the most common devices, the NDI *Aurora*®and Ascension *microBird*, focusing on different clinical environments. Concerning precision, most assessments show promising results below 1.0 mm. Only Yaniv *et al.* found critical outliers for the Ascension *Short Range FG* [206]. In his thesis, Much [117] tested different sensors of the Ascension system and found outliers up to a couple of centimeters for one of them, referred to as *Model 130*, but the sensor *Model 180* showed precise results, which are listed in Table III. Regarding environmental effects, studies show clearly that accuracy of EM tracking decreases dramatically in some clinical surroundings, such as on the patient stretcher in a CT suite [102, 206] or OR [196], as well as near medical devices such as a C-Arm [19]. Flat field generators such as the NDI Tabletop FG or the Ascension Flat FG shield the magnetic field from below and show much better results in some of these environments [102, 206]. Small FGs such as the Ascension Short Range FG and the NDI Compact FG also performed better [102, 206], probably because their smaller tracking volume is relatively far away from sources of distortion [102]. It should be mentioned that some FGs are suitable for being combined with other medical devices: Bø *et al.* combined the NDI Window FG with a C-Arm [19], and Franz *et al.* the NDI Compact FG with different US probes [39]. In both cases, these customizations improved the results of the assessments compared to the standard FG. However, Bø *et al.* still found a considerably high tracking error inside the C-Arm.

Unfortunately, there is less evidence for other tracking systems. We found some non-standardized assessment studies for the Polhemus and Calypso systems and these are listed in Table III(c). One possibility to reasonably compare these results is to consider the error as a percentage of the measured distance, as did Day *et al.* [25] who found jitter errors up to 5 % and positional errors up to 3 % for the Polhemus *Fastrak*®system. Birkfellner *et al.* compared the Polhemus *Isotrak II*®system to the Ascension Bird system and found the *Isotrak II*®to be more accurate but less robust against metallic distortions than the competing device [16]. Koerting assessed the *Isotrak II*®system in a thesis and found errors in the order of a couple of millimeters [82]. For the Calypso *GPS for the Body*®system Balter *et al.* [6] and Santanam *et al.* [159] found a precision that decreased with increasing distance from the FG but stayed far below 1 %, and a positional error up to 5 %. For other clinical systems, technical assessments are rare. Kwartowitz *et al.* compared the NDI *Aurora*®to the *CARTO XP* system and found slightly better results for the latter with errors in the same magnitude [89]. Schicho *et al.* tested the *StealthStation*®*Treon*®EM system and also found better results compared to the NDI *Aurora*® [162]. Koivukangas *et al.* also performed a study with a *StealthStation* system, comparing EM and optical tracking, and found a slightly better accuracy for the latter [79].

However, for most of these clinical systems, clinical trials have been performed and are further discussed in Sec. 6.

Automatic assessments basically confirm the results of other assessment protocols with higher numbers of acquired values. Shen *et al.* found increased positional errors up to 27 mm of the NDI *Aurora*®system near a patient stretcher in a CT suite but they only collected 36 positional measurements [169]. Gergel *et al.* used a tripod-shaped robot to examine 1000 positions inside the tracking volume of the NDI *Aurora*®system, also on a patient stretcher in a CT suite. Testing both the *NDI Planar FG* and the *NDI Tabletop FG* the results confirm the robustness of the latter against distortions from below [45]. Risholm *et al.* used a relatively small and inexpensive robot to collect 600 measurements in an OR suite that showed a highly disturbed field, and then applied compensation methods, see Sec. 5 [154]. Frantz *et al.* presented a method to collect data of random positions inside the tracking volume for accuracy assessment, which is the official approach of NDI to determine the accuracy of their tracking systems [38]. It should be noted that LEGO®robots are another relatively cheap approach to perform robotic assessments [51]. This was done by Wu *et al.* who measured the accuracy of the NDI *Aurora*®System and they also used this data for calibration of the system, see Sec. 5 [202].

A problem not addressed in most of the assessment studies is the effect of sensor movement during the measurements; also referred to as dynamic effects (see Sec. 3-E). For assessment of these effects Mor *et al.* moved two sensors, manually fixed on a wooden tool handle, and found the Ascension *microBird* system was more affected by sensor movements than the NDI *Aurora*®system [114]. Hummel *et al.* proposed a more reproducible approach by attaching a sensor to a pendulum and found an increasing position error of up to 2.3 mm for increasing velocities up to 1.2 m/s [60]. Murphy *et al.* used a turning plate for assessment of sensor motion to the Calypso *GPS for the Body*®system but found no effects [120].

Another property of interest for many applications is the latency of the tracking signal. While this was not in the focus of most of the papers investigated here, several studies on the topic have been published. Adelstein *et al.* tested the Ascension *Flock of Birds* and the Polhemus *Fastrack* system with a motorized swing arm and found latencies of up to 50 ms for both systems using the default configuration. By disabling internal filtering of the tracking data the latency could be reduced to less than 10 ms [1]. Wu *et al.* assessed the latency of the NDI *Aurora*®system, and found it to be 80 ms higher than the latency of an optical tracking system [203]. Nafis *et al.* reported a latency of around 4 ms for Polhemus systems [121].

We caution however, that such results pertain to the systems in existence at the time (2003 and 2006, respectively), and may not be reflective of the performance of similar systems today.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMI.2014.2321777, IEEE Transactions on Medical Imaging



TABLE III
ASSESSMENT STUDY RESULTS

(a) **Standardized assessment according to Hummel *et al.* [61]**: Shows the mean RMS error over 90 positions as precision (Prec.) and the mean error of 161 measured 5 cm distances between these points as positional accuracy (Acc.). The rotational accuracy (Rot.) is given as the mean error of thirty-one 11.5° measurements for two axes, because 5 DoF sensors were used for most assessments.

| *System* FG | Environment | Ref. | Pos. [mm] Prec. | Pos. [mm] Acc. | Rot. [°] |
|---|---|---|---|---|---|
| *NDI Aurora* | | | | | |
| Planar FG | Laboratory | [59] | 0.17 | 0.25 | 0.2/0.9 |
| | Laboratory | [102] | 0.20 | 0.80 | 1.2/1.0 |
| | CT Suite | [102] | 0.18 | 4.40 | 1.2/1.0 |
| | X-Ray Suite | [15] | - | 1.31 | - |
| Tabletop FG | Laboratory | [102] | 0.05 | 0.30 | 0.8/0.7 |
| | CT Suite | [102] | 0.05 | 0.90 | 0.8/0.7 |
| Compact FG | Laboratory | [102] | 0.05 | 0.50 | 1.0/0.8 |
| | CT Suite | [102] | 0.06 | 0.50 | 1.0/0.8 |
| | US probes | [39] | <0.2 | <2.5 | <3 |
| *Ascension microBird* | | | | | |
| Mid Range FG | Laboratory | [61] | 0.14 | 0.69 | 0.04 |
| *Ascension 3D Guidance* | | | | | |
| Mid Range FG | Laboratory | [117] | 0.15 | 0.24 | .05/.06 |
| Flat FG | Laboratory | [117] | 0.20 | 0.18 | .02/.02 |

(b) **Standardized assessment according to Wilson *et al.* [196, 206]**: Shows the precision (Prec.) as maximal sample variability of the distance between tracking system and the sensor averaged over 225 measured positions inside a cube volume of 18cm edge length. For positional accuracy (Acc.) a RMS error over these values after registration to the ground truth is given. This protocol does not include rotational measurements.

| *System* FG | Environment | Ref. | Pos. [mm] Prec. | Pos. [mm] Acc. |
|---|---|---|---|---|
| *NDI Aurora* | | | | |
| Planar FG | Undistorted | [19] | 0.67 | 0.76 |
| | near C-Arm | [19] | 1.09 | 7.59 |
| | Bronchoscopy Suite | [196] | - | 6.67 |
| | OR Suite | [196] | - | 3.14 |
| | OR Suite | [206] | 0.49 | 1.01 |
| | CT Suite | [206] | 0.54 | 5.76 |
| | Pulmonology Suite | [206] | 0.26 | 1.16 |
| Window FG | Undistorted | [19] | 0.37 | 1.16 |
| | C-Arm | [19] | 0.40 | 5.09 |
| *Ascension MicroBird* | | | | |
| Short Range FG | Laboratory | [206] | 3.63 | 0.55 |
| | CT Suite | [206] | 2.54 | 6.49 |
| Mid Range FG | Laboratory | [206] | 0.48 | 0.39 |
| | CT Suite | [206] | 0.48 | 3.64 |
| Flat FG | Laboratory | [206] | 0.71 | 1.19 |
| | CT Suite | [206] | 0.30 | 1.08 |

(c) **Non-standardized assessment/other systems**: The results of these studies are hardly comparable because different protocols are used in each study. The table shows sample studies of systems not covered by standardized studies of a) or b).

| Study | System | Results: Precision | Results: Accuracy |
|---|---|---|---|
| Day *et al.* [25] | Polhemus Fastrak® | increases with distance (up to 5%) | Pos. Error < 3% Rot. Error < 2° |
| Birkfellner *et al.* [16] | Polhemus Isotrak II® | - | Pos. Error 3.2mm Rot. Error 2.9° |
| Koerting *Thesis* [82] | Polhemus Isotrak II® | - | Pos. Error 1.5mm (Dist. < 200mm) |
| Balter *et al.* [6] | Calypso | 0.01mm (near/8cm) 0.48mm (far/27cm) | Error < 0.2mm (10mm distances) |
| Santanam *et al.* [159] | Calypso | 0.03mm (over 30 min.) | Error < 0.5mm (10mm distances) |

A couple of studies assessed the effects of metallic probes near EM tracking devices. Stainless steel and mild steel were found to cause the highest disturbance for Ascension systems [61, 128]. The NDI *Aurora*®and the Polhemus Fasttrack also were disturbed by these metals, but the error was much lower [61, 74, 128]. Cobalt-chrome, titanium, bronze and brass caused negligible distortions to all assessed EM tracking systems [61, 74, 110, 128]. However in the case of aluminum, there have been contradictory statements as to whether this is disturbing [74] or not [61].

Additionally, there are some studies that assessed the effects of real medical instruments to EM tracking. Schicho *et al.* tested a Langenbeck hook, a dental drill and an US probe and found that the NDI *Aurora*®system is more sensitive to these instruments (error up to 5 mm) than the EM tracker of the Medtronic *StealthStation*®(error < 1 mm) [162]. US probes also were assessed by Franz *et al.* [39] and Hastenteufel *et al.* [53], both of whom found that whether the EM tracking system was disturbed or not was highly dependent on the probe used. Patil *et al.* used the NDI *Aurora*®system inside an operating CT scanner and found increased distortions up to a couple of millimeters [132]. Poulin *et al.* placed different pieces of OR equipment near an Ascension *MotionStar*®system and found high distortions for an arthroscope, a oscillating saw, intra-venous monitoring equipment, positioning devices, scissors and an OR table. In contrast, for anesthesia equipment, including spreaders, a saw guide, an OR lamp, and the instrument table distortions were minimal [141]. Wegner *et al.* also found no relevant interferences caused by endoscopy instruments [188]. For the Calypso system, the influence of penile prostheses was tested and no measurable interference found [187].

### C. Assessments in Clinical Practice

In addition to technical assessments, there are studies that use more realistic settings to assess EM tracking in clinical practice. Phantoms of different anatomical structures such as the abdomen [199], the skull [165] and vessels [15] have been used. Some assessments have even been performed during actual interventions inside the human body [86, 172]. These types of studies are more realistic, and greatly show the potential and limitation of EM tracking on one hand but are less reproducible and comparable on the other.

The results from these studies indicate an error of up to a couple of millimeters in clinical practice [199]. The feasibility of tracking catheters, needles, and guide wires also has been shown [199]. For neurosurgical applications, an increased tracking error due to metallic instruments was found [165]. Although still experimental, Bien *et al.* successfully tracked a catheter by including a guide wire inside a vessel model [15].

Inside the human body, an accuracy assessment during total knee arthroplasty showed that optical tracking is more accurate than EM tracking [172]. Kruecker *et al.* found an error of 5.8 mm for tracking needles after percutaneous insertions into soft tissue [86]. However, beside these two exceptions, most studies with real patients were performed as clinical studies and are described in Sec. 6.

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### D. Discussion

In summary, technical assessment shows that accurate EM tracking with errors smaller than 1 mm is possible in suitable surroundings. Under laboratory conditions, depending on the specific study, the standardized measurements with the NDI and Ascension systems found position errors always below 1.2 mm for distances of a couple of centimeters (Hummel-Protocol: 5 cm, Wilson-Protocol: <18 cm) leading to errors up to 2.4 % of the measured value (see Tables III(a) and III(b)). Non-standardized studies assessing the Polhemus and Calypso systems are not really comparable, but also mostly stay below 3 %, except for some outliers of up to 5 % (see Table III(c)). However, when operated in the vicinity of disturbing objects, such as many medical devices in clinical environments, the accuracy of these systems may drop dramatically. In possibly disturbed clinical surroundings, standardized studies found errors of up to 7.6 mm for the NDI and Ascension systems that represents nearly 10% of the measured value for some cases (see Tables III(a) and III(b)). Table III shows an overview of recent studies and gives hints in which environments accuracy problems commonly occur. For some specific applications, customized EM field generators can help to avoid distortions and enable accurate EM tracking even in a complex environment. In this context, reduction of the size of the tracking volume can help to improve tracking accuracy as shown for different FGs [102] which leads to a trade-off between the size of the tracking volume and the accuracy within.

In the context of accuracy assessment, a direct comparison of EM tracking to optical tracking would also be of interest, but, even though some authors tested both systems in clinical environments and found better results for optical tracking (e.g., [79, 172], see Sec. 6-C), a similar standardized assessment for both technologies is not available. NDI, a manufacturer which sells both EM and optical tracking systems, published technical data obtained using the same method [189] for all their systems. Positional accuracies of 1.40 mm (NDI *Aurora*®, EM tracking, 5 DoF) and 0.50 mm (NDI *Polaris*®, optical tracking) as well as precisions of 0.70 mm and 0.25 mm respectively are available online[8]. In addition, a technical study compared the same two NDI systems with a custom protocol and found a positional EM tracking error that increased by a factor of 4 compared to the optical system [40].

As shown in this section, there are various assessment protocols that have been presented in many different papers. A problem arising here is the lack of comparability between these studies. Fortunately, there have been efforts to introduce standardized protocols. Two of these protocols already have been applied in several studies, resulting in some evidence for EM tracking in different clinical environments. These studies focus on the most common EM tracking devices from NDI and Ascension, as shown in Table III. However, it should be noted that comparability between the studies is still limited. For example, there are known differences between single models of sensor type series and often the studies even use different sensor types. Of course, the results of one device type cannot simply be assigned to another type, because there could be differences in the behavior of the tracking techniques, for example, between AC and DC field generation, and in the technical specifications such as the tracking volume (see Sec. 3).

Besides phantom-based approaches, which include the standardized protocols, robotic/automatic assessment methods have been proposed by different authors. The advantage of these is the ability to collect a large number of samples automatically within a short time. The drawbacks of robotic assessment protocols include the added cost and complexity, as well as the possibility that the device itself might disturb EM tracking. Nevertheless, the use of robotic devices is reasonable when large data sets are required, or when the same measurements must be repeated many times, as in the case of compensation/calibration approaches, which are discussed in Sec. 5. All in all, for single assessments of EM tracking devices, one of the standardized phantom-based approaches should be the method of choice. These are simple to apply and enable comparability of the results.

Considering the presented protocols in more detail, rotational measurement appears as an important issue. Many approaches, including protocols that rigidly register the measured positions to a ground truth, such as the standardized Wilson-Protocol [195], only change the position of the sensors but not the orientation for assessment, so that only three of the five or six DoF are analyzed. The standardized Hummel-Protocol introduces rotational measurements by using special holes arranged in a circle in the middle of the board [61]. However, Maier-Hein *et al.* reported problems with these measurements due to cable flipping [102]. Thus, a simple, easy to apply standardized solution for rotational measurements can be considered as an open research problem. Enhancement of the standardized protocols using such a method would be of great benefit. However, it should be noted that if orientation changes and positional and rotational errors need to be assessed simultaneously, hand-eye calibration would be necessary and this might introduce new sources of error [149].

Dynamic measurements also are not provided by the current standardized protocols, although several studies assessed dynamic effects with special phantoms [60, 120]. Another possibility would be to use robots for dynamic measurements because they can precisely reproduce defined movements. A question that arises in this context is the effect of latency and update rates. LaScalza *et al.* found that the error of the *Ascension Flock of Birds* system caused by disturbing metals depends on the update rate [92] and further investigation of these effects might be of interest for the future.

Some authors proposed to assess and evaluate the different DoF of a system separately, e.g., [6]. However, the standardized protocols mostly provide measures that usually are averaged over three positional DoF. As described in Sec. 4-A, the protocols do not always include equivalent variations in all three positional DoF which keeps them simple and easy to apply.

So, even if possible, covering every single effect in a controlled technical experiment can be very time consuming. At some point, experiments should be transferred into an actual

[8]*Aurora*®:http://www.ndigital.com/medical/aurora-techspecs.php; *Polaris*®:http://www.ndigital.com/medical/polarisfamily-techspecs.php

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clinical environment [63], [137, Chap. 18]. Many researchers employed a relatively simple protocol, such as a standardized one, and performed measurements in clinical environments to check the feasiblity of EM tracking, see Table III. This is the approach recommended by the authors, as it is important to evaluate EM tracking for the specific clinical application and we believe EM tracking is now robust enough for many clinical applications.

## 5. Distortion Compensation

Since the early days of the field, improving the accuracy of EM tracking has been a core research problem. This is well represented in the literature that was found during the literature search as described in Sec. 2. The findings of 31 publications include 6 patents, which shows the potential for commercial applications in this field.

The compensatable EM errors (see Sec. 3-E) may originate in the design of the FG [139], the imperfect manufacturing of the sensors, or may originate from external EM sources [62]. Compensation of these EM errors refers to the systematic action and effort to eliminate them.

Typically, system-level and FG calibration is performed by the developer/manufacturer, and verified by thorough testing before shipping [14]. Sensors are also calibrated and matched against their descriptive definition files. When new sensors, markers, or fiducials are (custom) built, they must be recalibrated [65]. Finally, calibration also can mean the assessment and compensation of the EM field distortions in a given environment [71]. Regarding the latter, the two fundamental approaches of accuracy improvement include (1) *passive protection* and (2) *active compensation*.

### A. Passive Protection

This may incorporate the overall optimization of the tracker setup, the arrangement of the experiment, and the employment of shielding. Since a large portion of the distortions originate from external ferromagnetic objects and EM sources in the vicinity of the generator, removing all disturbing objects is crucial for better performance. The literature points out that the entire setup should be located remotely from electric wires (that may be running in the walls) and sensor cables always should be separated from power cables and preferably unrolled [170].

Manufacturers implement various methods to improve passive protection; such an example is the *Flat FG* or *Tabletop FG* (see Sec. 3-D), where the EM field is protected from below by a metallic shield. Shielding should be employed when an EM tracking system is integrated with a C-arm or other imaging device [48]. The sensors themselves also may be protected and insulated. An additional protective coil may reduce the effect of eddy currents [27]. Recent studies found that the tabletop arrangement reduced the error by 63–70 % in the CT suite [102, 206]. NDI offers shielded sensors for better integration with critical equipment, such as electrophysiology mapping and ablation catheters (NDI Shielded and Isolated 5DOF Sensor, Part Number: 610057)[9]. In the meantime, the clinical workflow also should support the utilization of EM tracking. Most often, the tools are moved only when the most disturbing effect, for example, imaging devices such as a fluoroscope, or electric surgical equipment, such as an oscillating saw [141], is turned off. The overall shielding of the measurement setup also is possible, however, only against large, external sources of distortion.

### B. Active Compensation

For active compensation, usually tracking data is aquired on different poses inside the tracking volume of a possibly disturbed tracking device, e.g., [45, 154]. Additionally, reference ground truth to these poses is available, e.g., from an additional optical tracking system [31, 45]. Based on these data, compensation is achieved by employing a certain mathematical method to assess the EM field within the workspace, then directly correlating the measured and the reference values using mathematical functions and subtracting the systematic error from the measurement. Based on the resolution of the raster used as reference points, different methods can be identified:

- Point-based: the most simple methods, relating every point-of-interest to a nearby, previously measured point, e.g., by employing a Look Up Table (LUT),
- Interpolation: local (e.g., trilinear) or global [62] interpolation allows the computation of the compensation factor between known, measured points,
- Extrapolation: computes compensation for points outside the raster measured, but with typically lower accuracy, making it rarely used in EMT.

Table IV provides an overview of these alternatives. By far the most popular method is interpolation, for which various techniques have been researched, from polynomial fitting to multi-quadric methods, shape functions, and neural networks. A detailed survey is provided by Kindratenko *et al.* [72].

One of the major challenges with error calibration is the a priori data collection to acquire the reference measurements. It is considered extremely problematic to integrate any general, pattern-based data collection method into clinical workflows. Large calibration phantoms and robots are undesired and often impossible to introduce into the sterile environment prior to the intervention to perform the calibration measurements. This procedure also may have the drawback of being too time consuming and costly.

Collection methods include continuous, discrete modes; analogous to the methods presented in Sec. 4, both manual and automated [45]. Frequently, multi-sensor rigid bodies and sensor arrays are used to assess the field in real-time [68, 166, 167, 168].

Error corrections also can be performed with respect to a more precise tracking device. The reference measurement may come from an independent localizer (i.e., a high resolution optical tracker, a physical localizer), or a phantom with known physical parameters can be employed, trusting the precision of the manufacturing.

The error compensation can be performed *online* during the use of the tracking system, based on another independent

[9] http://www.ndigital.com/medical/aurora-accessories.php

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMI.2014.2321777, IEEE Transactions on Medical Imaging



TABLE IV
ERROR CALIBRATION TYPES

| Calibration method | Examples | Comments |
|---|---|---|
| **Point-based** | Himberg *et al.* [57] | Multi-sensor data collection with LEGO |
| | Feuerstein *et al.* [31, 32] | Combination of EM and optical tracking systems |
| | Birkfellner *et al.* [17] | Using discrete LUT |
| | Meskers *et al.* [107] | Measurements averaged over time at reference points |
| | Perie *et al.* [136] | LUT based on plexi phantom |
| | Day *et al.* [26] | Employing a calibration phantom |
| **Interpolation** | Raab *et al.* [148] | First polynomial fit |
| | Thormann *et al.* [177] | Online correction by Hardy's multiquadric method |
| | Himberg *et al.* [57] | Multi-sensor data collection with LEGO |
| | Ikits *et al.* [62] | $4^{th}$ order polynomial fit |
| | Bryson *et al.* [21] | $4^{th}$ order polynomial fit |
| | Hagedorn *et al.* [50] | Delaunay tetrahedralization for rotations |
| | Kindratenko *et al.* [71] | 3–$5^{th}$ order polynomial fit |
| | Nakamoto *et al.* [124] | 0–$4^{th}$ order polynomial fit |
| | Traub *et al.* [181] | Interpolation on the top of LUT |
| | Fischer [35] | Thin-Plate Spline Interpolation, Bernstein-polynoms |
| | Kelemen [67] | Delaunay tetrahedralization and polynomial fit |
| **Extrapolation** | Kelemen [67] | Extrapolation based on global polynomial fit |
| **Other** | Saleh *et al.* [156] | Neural network-based |
| | Much [117] | Comparison of four techniques |
| | Bien *et al.* [13] | Step-response-based method for AC EMT |
| | Khalfin [69] | Spectral and phase analysis to enhance AC EMT |

tracking system or multiple sensor coils' data (e.g., [177, 202]). Note that in this case some authors proposed the generation of an error map in advance [177], others aim at the acquisition of this map intra-operatively [124, 202]. The method of Feuerstein *et al.* does not require an error map at all, but a calibration of the used instrument instead [31, 32].

More typically, an *offline calibration* procedure is performed. Published studues have shown a mean error reduction of 4–22 % [16, 26, 57]. Either way, the method should be repeatable, and should be performed quickly, immediately following the calibration, and without interfering with the medical procedure taking place at the same location (see Sec. 6).

### C. Discussion

EM tracker calibration had long been seen as the Holy Grail for clinical applications, since the inherent accuracy of systems used to fall an order of magnitude behind that of the optical trackers. However, in recent years, the newer generation FGs exhibited better accuracy (see Sec. 4) due to improved materials, production techniques, and system design, and because a great deal of research was invested in the optimization of coil arrangement or through patented technologies [2].

System-level calibration must be performed in a structured manner. As discussed in Sec. 3-E, the mean and STD components of an error should be treated separately. While averaging and smoothing (e.g., using Kalman filters) can work against jitter, the static error needs a more systematic approach for alleviation. Most calibration techniques target the static error using distortion field assessment, mapping, and compensation, yet without measuring the overall error beforehand.

There is a clear cost-benefit consideration to be made regarding calibration for each clinical setup or research installation. While some degree of improvement in spatial accuracy can always be achieved by calibration, the time and additional effort this procedure requires may not be considered worth the effort. This is especially true in the case of clinical applications, in which the total time spent in the operating room for the procedure is a key performance indicator, and setup time, including distortion field mapping for compensation, should be minimized. Manufacturers might argue that static calibration methods are more realistic and feasible regarding clinical applications, and static measurements may be taken during every system installation and also periodically to maintain a certain level of accuracy. However, real-time model-based assessment and calibration of the whole EM field is neither practical nor achievable, since too many disturbing effects would need be be modeled and included in the equations.

Similarly, it can be assumed that performing dynamic calibrations makes sense only to the extent that the user may acquire a better understanding of the systems' baseline performance. For some applications, the velocity-dependent error might be considered as important, as it indicates a limit of speed for clinical motions.

Calibration should be considered at the system level. Where most accuracy improvement can be achieved, that particular area should be targeted. For example, if the jitter is significantly larger than the static distortion, calibration will not be of much help. The same is true if the patient's image is of low quality, the registration is performed poorly, or the instruments are not calibrated properly [63]. At the end of the day, the clinicians using the EM tracking systems will be the ones to affirm the usability of the tool, with accuracy being a critical component, but also soft requirements other than pure target numbers may be important.

It is worth noting that in many procedures, the absolute accuracy of tracking (relative to a world coordinate system) defined by the FG, is secondary to the accuracy of the position of an instrument relative to another. Such a situation occurs in many instances when navigating an instrument relative to a tracked imaging source, such as an endoscope [23] or an ultrasound transducer [113]. In these cases, any constant bias that may be introduced into the environment will affect both devices. Consequently, the relative accuracy between two sensors may be much higher than the absolute value relative to FG.

TABLE V
RANGE OF APPLICATION OF EM TRACKING

| Clinical application | | Comments |
|---|---|---|
| Percutaneous | Punctures (general) | mostly CT-guided, e.g. [135] |
| | Liver punctures | US- and CT-guided [205] |
| | Lung punctures | e.g., [47] |
| | Spinal punctures | case report [197] |
| Catheter | Heart | cardiac mapping [97] |
| | Aorta | studies are rare; e.g., [103] |
| | Vena cava | only animal study [171] |
| | TIPSS | only phantom trial [95] |
| | Neurovascular | case report [4] |
| Endoscopic | Bronchoscopy | review available [94] |
| | ENT surgery | studies are rare; e.g., [184] |
| | Colonoscopy | new area: recent study [175] |
| Surgery | Bone fractures | intramedullary nailing [58] |
| | Arthroplasty | e.g., knee [99] |
| | Neurosurgery | e.g., [134, 200] |
| | Liver | e.g., [10] |
| Others | Virtual sonography | acronym RVS, e.g. [112] |
| | Radiotherapy | mainly prostate [37] |
| | Nasogastric intubation | feeding tube placement [129] |

## 6. CLINICAL APPLICATIONS

There are many possible applications for EM tracking in medicine and there are commercial systems also available for some of them. Whenever line-of-sight to instruments is unavailable, EM tracking becomes the method of choice for localization. However, although many studies on EM-based CAI systems have been published, the evidence regarding the clinical outcome is variable between different applications. Based on the 79 papers found during the literature reseach as described in Sec. 2, a range of applications was identified and are presented in this section. An overview of these commercial systems is given later in this section and the clinical evidence on the different applications is summarized.

### A. Range of Application

According to the findings in the literature, EM tracking has been widely used in clinical applications. An overview is given in Table V. EM tracking is always the method of choice when line-of-sight to the instrument is an issue. Numerous papers present EM-based CAI methods for minimally invasive interventions in the areas of percutaneous punctures, catheter applications, and endoscopic applications. However, in some cases EM tracking was also used for open surgery or other medical applications.

Percutaneous procedures, performed for diagnosis (e.g., biopsy) or treatment (e.g., ablation) are possible on different parts of the human body. Computer-assisted approaches are usually performed under US or CT guidance [84, 135], but MRI, fluoroscopy, or Positron Emission Tomography (PET) guidance, as well as combinations of these are also possible [183]. Krücker *et al.* and Wallace *et al.* performed patient studies of EM navigated punctures to many different organs/structures such as liver, lung, spine, kidney, adrenal gland, pancreas, lymph nodes, and pelvis [85, 186]. Other publications mostly focus on one intervention, such as navigated punctures into the liver [205], the lung [47] or less commonly, the spine [197]. However, in the domain of percutaneous punctures, line-of-sight is available in many cases, so optical tracking should be kept as a robust and accurate alternative for instrument and patient localization [198]. The trade-off between the different tracking technologies should be considered, depending on the needs of a specific application.

Catheter interventions which are possible in the human circulatory system are part of modern medical care. These commonly include a guidewire to steer the catheter inside the vessel tree. Diameters of guidewires are in the order of 1 mm or less which makes it hard to include sensors. However, most of the recent studies on catheter applications with EM tracking do not track guidewires, but track catheters without guidewires, which offer a larger diameter to include sensors. Most studies deal with catheterizations into the heart to perform cardiac mapping or ablation [97]. It should be noted that the frequently used term *Magnetic Navigation* may be misleading in this relation. It is part of the term *Remote Magnetic Navigation* (RMN) that describes a method to steer a catheter by means of permanent magnets instead of the guidewire, but not to localize it [178]. To make things even more confusing, RMN is sometimes combined with EM tracking to localize the steerable catheter during the intervention [178]. Other catheter applications using EM tracking are rare in the literature, but there are examples of aortic [103], neurovascular [4], and vena cava catheterizations [171]. Transjugular Intrahepatic Portosystemic Stent Shunting (TIPSS) was also tested in a phantom trial [95]. For catheter interventions, EM tracking often is the only technology to localize the instruments when line-of-sight is not available. However, the need for a cable connection to the sensor is still a problem for these types of interventions, because it usually blocks the catheter and does not allow the use of guidewires. Recently, new methods to include EM sensors into guidewires have been presented but were only tested in phantoms so far [24].

Endoscopes offer a much larger diameter than catheters, making EM tracking easier to apply. Most studies were found on computer-assisted bronchoscopy, where the bronchoscope can be navigated through the bronchial tree by localizing the tip and registering preoperative data, for example CT to patient [94]. Laparoscopic interventions such as lung brachytherapy [96] or Radio Frequency Ablation (RFA) [56] also have been performed. In the case of otolaryngologic (ENT) surgery, endoscopes have been localized using EM tracking to apply navigation under US/CT guidance [41, 184]. Colonoscopes have been tracked by means of an integrated sensor to visualize the path of the instrument during the intervention [175]. Thus, tracking endoscopes during an intervention seems to be a reasonable application for EM tracking and is feasible with the current technology. However, establishing clinical use of these systems is often hindered by other problems, which are discussed in Sec. 6-C and 6-D. One system that has been described recently [113] has demonstrated utility for navigation during intracardiac mitral valve repair. This system relies on the relative accuracy between the position of an instrument and the imaging ultrasound transducer. Also, because it is concerned only with the safe navigation of the instrument to the site where image-guided repair will take place, (rather than guiding the entire procedure, including the action on the target that is achieved under local real-time ultrasound guidance) the accuracy of instrument positioning relative to the US image needs only to be in the range of 3-5mm [97].

In the case of open surgery, EM tracking has been used for some specific applications. For instance, it is an interesting option for enabling computer assistance during intramedullary nailing, a special bone fracture therapy in which the nail is inserted into the bone while line-of-sight is blocked [58]. Additionally, one study tested EM tracking in comparison to optical tracking for bone surgery [98]. Knee/hip arthroplasty has also been performed using EM tracking in comparison to optical tracking [99]. Computer-assistance for neurosurgery is well developed in clinical practice, but mostly mechanical or optical tracking is used [49, 75]. Although high accuracies are required, which usually points to optical tracking as method of choice, a few researchers have navigated neurosurgical interventions using EM tracking [174, 134]. In some cases, namely placement of depth electrodes for epilepsy treatment [200] or catheter placement in the cerebral ventricular system [155], line-of-sight is blocked and so EM tracking is the only option to track the instrument. EM tracking also was used during open liver surgery in combination with an optical tracking system [10]. Hence, some specific cases in open surgery in which line-of-sight is blocked, also seem a field of application for EM tracking.

Remote Virtual Sonography (RVS) involves fusion of US and CT/MRI images and is often achieved by tracking the US probe using EM technology [112]. This technique is sometimes used for guidance of punctures without tracking the puncture needle itself, but instead using conventional US-guidance for needle insertion. Another possibility is to use this technology for non-invasive diagnosis, such as for breast cancer [126]. Some manufacturers offer such RVS systems that include EM tracking, see Sec. 6-B. US probes also have been tracked electromagnetically to enable 3D US by combining multiple 2D US scans from different directions into a 3D image [33]. Especially for laparoscopic US, this approach was proposed by several groups, [42, 190] because line-of-sight is unavailable. This excludes optical tracking and the probes must be small, which makes it hard to use other techniques for 3D US, such as special 3D probes.

In the case of radiotherapy, EM tracking is used for localization of tumors and surrounding critical structures, such as in and near the prostate [37]. Placement of feeding tubes is another application in which EM tracking is frequently used [129]. There also have been some feasibility studies published for speech production research [83] and back pain diagnosis [152] that used EM tracking to localize bodily parts.

As shown in Table V, there are publications on most of the areas of application for EM tracking that seem reasonable. However, most of the presented systems are still very complex to apply, hindering widespread clinical use see Sec. 6-D. Thus, practical and simple solutions that are applicable in clinical workflow still are missing for most of the applications, and this should be considered as the main challenge in this area.

### B. Commercial Systems

The literature on EM tracking included more than 20 commercial systems based on EM tracking technology. Products such as *Cath-Finder*™(Pharmacia Deltec Inc., St. Paul, Minnesota, USA) and *CathTrack*™(C.R. Bard Inc., Murray Hill, New Jersey, USA) were introduced in the early 1990s, but localization was only possible in 2D, and accuracy was in the order of 1 cm [138]. Later, more accurate systems were presented that allowed real in-body navigation. For percutaneous punctures, the US-guided *Ultraguide* system (Ultraguide Ltd., Yokneam, Israel, *out of business since 2003*) [18] and the CT-guided *Magellan* system (Biosense Webster Inc., Diamond Bar, California, USA) [123] are some early examples that are now unavailable. In the case of neurosurgery, *NEN-NeuroGuard* (Nicolet Biomedical, Madison, Wisconsin, USA) is another historical device from the late 1990s [174]. The failures of these systems may be attributed to various reasons, including the complexity of such navigation approaches in general, and specific robustness problems of EM tracking. Although some improvements were developed, these problems cannot be considered as solved and will be described for current systems in this review.

Today, many devices are available using EM tracking, some of which have seen multiple generations. For needle punctures, the *Veran ig4*™(GE Healthcare, Chalfont St Giles, Buckinghamshire, UK) [160] and the *Cappa C-Nav* (Siemens AG, Erlangen, Germany) [135] are examples of such systems. The *StealthStation*®*AxiEM*™(Medtronic Inc., Fridley, Minnesota, USA) is a similar system that also can be used for punctures [200], but also for a wider area of application, such as knee surgery [99]. *StealthStation*®and *Cappa* also have the ability to perform optical tracking. It is notable that the latter system has abandoned the use of EM tracking; an indication perhaps of the low level of clinical uptake of this procedure. For fluoroscopic interventions, the *GE OEC 9800 Plus/Fluorotrak* system (GE Healthcare) is available and offers real-time visualization of a catheter behind a frozen fluoroscopy image [185]. RVS is supported by the systems *LOGIQ E9* (GE Healthcare) [205] and *Fusion*™(Medtronic) [184]. Another company, Hitachi (Hitachi Ltd. Corporation, Tokio, Japan) offers a RVS extension for their products. In all these cases of RVS, US probes are tracked electromagnetically [77].

Navigation systems for cardiac catheter mapping are the *CARTO XP* (Biosense Webster) [89] and the *MediGuide*™(St. Jude Medical, St. Paul, Minnesota, USA). For this application, no additional imaging data is necessary because only the position of the catheter tip is needed. However, Biosense Webster also offers the possibility for navigation in combination with fluoroscopy images. *CARTO RMT* (Biosonse Webster) is a cardiac mapping/navigation system specially designed as an extension for the Stereotaxis RMN system (Stereotaxis Inc., St. Louis, Missouri, USA) [163].

Navigated bronchoscopy is supported by the *iLogic*™system (superDimension Inc., Minneapolis, Minnesota, USA) that offers guidance by means of preoperative CT data [94].

In radiation therapy, the Calypso *GPS for the Body*®system

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMI.2014.2321777, IEEE Transactions on Medical Imaging



(Calypso, Seattle, Washington, USA) is designed to track tumor and surrounding critical structures by implanted sensors, referred to as *beacons*. The Calypso tracking technology differs from other EM tracking systems (see Sec. 3) in not requiring cable connection to the sensors. So the *beacons* stay implanted and may be used for multiple radiation therapy sessions.

For neurosurgical and ENT interventions *InstaTrak* (GE Healthcare) is a system that uses EM tracking to visualize preoperative CT data relative to the instrument [78].

Recently, some new systems appeared on the market to cover new areas of application. The *ScopeGuide* system (Olympus, Tokyo, Japan) tracks the shape of the colonoscope during a colonoscopy and visualizes the instrument in 3D, which is helpful in the case of loops [175]. For feeding tube placement the *CORTRAK*®system (CORPAK Medsystems, Buffalo Grove, Illinois, USA) uses a transmitter inside the feeding tube and a mobile receiver unit attached to the torso of the patient [81]. For intramedullary nailing, the *TRIGEN SURESHOT* system (Smith&Nephew) tracks the intramedullary nail and uses a mobile FG to guide a drill [58].

Some systems were recently introduced for US-guided punctures. The *Virtual Navigator* (Esaote) enables needle navigation under US guidance using preoperative CT data. A similar approach is followed by the *SonixGPS*™system (Ultrasonix, Richmond, BC, Canada), the PercuNav system (Philips Healthcare, Hamburg, Germany), and a needle navigation extension of the *LOGIQ E9* system. The *eTRAX*™Needle Guidance System (Civco) is more focused on EM tracked needles, but also offers navigation software.

### C. Clinical Evidence

An overview on relevant clinical evidence related to EM Navigation is given in Table VI and Fig. 9. Most clinical evidence was found for EM navigated bronchoscopy (ENB), where the *iLogic*™is the most common system. This is the only domain in which review papers are available [9, 29, 94]. The main advantage of ENB is reduced radiation, because EM tracking can replace fluoroscopy most of the time [94]. Drawbacks are the extended costs of this technique, and the fact that no improvement of diagnostic yield compared to the conventional method has yet been demonstrated [94]. Motion compensation is an important issue, because the lung is affected by breathing motion [44]. In spite of the number of studies in this area, there still is a lack of high level evidence such as comparative studies [94].

There have been many studies relating to EM tracking for percutaneous punctures. However, a comparison of these efforts is difficult, because different imaging modalities (US, CT, PET, or combinations of) were used, and the applied commercial systems also differ between these studies. Moreover, the results are not consistent for all parameters. Grand *et al.*, for example, found no improvements, but an increased procedure time compared to the conventional approach using the CT-guided system *Veran ig4*™ [47]. In contrast, Narsule *et al.* found a decreased procedure time for the same system [127]. Motion of the target structure is a problem for some percutaneous interventions, mostly due to breathing during punctures in the field of the abdomen. Motion compensation may be beneficial in this area [198]. Some studies determined the overall targeting accuracy of navigated punctures, which is shown in Table VII. A mean accuracy of 6 mm and below seems feasible for good systems.

TABLE VI
CLINICAL EVIDENCE OF EM TRACKING

| **Application [System]** | **Clinical Evidence** |
|---|---|
| Bronchoscopy (ENB) [*iLogic*™] | Many studies, reviews available [9, 94].<br>Advantages: no radiation<br>Drawbacks: costs, no improvement of diagnostic yield shown<br>*(high level evidence still missing) [94]* |
| Percutaneous punctures [different systems] | Many studies, lack of comparability<br>- US-Guided: [18, 52, 205]<br>- CT-Guided: [47, 109, 127, 135, 160]<br>- Others/Combinations: [100, 111, 183] |
| Nasogastric intubation [*CORTRAK*®] | 5 studies [81, 105, 106, 129, 192]<br>Advantages: no endoscope needed [105], faster [129], cost-saving [129]<br>Drawbacks: none reported |
| Virtual sonography (RVS) [different systems, same principle] | 5 studies [76, 126, 125, 112, 91] Improved diagnosis compared to conventional US. [126, 125, 112] No benefit compared to contrast enhanced sonography. [76] |
| ENT surgery [*InstaTrak*] | 4 studies, when compared to optical tracking [108]: no differences. Others without control group [41, 78, 184]<br>Advantages: Accurate structure localization [78, 184], fast setup time [41]<br>Drawbacks: High costs, low availability [184] |
| Radiotherapy [Calypso] | 3 studies [37, 157, 193]<br>Advantages: Better patient outcome compared to conventional radiotherapy [157]<br>Drawbacks: High costs, lower accuracy than US localization [37], tracks position (no orientation) only of up to three sensors [104], more prospective validation is needed [90] |
| Knee/hip arthroplasty [*StealthStation*® *AxiEM*] | 3 studies [99, 176, 179]<br>optical tracking also possible, no significant difference in comparison |
| Cardiac catheterization [*CARTO*] | 2 studies [70, 131] and 3 case reports [93, 161, 182]. Problem: most studies focus on RMN, not on EM Navigation. |
| Neurosurgery [*NEN-NeuroGuard*] | 1 study [134] and 3 case reports [22, 174, 208], mostly from 2001 and 2002, commercial system meanwhile disappeared from the market. |
| Other applications | Only single clinical study or less (phantom/animal trials, case reports) |

Feeding tube placement by nasogastric intubation was the focus of a few studies in which the relatively new *CORTRAK*®system showed very promising results. No endoscope was necessary, the procedure was faster and less costly, and no drawbacks were reported [81, 105, 106, 129]. An earlier study that used a different system also showed promising results [192].

Concerning virtual sonography (RVS), which is used for diagnosis and puncture guidance, a better detection rate for breast tumors was found compared to conventional US/MRI combined diagnosis [126]. In a study investigating the detection of the ablation area after RFA, contrast enhanced sonography seemed to be a good alternative to RVS [76].

For ENT surgery, the *InstaTrak* system was tested in several

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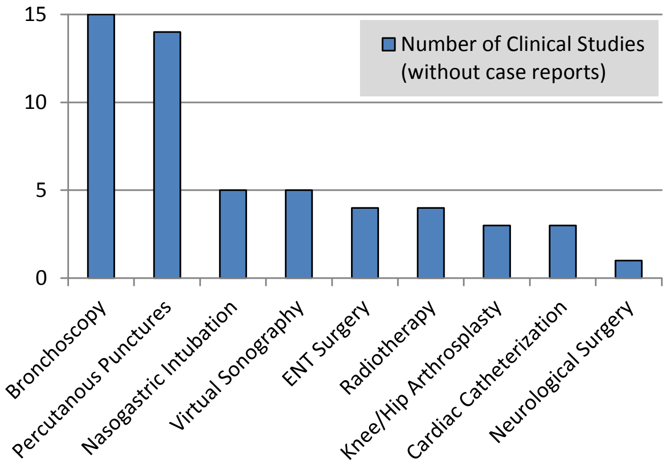


Fig. 9. Shows the number of clinical studies with EM tracking based CAI systems per clinical application found during the literature research.

patient studies. Compared to another system with optical tracking, Metson *et al.* found no significant differences [108]. Other studies did not include a control group and a comparison to conventional ENT surgery was missing. Among the advantages of EM navigation, the authors listed accurate structure localization during the intervention [78, 184] and fast setup time [41]. As drawbacks, high costs and thus low availability of such systems were reported [184].

In radiotherapy, the Calypso *GPS for the body*®system was tested in several studies. Although the results were promising because of better quality of life outcome and a reduced mortality [157], more prospective validation is needed [90].

EM navigated arthroplasty on the knee or the hip using the *StealthStation*®*AxiEM* system was the focus of three clinical studies. In this area, optical tracking is commonly used, so all these studies compared the EM-based system to one of the optical systems, but no significant differences were found [99, 176, 179].

For cardiac catheterization, Kim *et al.* found a reduced fluoroscopy time when using the *CARTO XP* system [70]. Most of the other studies used RMN in combination with EM tracking, focusing on RMN. Drawbacks, such as the fact that navigation is not allowed for patients with pacemakers, may occur when using RMN. The results mostly cannot be attributed to the use of EM tracking.

In neurosurgery the *NEN-NeuroGuard* system was subject to studies in 2001–2002 [134, 174, 208], but the system meanwhile disappeared from the market and current navigation systems for neurosurgery use optical tracking [49]. However, there are some newer studies that tested EM tracking in neurosurgery, although they focus on very specific applications such as radiofrequency thermocoagulation [22] or depth electrode placement [200].

All other applications were either single clinical studies, or less evidence-based case reports or phantom/animal trials.

## D. Discussion

As shown above, a wide range of applications has been tested using computer-assisted methods based on EM tracking. However, problems with accuracy and robustness (see Sec. 4) raise the question whether these drawbacks should be accepted if alternative modalities, such as optical tracking devices, are available. A few clinical studies directly compared EM with optical tracking and confirmed the better accuracy and robustness of the latter [99, 153, 172]. Optical systems mainly are used for neurosurgery [49, 75], and it is perhaps not surprising that the EM-based system *NEN-Neuroguard* quickly disappeared from the market. Most of the current EM-based navigation systems cover applications for which line-of-sight cannot be established, making optical tracking infeasible.

Many publications on the clinical utility of EM tracking are available, but most are feasibility studies performed on phantoms or animals, and clinical studies are rare. Review papers only are available for ENB applications, but even there the authors complain of the lack of high level evidence by prospective comparative studies [94]. As shown by assessments of EM tracking devices (see Sec. 4), tracking accuracy suffers in some clinical environments, although this fact is not clearly reflected by the published clinical evidence. Possibly, problematic applications already fail in a phantom state and/or are not published due to publication bias [28]. Thus, one must be very careful when applying EM-based navigation systems in a new clinical environment.

Besides all known problems of EM tracking, navigation failures also can be caused by other factors. In this context, a clear distinction between the terms *tracking* and *navigation* is necessary. Tracking, as discussed at length in this paper, is the technology to localize instruments, and it is only one component of a medical navigation system. When analyzing such systems more errors of other components, due to such aspects as image-to-patient registration, calibration or operator errors can easily exceed the error of the tracking sub-system. For example, physiological motion (e.g., due to breathing or heartbeats, which can corrupt the image-to-patient registration) is a serious problem for abdominal interventions [198]. Thus, for most CAI systems, an error model [54] helps to understand possible error sources and estimate risks for clinical application. This information could help to estimate the required minimal accuracy of a tracking system to meet the needs of a specific navigation task. However, typically in the case of instrument navigation, the errors are usually in the order of a couple of millimeters, see e.g., Table VII, and for such applications, sub-millimeter tracking accuracies are needed to assure that the tracking error does not dominate the overall whole system accuracy.

Another possible reason for the lack of evidence is the fact that clinical trials with research prototypes are difficult. It becomes easier if commercial devices are available that are already approved as medical devices. More than 20 of such systems have been presented (see Sec. 6-B), with most having been used for clinical studies and demonstrating acceptable results. In addition, the manufacturers are obligated to carry out essential performance tests (and sometimes accuracy as-

TABLE VII
PATIENT STUDIES ON ACCURACY OF EM NAVIGATED PUNCTURES

| Study | Organ | System | Accuracy |
|---|---|---|---|
| Meyer *et al.* [109] | Pelvis, Pleura, etc. | *CAPPA* (C-Arm) | $5.4 \pm 1.9mm$ [n=12] |
| Penzkofer *et al.* [135] | Liver, Pelvis, etc. | *CAPPA* (CT) | $3.1 \pm 2.1mm$ [n=25] |
| Krücker *et al.* [85] | Lung, Liver, Kidney, Spine | custom (CT) | $5.8 \pm 2.6mm$ [n=65] |

sessments) to get legal approvals for their systems in most countries. In this context it is worth mentioning that the American Society for Testing and Materials (ASTM) lately published a protocol for surgical navigation system accuracy under the title ”Standard Practice for Measurement of Positional Accuracy of Computer Assisted Surgical Systems” (ASTM F2554-10).

However, none of the commercial systems has reached wide clinical use, and some have already disappeared from the market. This could be attributed to the high costs and added complexity when compared to conventional approaches, which is manifested through the following drawbacks of EM tracking:

- need for cables to connect sensors,
- expensive sensors and re-using them is complex,
- technical problems of EM tracking (e.g., no patients with pacemakers, no metal near the tracking system),
- need for additional hardware, especially the FG, which leads to long setup times in clinical practice.

These drawbacks must be compensated for by real clinical benefits to achieve widespread use of a system. Additionally, factors influencing clinical utility—such as distance to large-scale medical devices (e.g., CT scanners) that might influence the tracking accuracy—have to be considered [206]. Taking these factors into account, a system must be integrated seamlessly into the clinical workflow to find acceptance in practice. In this respect, a particular problem arises for interventions that take place in or near an MRI suite. So far, no EM tracking system is ready for use inside strong external magnetic or electromagnetic fields, such as those originated by an MRI scanner.

Nevertheless, some new commercial systems have appeared on the market recently and show promising results in the first clinical studies. The *ScopeGuide* (Olympus) for colonoscopy, *CORTRAK*® (CORPAK) for feeding tube placement, and *TRIGEN SURESHOT* (Smith&Nephew) are examples of systems that open new applications for CAI by the use of EM tracking. The latter two use relatively small mobile FGs attached to the patient. This approach is promising because it makes the system more robust against field distortions [102]. Results also show that the *CORTRAK*® system is adding real clinical benefit by reducing time and cost of a feeding tube placement [129].

## 7. SUMMARY & OUTLOOK

As shown in this review, more than 300 studies related to EM tracking in medicine currently have been published. Fig. 10 shows the findings per annum subdivided into the four areas: *Fundamentals* (Sec. 3), *Assessment* (Sec. 4), *Compensation* (Sec. 5) and *Clinical Applications* (Sec. 6). The number of publications per year has increased from below 10 in the early 1990s to 50 in 2012. In clinical applications, including clinical studies, the number has been growing steadily since 2004 and has recently led to the first review papers in the field, which indicates the growing interest in the technology. While there are only three different manufacturers of standalone EM tracking systems, we found that 24 different commercial systems for medicine based on EM tracking have appeared. Although not all manufacturers describe their tracking technology in detail, some of them have clearly integrated one of the standalone systems, while others have developed their own solutions. We identified three fundamentally different EM tracking technologies (AC EM tracking, DC EM tracking, passive transponders), as described in Sec. 3, which have been evaluated in more than 60 assessment studies. Some of them use standardized, comparable assessment protocols that allow for interesting comparisons of the results, as shown in Table III. It was noted that the robustness of EM tracking suffers from nearby metallic objects, which are often part of the clinical environment. In addition, more than 40 studies presented and evaluated methods to compensate for these errors as described in Sec. 5. Finally, some manufacturers have also developed systems that can be used in environments such as those with a metal operating room table, and this is one possible solution for those environments.

However, until now, no CAI system based on EM tracking has reached widespread clinical use, perhaps indicating the difficulty of integrating this technology into the clinical environment. The question naturally arises: How will EM tracking develop in the future? What developments are needed to improve robustness and accelerate clinical application?

In general, EM tracking still is the best established method of tracking when no line-of-sight is available [137, Chap. 2]. To date, no universally applicable alternative has been presented, and if this stays unchanged, EM tracking will remain an important technology, despite the known drawbacks. Besides the technical drawbacks, such as the lack of robustness (see Sec. 4) and the need for additional hardware (see Sec. 3), cost also may be a factor to be considered. While EM tracking is generally less expensive than optical tracking, it requires specially constructed tools with a trackable embedded sensor. However, given the costs of other disposable items such as ablation catheters, this may not be a limiting factor. Reusable sensors currently are not practical for many cases and may lead to issues of sterilisability and fatigue of materials, causing the sensors to break or provide false measurements.

In the field of standalone medical EM tracking systems, there are still very few manufacturers. One of these, Ascension, was recently bought by NDI, leaving only two manufacturers: NDI and Polhemus (see Sec. 3-F). Since many patents in this area remain (see Sec. 3-C [138]), more vendors may arise if EM tracking finds widespread use which might lead to a stronger competition in the market and thus better products.

Besides stand-alone EM tracking systems, manufacturers who develop their own systems as part of CAI products should also be considered [104]. Unfortunately, these tracking

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMI.2014.2321777, IEEE Transactions on Medical Imaging



systems may be difficult for researchers to access.

From a technical perspective, there are actual technical differences between the different tracking systems (see Sec. 3-C). While the pros and cons of the AC and DC EM tracking technologies are similar (see Sec. 3 and Sec. 4), the passive transponder technology offers an interesting advantage—the transponders are small and wireless. Unfortunately, the only working passive transponder system is integrated into a complex medical product—the Calypso system [104], which covers only a small tracking volume (see Sec. 3-C) and is not available as a standalone tracking device [104]. Other research groups and manufacturers are working on passive transponder tracking systems, one example being based on RFID technology [158], but at the time of writing, all are at an early stage and not yet capable of tracking with high (mm) accuracy [158]. Hopefully, these systems will become functional, robust, and accurate in the near future and this might open new possibilities for EM tracking. If so, the next step would be to evaluate them carefully (preferably by using a standardized protocol) and compare them with the currently available systems. Some non-standardized assessments of the Calypso system (see Sec. 4-B) already are available and providing promising results [159].

Given the issues mentioned above, the question arises whether fundamentally different technologies are needed to achieve feasible tracking without line-of-sight. Some authors presented approaches to combine EM tracking with other technologies, such as image registration [115, 173] or localization using accelerometers [101]. Recently, the NDI Compact FG (see Sec. 3-D) was combined with a robot plus an additional optical tracking system to constantly move the FG such that the sensor stays in a central area of the EM field where accuracy is best [149]. Alternatives to completely replace EM tracking have been proposed when additional information of the tracked instrument is available, such as a color or range image of an endoscope [80, 116]. In these cases, camera pose estimation algorithms can be used to track the position of an instrument relative to the region of interest. Another possibility is fiber-optic based tracking [130] such as the systems presented by Luna Innovations Inc. (Roanoke, VA, USA) [30]. Besides these, real-time medical imaging modalities such as fluoroscopy also can be used for image-based tracking algorithms [5, 133]. However, all these tracking technologies are quite specific and not generally applicable. Most of the technologies are still in an early stage and/or are not robust enough for clinical use. Nevertheless, EM tracking seems to be the most advanced technology, reflected by the fact that we found no medical products included in any of the other tracking technologies.

Regarding error compensation of EM tracking, much work has already been published (see Sec. 5), but few of the methods are practical in a clinical situation. Some approaches propose additional calibration procedures (see Sec. 5), but most CAI systems add complexity to clinical workflows even without these additional procedures. If such approaches are needed to improve EM tracking in the future, they should be simple and easy to use, preferably without any user interaction. A very useful feature in this context that might be easier to implement would be to track error detection, so that the system would be able to issue a warning if accuracy was compromised at any given moment [118]. This would make systems much safer in practice.

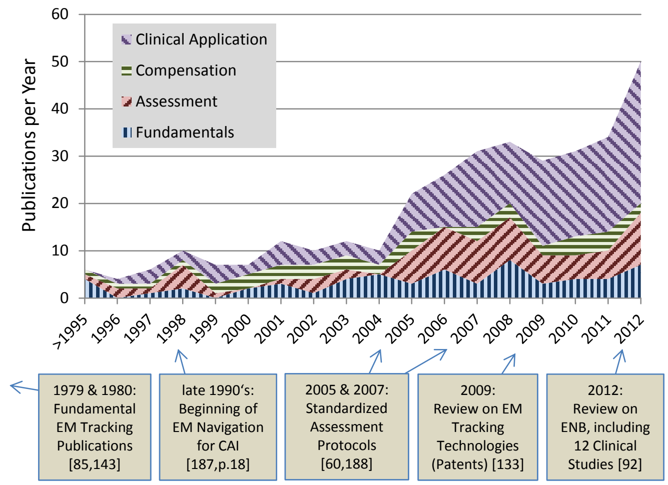


Fig. 10. Publications per year from the literature research of this review. The lower boxes mark some important milestones.

A more widely used approach to avoid errors is customization of EM tracking systems. For example, if the EM field is shielded using a special design or if the tracking volume is limited to a small area of interest, fewer tracking errors will occur in practice [102]. Some commercial systems already use customized EM tracking systems and the results of the first studies look very promising (see Sec. 6-C).

The robustness of EM tracking may cause some concerns, but this issue can be addressed with careful verification in actual clinical environments. New customized EM tracking systems should be evaluated carefully, in the same way as classical systems, and this will accelerate standardization. The current standardized protocols provide a good starting point, but some drawbacks have been reported and they should be extended to cover all relevant aspects, such as rotational errors and dynamic effects [102]. It is notable that several prominent research groups[10] have formed a joint initiative to provide the community with a unified approach to system assessment that should be published in the near future.

## 8. Conclusion

When accurate localization without line-of-sight is required, EM tracking is the method of choice, and an averaged accuracy of 1.0 mm is achievable in good environments. However, an awareness of the lack of robustness against sources of

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distortion is necessary, because the accuracy might drop dramatically.

While several clinical EM tracked systems have emerged, so far none has reached wide clinical use. When new products are developed in the future, some of the problems of previous systems should be taken into account, notably

1) problems with workflow integration,
2) robustness problems of EM tracking and
3) cost issues with embedding sensors into clinical tools.

Some of the problems can be avoided using customized systems, however, the robustness of EM tracking can be an issue in some environments so all systems should be evaluated very carefully in clinical practice. In some situations in which an instrument must be tracked relative to an imaging probe such as US or video-endoscopy, direct image-bases tracking may be contemplated [64, 119].

In conclusion, EM tracking is useful for specific medical applications if (1) tracking without line-of-sight offers great benefits and (2) the accuracy achievable is suitable for the clinical application. Careful evaluation of an EM-based CAI system in a specific clinical context is required, risks must be analyzed and finally, the benefit for the patient demonstrated by the use of clinical trials.

## Acknowledgments

This research was supported by the Research Training Group 1126: "Intelligent Surgery" funded by the German Research Foundation (DFG), by the Hungarian NKTH OTKA CK80316 grant at BME and by the Intramural Funding Program of the German Cancer Research Center (DKFZ), Grant for Young Investigators: "Radio-frequency identification (RFID) for wireless tracking of medical instruments". T. Haidegger is a Hungarian Eötvös Fellow, his work is supported by the HAS Bolyai Fellowship. The Authors further thank Thomasz Bien for the insightful comments about EM tracking and helpful hints regarding interesting papers as well as Árpád Takács for assistance in creating Fig. 2. The manufacturers of EM tracking systems Northern Digital Inc., Polhemus Inc. and Varian Medical Systems Inc. kindly provided pictures of their products for this publication. Special thanks to Jackie Williams for careful proofreading of the manuscript.

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