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Information technology — Real time locating systems — Test and evaluation of localization and tracking systems

Technologies de l'information - Systèmes de localisation en temps réel - Essais et évaluation des systèmes de localisation et de suivi

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Contents

Page

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

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Introduction

There exists a potentially large market for personnel / asset Localization and Tracking Systems (LTSs) in diverse application domains such as:

— emergency response;

— military;

— law enforcement;

— mining;

— E-911;

— offender tracking;

— personal vehicular navigation;

— smart phones / social networking;

— fleet management;

— asset tracking in factories / warehouses / hospitals;

— tracking the elderly / children; and

— personal navigation in museums / shopping malls.

Some applications of localization and tracking – such as personal navigation, fleet management, and asset tracking in factories / warehouses / hospitals – are commonly referred to as Location-Based Services (LBS). The use of LBS alone is expected to grow dramatically by 2020. Yet, lack of standardized Test and Evaluation (T&E) procedures has been an impediment to market growth for LTSs, because:

i) potential users cannot easily determine whether these systems meet the users' requirements;

ii) it is hard to interpret T&E results when different metrics and procedures are used to evaluate a given system or even worse to evaluate different systems; and

iii) the use of disparate minimum performance requirements by various buyers / jurisdictions forces manufacturers to develop jurisdiction-specific products, thereby raising manufacturing costs.

In contrast with LBS, there are many applications of localization and tracking that are essentially governmental functions in the sense that the government is the entity that is most concerned about the effectiveness of solutions for such applications. Examples of these applications include tracking firefighters entering a burning structure for command and control purposes and to launch a rescue mission if a firefighter becomes incapacitated, prevention of friendly fire when soldiers or Special Weapons And Tactics (SWAT) team members enter a building where either hostile forces or armed individuals threatening public safety have taken refuge, and guidance and navigation for missiles and precision-guided munitions. Many of these applications have more stringent localization accuracy and latency requirements than other applications of localization and tracking used by the general public, such as navigation in museums / shopping malls, tracking the elderly in nursing homes, ensuring children are not abducted from school grounds, and fleet management for a trucking company.

This document deals with T&E of LTSs. Once standardized T&E procedures have been established, it is possible to set minimum performance requirements for various applications of localization and tracking. For example, regulations promulgated by a government agency may require coal mine operators to have the capability to track the miners on duty within 5 m accuracy during normal mine operations and 100 m accuracy in the aftermath of a catastrophic incident in the mine, such as an explosion or a roof collapse. It makes sense to separate the T&E issue from minimum performance requirements, because the same T&E standard may be applicable to many applications of localization and tracking, but the minimum performance requirements typically vary from one application to another. This document deals with T&E only; it does not set minimum performance requirements for any localization and tracking applications.

T&E of LTSs is challenging for several reasons:

i) Many systems work in a "networked" fashion. That is, several devices would have to communicate with each other in order to estimate the location(s) of one or more such devices. Therefore, the LTS performance is affected by how these devices are situated with respect to each other, i.e. by the network topology.

ii) The physical environment in which the devices are situated affects communications between them and functionalities such as ranging or estimating direction of another device and hence LTS performance. For example, Radio Frequency (RF) communications in a single-family house with a wooden structure is very different from that in a large high-rise building with a steel and concrete structure.

iii) Even though it is best to take a "black-box" approach to LTS T&E, one needs to be cognizant of the failure modes of various location sensors (such as Global Positioning System (GPS), RF ranging, RF direction of arrival estimation, accelerometer, gyroscope, and altimeter) that "might" be used in an LTS in order to design a comprehensive T&E procedure.

Yet another difficulty of a different nature is that some systems rely on the availability of a networking infrastructure, such as a Wi-Fi network, or other devices, such as Radio Frequency IDentification (RFID) or Real Time Locating System (RTLS) tags, to facilitate localization and tracking in a building or structure. Some allow deployment of such devices – sometimes called "breadcrumbs" – as users enter a building. Other systems are designed to function based on the assumption that they cannot get any help with localization and tracking from the building and breadcrumb deployment is not allowed. Therefore, the T&E procedure has to account for these possibilities or classes of LTSs.

The main purpose of this document is to develop performance metrics and T&E scenarios for LTSs. LBS are envisaged in many application domains in both governmental operations and general public usage scenarios. Therefore, industry, consumers, trade, governments, and distributors are all affected by this document. Every effort has been made to write this document in such a way that it would be applicable to as many applications of indoor localization and tracking as possible. This document provides explicit instructions on how to report the T&E results, i.e. what information to document and what kind of tables and figures/plots to include to best visualize the results of the T&E effort. LTS T&E is complicated even once this document has been published, because there has to be a "network deployment" and testing in at least a few types of buildings. One should not expect that LTS T&E can be done in a laboratory. Performance results can depend on the particular building(s) used in the T&E procedure, but at least there will be a standardized way of doing the T&E, and if multiple LTSs are evaluated according to the standard in the same set of buildings, then the performance results can be compared. Localization and tracking technology has not yet matured. New systems and approaches will be developed in the next several years, but the T&E procedure can be standardized regardless of what takes place on the technology front and it may in fact foster technology development. In the absence of a T&E standard, the present uncertainties in the LTS market, where it is hard for users to ascertain whether LTS products meet their requirements and LTS vendor claims are hard to verify, will continue. Therefore, this is indeed the right time for development of this document.

Extensions of this standard to other application domains, such as miners trapped in an underground mine, navigation for submersible vehicles or tiny medical devices moving around inside a human body, may be the subjects of future standards that will be extensions of this "base" standard.

As a final note, the term "localization and tracking" has been used to denote the types of systems this document is meant to be applied to. However, this is not the only term in use for referring to such systems. ISO/IEC JTC 1/SC 31 uses the term RTLS, which also appears in the full name for this document. SC 31, in its deliberations, considered the use of the term "positioning" for the situations in which a person/object equipped with an appropriate device, uses that device possibly in conjunction with others and as part of a system to determine its own location. That is, "positioning" is for self-awareness. On the other hand, SC 31 regards "locating" as the appropriate term for the situation in which some other entity needs to determine the location of a person/object remotely. In other words, “locating” is for tracking and accountability purposes. There is also the possibility that a system needs to provide both ”positioning” and “locating” functionalities (see 5.4.4), using the terminology just defined. “Tracking” is another frequently used term that has a time dimension to it. That is, one needs to keep track of a person/object’s movements over a period of time. In its simplest form, tracking can be done by invoking a locating capability periodically over the time interval of interest. However, tracking can also take into account the mobility characteristics of the person/object being tracked. For example, it is highly unlikely that a firefighter would move faster than 1 m/s while putting the fire down in a burning building, and this information can be used to do a better job of estimating the firefighter’s location at any given time. “Location System” is another term used in the literature. Yet another term, often encountered in military applications, is “navigation”. In order to navigate a person/object to some destination point, it is necessary to know the person/object’s starting location at a minimum. In case of navigating a missile or smart bomb, where missing the target or hitting something else can have catastrophic consequences, it is necessary to know the missile’s/bomb’s location continuously so that any deviations from its intended path/course can be corrected. Navigation includes computing a path to the destination. This path is not always the direct line from the starting location to the destination. For example, consider navigation in city streets or for providing guidance to a disoriented firefighter to get out of a burning building. Even though this document does not deal with navigation, it does deal with that component of navigation that has to do with where a person/object is at a given time.

This document adopted the term “localization” to capture both locating and positioning functionalities, because the person/object has to be “localized” in either case. It also adopted the term “tracking” to ensure the standard is not just about a snapshot of person/object’s location, but also addresses its evolution over time. As a matter of fact, SC 31 has so far focused on purely RF–based systems, but this document considers systems that may use a variety of sensors for localization and tracking, including Inertial Measurement Units (IMUs), whose performance is indeed affected by how the person/object is moving.

Information technology — Real time locating systems — Test and evaluation of localization and tracking systems

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document identifies appropriate performance metrics and test & evaluation scenarios for localization and tracking systems, and it provides guidance on how best to present and visualize the T&E results. It focuses primarily on indoor environments.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
entity to be localized/tracked
person / autonomous robot that needs to know its location for context-awareness / navigation purposes or person/object whose location is needed by a tracking authority at a given time instance or over a time interval

Note 1 to entry: See the abbreviation ELT in Clause 4.

3.2
location sensor
device that measures a physical quantity to facilitate estimating the spatial coordinates of a person/object in a reference coordinate system

3.3
entity localization/tracking device
equipment carried by a person or affixed to an object comprising one or more location sensors that facilitates estimating the location of the person/object at a given time instance or over a time interval

Note 1 to entry: to entry: See the abbreviation ELTD in Clause 4.

4 Abbreviated terms

AOA	angle-of-arrival
AP	access point
CCD	charged coupled device
CDF	cumulative distribution function
CE95	circular error 95%
CEP	circular error probable
ELT	entity to be localized/tracked
ELTD	entity localization/tracking device
EMI	electromagnetic interference
ERP	effective radiated power
GDOP	geometric dilution of precision
GNSS	global navigation satellite system
GPS	global positioning system
IMU	inertial measurement unit
INS	inertial navigation system
ISM	industrial, scientific, and medical
IT	information technology
LBS	location-based services
LOS	line-of-sight
LTS	localization and tracking system
MEMS	microelectromechanical systems
PDOA	phase difference of arrival
PII	personally identifiable information
RF	radio frequency
RFID	radio frequency identification
RMS	root mean square
RSS	received signal strength
RSSI	received signal strength indicator
RTLS	real time locating system
SE95	spherical error 95%

SEP spherical error probable

SLAM self-localization and mapping

T&E test and evaluation

TDOA time difference of arrival

TOA time-of-arrival

TOF time-of-flight

UTM universal transverse Mercator

UV ultraviolet

UWB ultra wideband

VE95 vertical error 95%

VEP vertical error probable

WGS 84 world geodetic system 84

5 LTS taxonomy

5.1 Types of location sensors

GPS has been the dominant technology for outdoor navigation and for tracking entities such as a fleet of taxicabs or trucks. Inertial Navigation Systems (INS) have been used for navigation purposes for a long time. These trends preceded the recent flurry of activities in indoor localization and tracking, which have focused primarily on RF-based methods. Two approaches have played key roles in fuelling the recent drive in development of LTSs. One is based on processing the signals received by a mobile device / smartphone from the base stations of a cellular telephony system. This approach works both indoors and outdoors, but its localization accuracy is not adequate for many applications. The other is based on the strength of signals received from Wi-Fi Access Points (APs) that are widely deployed in buildings / structures throughout the world. Once again, the localization accuracy of this approach may not be adequate in certain applications, and not all buildings have Wi-Fi APs.

These efforts were followed by exploring other RF-based methods, particularly for indoor environments where GPS receivers do not work due to the lack of Line-of-Sight (LOS) RF propagation paths to at least four GPS satellites. Since about ten years ago, researchers have significantly increased their efforts to develop various RF techniques for localization. Angle-Of-Arrival (AOA) estimation, even though it has been around for a long time, has been explored for indoor localization. Time-Of-Arrival (TOA) estimation has also been around, but it has been the subject of renewed interest due to the advent of Ultra WideBand (UWB) communications and ranging techniques. Widely used RF technologies such as Bluetooth, ZigBee, and RFID have been explored for indoor localization and tracking. Each of these technologies and approaches has its own pros and cons. Over time, it has become abundantly clear that purely RF-based approaches may not provide the desired localization accuracy or may not meet all the operational requirements of a particular application. For example, firefighters responding to a fire cannot assume that Wi-Fi APs or RFID tags/readers are available in the building that could be used for localization purposes. Therefore, there has been considerable effort lately to look at the use of other sensors for localization and tracking. Of particular interest and promise are hybrid LTSs that fuse the data from a number of location sensors to produce accurate location estimates. In this regard, one can design an LTS that employs a fixed set of location sensors or one that is sufficiently flexible to take advantage of whatever location sensors that might be available at any given time. For example, as a mobile platform such as a ground vehicle moves around, it may be able to use the signals from a radio station or TV tower together with the location of the transmitting antennae from the radio/TV stations for localization purposes. Such signals are called signals of opportunity.

Given below is a non-exhaustive list of location sensors:

— RF-based location sensors;
— Received Signal Strength (RSS);
— proximity, including RFID;
— TOA;
— Time-Difference-Of-Arrival (TDOA);
— AOA;
— signals of opportunity;
— range / pseudo-range finder;
— GPS / Global Navigation Satellite System (GNSS);
— differential GNSS;
— accelerometer;
— gyroscope;
— magnetometer;
— IMU;
— pedometer;
— inclinometer;
— altimeter;
— acoustic sensor;
— imager;
— optical;
— infrared; and
— lidar.

More is said about these sensors and their failure modes in Annex B.

5.1.1 Unimodal systems

Some LTSs use only one type of sensor for localization and tracking purposes. An example of such a system is the widely used Wi-Fi localization system. Such a system uses the Received Signal Strength Indicator (RSSI) available on Wi-Fi receivers to estimate location. Specifically, the Entity to be Localized/Tracked (ELT), as a Wi-Fi client, uses RSSI measurements from various APs in the building to estimate its own location. Alternatively, the APs can collaborate with each other and estimate the ELT location based on the strengths of the signals they receive from it. Another example would be an LTS that uses RFID technology only. In one variation of such a system, called Reverse RFID, passive RFID tags are deployed in the building and the ELT is equipped with an RFID reader that reads all RFID tags in its vicinity. This information enables the ELT to estimate its own location.

5.1.2 Multimodal systems

These are systems that use more than one type of location sensor. Such systems are also called hybrid systems. They use data fusion methods to combine various sensor measurements to arrive at a location estimate. The fusion process can take place on the ELT or at a designated node in the LTS. There are situations where no unimodal LTS would meet the requirements of a particular application. For example, when firefighters respond to a fire in a building, they cannot assume the building has any infrastructure (Wi-Fi APs, RFID, or other wireless technology) that could help with localization and tracking. If the firefighters and the incident command wish to have localization and tracking capability, it would have to be provided by the equipment they bring to the scene. If the building poses challenges to RF propagation, which would be the case for large buildings made of heavy construction materials like steel and concrete, then no RF-based method brought to the scene can provide the desired localization and tracking capability. (Note that firefighters are not fond of a breadcrumb solution either, because breadcrumbs may be destroyed by fire and are hard to retrieve even if they survive.) This is an example of a situation where the operational requirements of the application dictate the use of a multimodal LTS that could use GPS for outdoor tracking and inertial navigation and some form of RF ranging – even if it is not available all the time – for indoor localization and tracking.

Equipment cost might be another reason for using a multimodal LTS. There are cases where a multimodal LTS outperforms any unimodal LTS, for a given total system cost. The design of multimodal or hybrid LTSs is an active area of research and development.

5.2 Reliance on pre-existing networking / localization infrastructure

5.2.1 LTSs requiring infrastructure

A Wi-Fi localization system is an example of such a system, because it requires availability of Wi-Fi APs in the building.

Another example is LTSs that use RFID technology. There are two ways of using RFID for localization, the so-called direct way and Reverse RFID. The latter has already been described in 5.1.1. In a Direct RFID system, RFID readers are deployed throughout the building and the ELTs are equipped with RFID tags. Once a reader reads a tag, the system knows the tag is in its vicinity. If multiple readers can read/"see" a tag, then some weighted average of the reader locations would be a reasonable estimate of the tag location. Note that an RFID reader is always an active device, but the tag can be passive or active. So, there are two ways of implementing a Direct RFID system and two ways of implementing a Reverse RFID system.

It is useful to explain which type of application each system is most suited to. In a scenario where a large number of items need to be accounted for in a store, a Direct RFID system would be the appropriate choice. In this case, most likely a passive RFID tag is attached to each item and RFID readers are deployed throughout the store. This would make it possible to know the location of each item. Note that RFID readers are a lot more expensive than passive RFID tags.

On the other hand, it would be more cost effective to equip each firefighter with an RFID reader and deploy passive RFID tags throughout the building in a firefighter tracking scenario, because the number of tags that have to be deployed in any moderate to large size building in order to determine the location of firefighters with adequate accuracy is a lot larger than the number of firefighters responding to the fire that have to be tracked and accounted for. Therefore, a Reverse RFID system makes more sense in this case.

5.2.2 LTSs capable of infrastructure-less operation

Firefighters and soldiers entering a building/structure may benefit from having a localization capability, but they cannot presume that any networking/localization infrastructure is available. They need to be able to localize themselves or their comrades with the equipment they bring to the site only.

One solution in such a case is to use an INS, but the drift associated with such systems may become problematic if the user, i.e. the firefighter/soldier, spends an extended period of time moving around in the building/structure. A well-known solution to this problem is to occasionally provide the user with absolute location estimates to zero out the INS drift. For example, anchor nodes could be deployed outside the building/structure when the user arrives at the site. An anchor node is a transceiver whose location is known to the LTS, perhaps through a GPS receiver available at the anchor node. If the user has RF ranging capability and knows its distances from four anchor nodes, then the user's 3D location can be computed through trilateration. The INS is still needed for any decent size building/structure, because it is often not possible to determine the range to as many as four anchor nodes due to signal attenuation by walls, ceilings, and other objects. This is just one example of a design option for such an LTS. A number of other location sensors could be used, per the discussion of multimodal systems under 5.1.2.

5.2.3 Real-time deployment of nodes facilitating localization

In some applications it is acceptable to deploy auxiliary devices as the users arrive in a building. For example, emergency responders may deploy communication relay nodes to facilitate not only radio communications but also localization and tracking. One may regard an LTS operating based on this concept as something between an infrastructure-less system and one that needs infrastructure in the building to facilitate localization and tracking.

5.2.4 Opportunistic use of infrastructure/environment

There are some LTSs that can function with or without the availability of infrastructure in the building/structure. They typically perform better when infrastructure is available than when it is not. This is called opportunistic use of infrastructure/environment. One example of such an LTS is one that does not need availability of Wi-Fi signals in the building/structure in order to function, but it would use the Wi-Fi signals, when available, to offer more accurate localization. Another example is when the LTS uses the signal(s) from radio/TV station(s) and the location of the radio/TV transmission tower(s) to improve its localization performance compared to situations where such information is not available.

5.3 Off-line, building-specific training

5.3.1 LTSs requiring off-line training

The best example for this type of system is a Wi-Fi fingerprinting localization system. Suppose *n* Wi-Fi APs are deployed throughout a building. There are three approaches for implementing a Wi-Fi fingerprinting localization system. The first step in all three approaches consists of selecting a number of training points throughout the building, such that all areas in the building are covered with adequate density. The fingerprinting step in all three approaches is done off-line and before the system is used to estimate the location of an ELT equipped with a Wi-Fi client card.

The fingerprinting step in the first approach, which is called AP-based fingerprinting, involves recording the RSSI from a Wi-Fi client located at a given training point at all APs that can "hear" the client. Therefore, for each training point there shall be an *n*-tuple of RSSI values, with a default minimum value for the RSSI used when an AP does not hear the client. For each training point, the location of the point along with the *n*-tuple of RSSI values are stored in a fingerprint database. The localization process consists of comparing the *n*-tuple of RSSI values from the ELT measured by the *n* APs with all the fingerprints stored in the database and selecting the fingerprint that is "closest" to the APs' measurements according to some distance measure. The location of the ELT is estimated to be the location associated with the closest fingerprint or a combination of the locations associated with a few closest fingerprints. The location estimate is then communicated by the system to the ELT.

The fingerprinting step in the second approach, which is called client-based fingerprinting, involves recording the RSSI from the *n* APs at a Wi-Fi client located at a given training point. If the client cannot hear an AP, a default minimum value for the RSSI is used for that AP. Hence, for each training point there shall be an *n*-tuple of RSSI values. This *n*-tuple and the location of the training point are stored in a fingerprint database. The localization process consists of comparing the *n*-tuple of RSSI values measured by the ELT with all the fingerprints stored in the database and selecting the fingerprint that is "closest" to the ELT's measurements according to some distance measure. The location of the ELT is estimated to be the location associated with the closest fingerprint or a combination of the locations associated with a few closest fingerprints.

In the first approach the burden of localization is on the APs. The APs need to communicate their RSSI measurements to a central processor that searches the fingerprint database for the best match. This has the advantage that the ELT does not need to store or know anything about the fingerprint database and it does not have to do any work at all. The advantage of the second approach is that the APs do not need to communicate any RSSI measurements, but each ELT has to store the fingerprint database. This approach is not suitable for localizing general public visiting a shopping mall.

The third approach is a variation of the second one. The fingerprinting step is the same, but when the ELT measures the RSSIs from the *n* APs, it communicates the *n*-tuple to the localization system which returns to the ELT a location estimate for the ELT that is either the location associated with the best match in the fingerprint database or a combination of the locations associated with a few closest fingerprints. The advantage of this approach is that the ELT does not need to store the fingerprint database.

This was just one example of a system that requires off-line training, but it happens to be the one most used. In principle, it is possible to use the same procedure with other wireless technologies, such as ZigBee, Bluetooth, or even RFID.

Fingerprinting is a time-consuming process, and fingerprints change with time if:

i) new APs are installed in the building;

ii) an AP is removed; or

iii) any changes are made to the floor plans of the building by new construction or even by moving furniture around. In practice, the fingerprinting process has to be repeated once in a while and after any substantial changes in the Wi-Fi landscape.

Therefore, the need for fingerprinting is regarded as a drawback for an LTS.

Some Wi-Fi LTS developers use predictive models for signal attenuation in lieu of actually measuring RSSI values associated with each training point. The predictive model could be as simple as a power-law path loss model or as complicated as a ray tracing method. This approach is simpler than the fingerprinting methods described above, but it is not as accurate. It results in inferior localization performance, but that might be acceptable in certain applications.

5.3.2 LTSs not requiring off-line training

A Wi-Fi localization system does not necessarily need fingerprinting (off-line training). It is possible to use a formula to convert an RSSI value for an AP measured by a Wi-Fi client to a range from the client to the AP. However, such range estimates are not accurate due to the weak correlation between RSSI value and range.

One other example of a system that does not require off-line training is one that uses RF ranging. In that case, the building is equipped with a number of anchor nodes whose locations have been determined as part of the process of deploying the LTS. The ELT is equipped with an RF transceiver capable of communicating with the anchor nodes and estimating its range from them. The location of the entity is computed through ranging to different anchor nodes.

5.4 Ultimate consumer(s) of location information

5.4.1 Introduction

When the ELT has to be tracked by a tracking authority <u>and</u> the location estimation takes place solely at the ELT, the location estimate needs to be communicated to the tracking authority. This may be the case when the ELT is a firefighter and the tracking authority is the incident command set up outside a building on fire. In such a case, a radio link is needed between the ELT and the tracking authority,

