The Challenges of Indoor Environments and Specification on some Alternative Positioning Systems

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Abstract. **This paper gives an overview of the current and near future positioning capabilities for indoor environments with focus on the research activities in that field at the Institute of Geodesy and Photogrammetry at the ETH Zurich. Object of study are those novel indoor-position systems that have the potential to achieve cm-level accuracy or better which is seen as a requirement for most geodetic applications. The focus is given on four alternative positioning systems where the GeomETH group at the ETH Zurich has made some experiences. These systems are iGPS, which is a system based on a rotating infrared laser fan, the Locata system that uses GNSS similar signals on pseudolites, the Cricket ultra-sound system and a photogrammetric laser beam positioning systems (CLIPS) that is currently under development. As a result it can be noted that there are several unconventional positioning systems on their way that may compensate for the deficiencies of GNSS or total stations.**

Keywords: **Indoor positioning, alternative and novel positioning systems, future positioning scenarios**

1. INTRODUCTION

Well established positioning systems such as GNSS (Global Navigation Satellite Systems) as well as surveying total stations cover most geodetic applications for determining 3D real-time positions indoors and outdoors. However, various weaknesses and gaps remain inherent in total station systems such as the requirement of direct line-of-sight and manual setup of a relatively large sized and expensive instrument. GNSS systems clearly suffer from the attenuation and distortion in indoor environments. This paper addresses these weaknesses and looks forward to alternative positioning methods.

In general, we can not clearly separate between indoor and outdoor systems. However, precise positioning in indoor environments faces different challenges than outdoors. While indoor environments are limited in size to rooms and buildings, outdoor positioning capabilities require regional or even global coverage. Secondly, the difficulty of receipting satellite signals indoors has triggered the development of high sensitive and Assisted-GNSS receivers – with many issues remaining unsolved. Thirdly, the accuracy requirements are dissimilar between indoor and outdoor environments – typically there is a higher demand for relative accuracy indoors. Despite different conditions between indoor and outdoor environments, most indoor systems are also operable under open sky. But due to their limited operating range and their sensitivity to weather conditions, their efficiency is degraded outdoors. Vice versa we are in a similar situation: e.g. when the faded GNSS signals are used indoors, the performance for positioning is poor. Radio signal attenuation from walls causes standard GNSS receivers to perform poorly in indoor environments. The weak signals from the satellites become nearly undetectable for the receivers. Depending on the electrical properties such as the dielectric coefficient of the building material, GNSS signals are attenuated indoors by 20-30 dB (a factor of 100-1000) compared to outdoors, see Table 1. As a consequence, the attenuation in buildings is 5 – 15 dB for residential houses, 20 – 30 dB for office buildings and >30 dB for underground car parks and tunnels, see Table 2.

Table 1: Attenuation of various building materials for the L-Band (L1 = 1500 MHz), according to Stone (1997)

Material	[dB]	Factor [-]
Dry Wall	1	0,8
Plywood	1 - 3	0,8 – 0,5
Glass	1 - 4	0,8 – 0,4
Painted Glass	10	0,1
Wood	2 - 9	0,6 – 0,1
Iron Mat	2 - 11	0,6 – 0,08
Roofing Tiles / Bricks	5 - 31	0,3 – 0,001
Concrete	12 - 43	0,06 – 0,00005
Ferro-Concrete	29 - 33	0,001 – 0,0005

Table 2: Signal Strength in Decibel watt (decibels relative to one watt) of GNSS Satellites.

Environment	[dBW]	Comment
Satellite	+ 14.3	signal strength delivered from satellite
Outdoors	-155	unaided fixes OK for standard receivers
Indoors	-176	decode limit for high sensitive receivers
Underground	-191	decode limit for aided, ultra-high sensitive receivers

Besides the attenuation of the GNSS signal, the topic is more complex and high sensitivity is only one milestone according to Hein et al. (2008). Phenomena such as reflections, diffraction or scattering occur when the signals enter a building. These affects are much less well understood compared to the fading taking place in the troposphere and ionosphere that has been modeled well.

In general, the poor signal propagation and restrictions in the line of sight causes any indoor system to fail to satisfy all user requirements for positioning. Since there is no overall practical solution for precise positioning on the market yet, there are various systems under development. Figure 1 shows different systems sorted by positioning accuracy and their area of coverage. Table 3 gives some performance parameters for some selected systems.

Some attempts exploit new sensors that measure inter-nodal ranges, signal strengths, acceleration or angles for localisation; as well as research, leading to higher sensitivity algorithms for signal acquisition and tracking in harsh environments. There is also the trend of combined usage or integration of different sensor systems and data sources. The large number of available sensors has lead to a variety of localisation schemes such as triangulation, trilateration, hyperbolic localisation, data matching and many more.

The employed signal technologies include RF (radio frequency) technology, ultrasound, infrared, vision based systems and magnetic fields. The RF signal based technologies can be split into WLAN (2.4 GHz and 5 GHz band), Bluetooth (2.4 GHz band), Ultrawideband and RFID.

In general, most techniques and algorithms can be applied for both outdoors and indoors. This paper focuses on innovative positioning hardware and techniques that are currently or in the near future available to determine positions inside buildings or in the underground. In the following, some alternative positioning systems are detailed and the experiences that the ETH Zurich has made with those systems are exchanged.

Table 3: Overview of various Positioning Systems. The figures reflect only rough estimates and may vary depending on the product and are subject to change.

System	Outdoor	Indoor	Real-time	Accuracy	Range	Signal Frequency	Update Rate	Principle	Market	Cost
Geodetic GNSS	✓	✗	✓	mm	global	RF	20 Hz	TOA, lateration, differential technique	yes	moderate to high
AGPS	✓	(✓)	✓	variable, 10 m	global	RF	1 Hz	TOA, lateration	yes	low
GNSS-INS	✓	✓	✓	variable	global	RF	20 Hz	TOA, integrating angular velocity and linear acceleration	yes	variable
Locata	✓	✓	✓	6 mm, 2 mm static	2-3 km	RF	1 Hz	TOA, lateration	in progress	high
Laser Tracker	(✗)	✓	✓	10 µm + 5 ppm	15 m	RF	2 kHz	angular measurements, interferometric distances	yes	extremely high
iGPS	✓	✓	✓	0.1 – 0.2 mm	2 – 50 m	RF	40 Hz	TOA angular measure-ments, spatial forward intersection	in progress	high
Cricket	✗	✓	✓	1 – 2 cm	10 m	ultrasound	1 Hz	TOA, lateration	available for development	low
DOLPHIN	✗	✓	✓	2 cm	room scale	ultrasound	20 Hz	TOA, lateration	no	moderate
Active Bat	✗	✓	✓	1 – 5 cm	1000 m^2	ultrasound	75 Hz	TOA, lateration	no	moderate
Symeo	✓	✓	✓	5 cm, 2D	400m	5.8 GHz, 61 GHz, ISM-Band	20 Hz	TDOA, lateration	yes	low
Sonitor	✗	✓	✓	m-level	15 m	ultrasound	0.3 Hz	RSSI, Cell ID	yes	low
RFID	✗	✓	✓	dm-m	20 m	RF, 866 MHz		Signal Strength	no	low

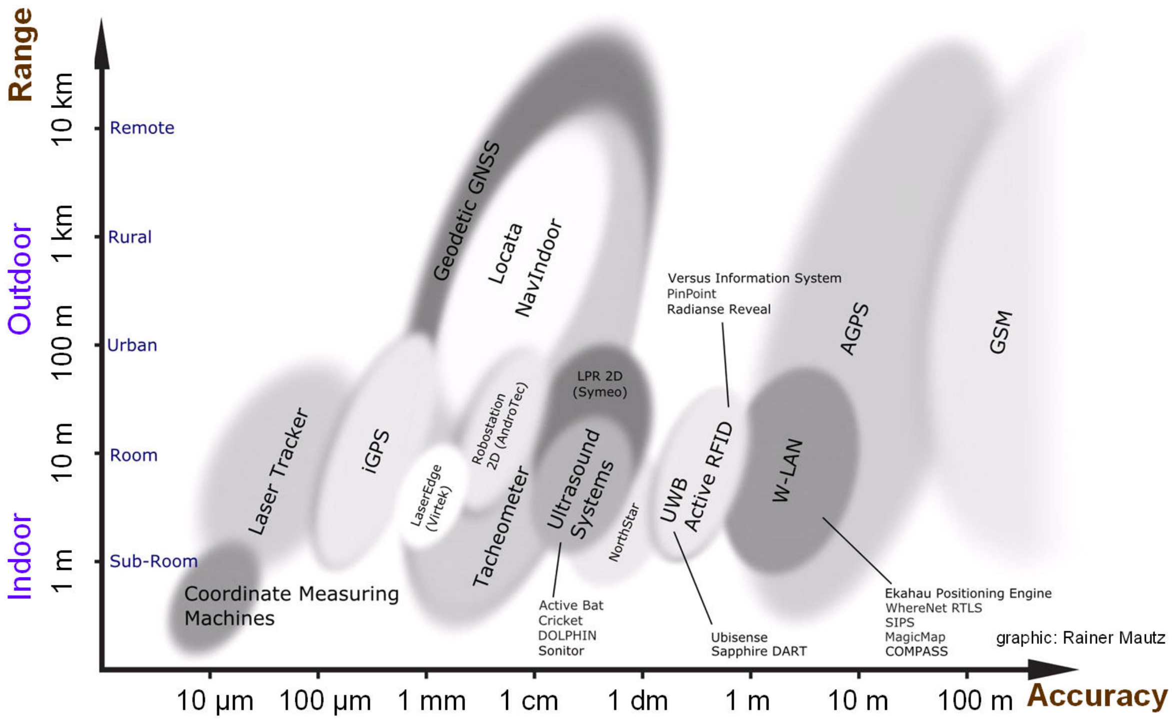

Figure 1: Current positioning systems according to their accuracy and coverage area.

2. RESECTION USING INFRARED LASER (IGPS)

The name "iGPS" is misleading, because this system is neither using GPS nor based on the principle of GPS. It is a high-precision tracking system offered by Metris that allows monitoring of several sensors simultaneously. It has a range from 2 m to 80 m for indoor and outdoor applications. According to the manufacturer an accuracy of ±0.1 mm for 3D positions can be reached. The principle is that two or more iGPS transmitters continuously send out infrared signals and rotating fan-shaped laser beams.

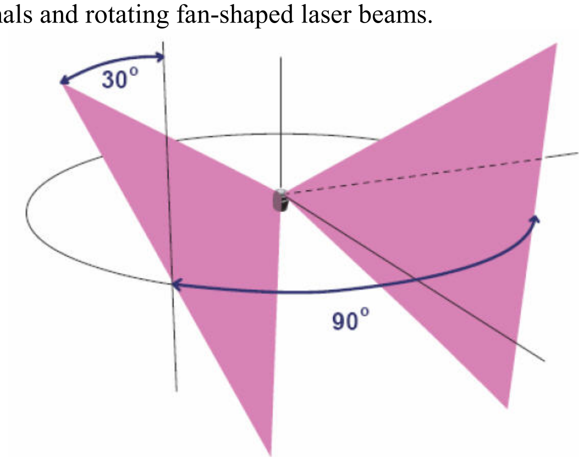

Figure 2: The two rotating fan-shaped laser planes of iGPS, graphic from Metris

According to Figure 2, the first laser beam follows the second at a 90° angle. Both laser beams have an inclination of 30° from the vertical (one to the left, the other two the right). The vertical angle between transmitter and sensors is determined by the time interval between the two laser beams. The horizontal angle can be derived from the time interval between a third signal that is sent out every other rotation and the arrival of the laser beams. With receiving light signals form multiple transmitters simultaneously the own 3D position of a sensor is determined from multiple horizontal and vertical angles by spatial forward intersection. A more detailed description of the system can be found in Krautschneider (2006). He concludes that the dynamic mode allows real-time applications such as machine control and monitoring. Figure 3 shows some system components.

Figure 3: iGPS transmitter and sensor during a test in a tunnel

Ulrich (2008) carried out long-term measurements within his Master Thesis at the ETH Zurich. He analysed the iGPS performance in the influence of light, multipath, temperature and humidity. Furthermore kinematic measurements on a calibration track line and a swinging concrete girder were recorded. Special attention was given for the use in underground and tunnel environments. A typical scenario is illustrated in Figure 4.

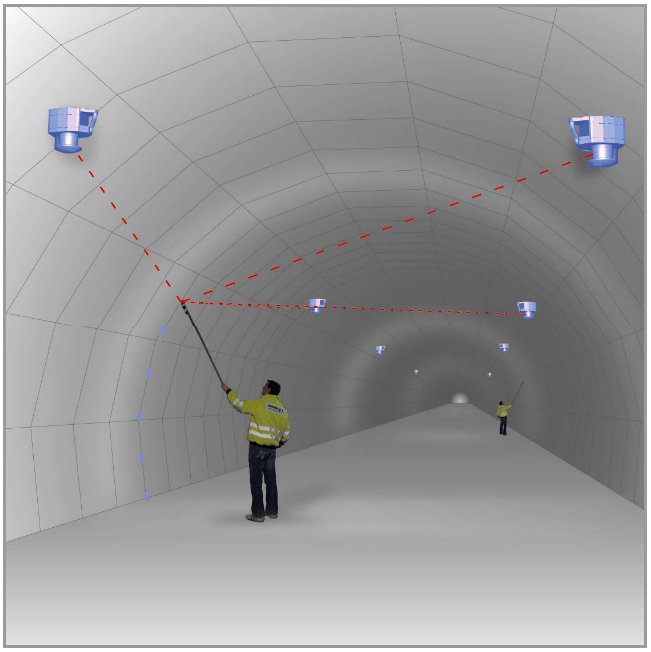

Figure 4: Application of iGPS in a tunnel. Graphic by David Ulrich

These test measurements confirmed the high accuracy of better than 0.1 mm for static measurements and proofed that the real-time operation of iGPS for surveying applications such as staking out, profiles and deformation measurements in tunnels and indoor environments is feasible and that the system features a high potential for the surveying market. Furthermore, kinematic applications are possible within a measurement rate of 40 Hz. Certain limitations and necessities of development have been detected, such as the problem of multipath and measurement noise caused by the influence of light sources. The maximal range of 50 m as stated by the manufacturer could only be achieved in total darkness.

3. Pseudolites Using GNSS similar signals (Locata)

The Locata System is a radio signal based positioning technology, developed and marketed by Locata Corporation based in Canberra, Australia. Featuring many characteristics of a pseudolite system, it is designed as an augmentation to space based positioning systems like GPS, trying to overcome their limitations. In particular it tackles the problem of non-availability in locations, where no or not enough satellite signals are receivable such as in urban canyons, open pit mines or inside buildings. This is mainly achieved through the use of signals in the 2.4 GHz band, where international regulations allow transmit power of up to 1 watt that allows the positioning signals to penetrate through structures and the inside of buildings. The System is mainly laid out for local use within a range of several hundred meters up to several kilometres. Using the carrier phase for positioning, the system allows sub centimetre precision under certain circumstances.

The Locata system consists of two types of core components, the transceiver units (LocataLites as shown in Figure 5) and a standalone receiver unit (Locata). A minimum of four LocataLites are necessary to form a working network (LocataNet). The LocataNet, consisting of four or more LocataLites then synchronises its clocks to better than 30 pico-seconds using a sophisticated synchronisation process. The time synchronisation of the positioning signals makes the use of a reference receiver for precise positioning unnecessary. The Locata receiver is a standalone device that records code and carrier phase measurements of the available LocataLites. The commercial version comes with an on-board positioning software that allows for real-time positioning at a rate of 1 Hz. Raw measurement data (pseudorange and carrier phase) are recorded on a compact flash card or streamed serially via RS232. At the time of writing, the ambiguity solution was only available through initialisation of the receiver on a known point.

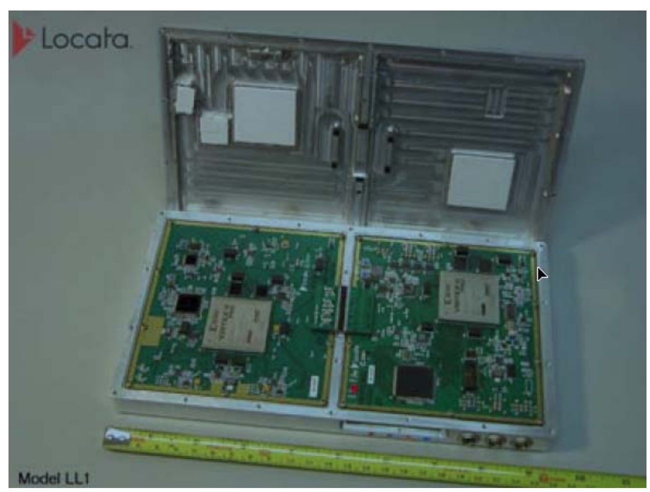

Figure 5: Locata transceiver (Barnes et al. 2005)

3.1. Problems and Challenges

When working with the Locata positioning system, similar error sources as for GNSS have to be taken into consideration and mitigated. Some differences to satellite based systems exist, mainly due to the transceivers being placed on the ground. The ionosperic delay, which is a major issue in precise GPS-surveying, can be neglected as the Locata signal does not propagate through the ionosphere on its way from the transceiver to the receiver. However, due to the commonly low elevation angles inherit in a ground based system, multipath is a more serious error source. Because of commonly low elevation angles, cut-off angles like known from GPS-receivers cannot be used to mitigate multipath. The presence of multipath errors can be indicated by low signal-noise-ratio values which are given from the Locata receiver for each measurement. This information allows preventing signals suspected to contain multipath errors from being used for the calculation of the position solution.

Low elevation angles also make the estimation of the tropospheric delays more difficult. The troposphere delay is largely independent of the signal frequency, so it cannot be estimated by a combination of two or more frequency signals.

Since both, receiver and transceivers, are usually situated on or close to the ground, the height component is often critical. This circumstance has to be considered in network design.

More details can be found in the ETH master thesis of Bertsch (2009), who implemented important improvements for the on-the-fly ambiguity resolution.

3.2. Performance

Barnes et al. (2003) achieved a real-time positioning standard deviation of 6 mm or 1 cm 93% of the time to a maximum of 100 m distance. In a kinematic test, 16 mm standard deviation with 82% values being less than ±20 mm. The authors conclude that their system can operate indoors and outside anywhere within sub-cm accuracy despite multipath errors. The Locata Technology Primer (2005) demonstrates a standard deviation of better than 5 mm indoors. Barnes et al. (2005) demonstrate the suitability of the Locata technology for RTK machine tracking/guidance in warehouses within cm-level and offices within sub-metre-level where GNSS satellite coverage is limited. This level of precision is significantly better than currently achieved by high-sensitivity GNSS receivers indoors. Barnes et al (2007) conclude that movements of less than 1 cm can be detected. Due to the signals being orders of magnitude stronger than GNSS, Locata signals can penetrate walls. However, the performance degrades to decimetre level accuracy inside buildings.

4. ULTRA SOUND SYSTEMS

Various indoor localisation systems employ the Time Of Arrival (TOA) or the Time Difference Of Arrival (TDOA) methods for ranging between nodes of a network. Different types of signals are used to infer the inter-nodal distances. The problem of using electromagnetic waves for TOA or TDOA is the enormous speed of light with which these signals travel. In order to detect a difference in distance of 1 mm, the time resolution needs to reach 0.3 picoseconds ($3 \cdot 10^{-13}$ s) which is a challenge for the application in tiny low-cost devices. Therefore, many low cost systems exploit the propagation of sound, which travels about 1 million times slower.

The ultra sound systems consist of beacons that are typically static units mounted on the ceiling above one or more mobile listeners. Each beacon unit broadcasts periodically ultrasonic (US) pulses and simultaneously radio frequency (RF) messages with its unique ID number. Using the TOA information from different beacons and the temperature corrected speed of sound measurement; the listener calculates its distances from the beacons. Because RF travels so much faster than ultrasound, the listener can use the time difference of arrival between the start of the RF message from a beacon and the corresponding ultrasonic pulse to directly infer its distance from the beacon. The position of the listener can then be determined based on the beacons' coordinates and the measured ranges. With several distances to known reference beacons being available, the 3D coordinate position can be determined using a trilateration or a multilateration technique.

4.1. Crickets

The Cricket nodes are tiny devices developed by the MIT Laboratory for Computer Science as part of the Project Oxygen. A 3D positioning accuracy of 1-2 cm can be reached indoors within a maximum volume size of 10 m. A Cricket board is shown in Figure 6. The Cricket unit can be programmed either as a beacon or as a listener. Real-time tracking is generally possible with an update-rate of 1 Hz.

One reason to choose the Cricket system as a test bed for the novel positioning algorithm was its flexibility and programmability. For example, Cricket listeners and beacons consist of identical hardware. Even the software that is running on listeners and beacons can be the same – a simple command from the host can change a Cricket node from a listener into a beacon and vice versa. The embedded software that is running on a Cricket device can be replaced simply by uploading the flash memory with modified or self-developed programs. The open architecture of Crickets has inspired researchers all over the world to use Cricket as a platform to develop new wireless positioning strategies and for algorithm testing. There is plenty of literature on Crickets and applications available. The thesis of Priyantha (2005) describes the design and implementation of the Cricket indoor location system in detail. Haggag and Mehraei (2006) document their modification of the default architecture that enables coordinated robot interaction. Wang (2004) lays the foundations for leveraging the Cricket indoor location system to supply orientation information. He also demonstrates end-to-end functionality of a Cricket Compass.

Figure 6: Cricket unit

However, there are several disadvantages when choosing Cricket as a platform for positioning and tracking. One severe problem is that of multipath signals, which are receipted in particular indoors due to reflections at walls, windows, tables or the floor. When a listener receives a reflected signal instead of the direct signal along the line-of-sight, a too long range is determined. A multipath signal is particularly likely to occur when a beacon node is not orienttated towards the listener. Typically, a listener unit can detect ultrasonic signals from a beacon within a 40 degree cone. If the beacon node is not orientated directly towards a listener, the listener receives a reflected signal instead of the direct signal. Figure 7 shows such a scenario, where a multi-path signal is received. In order to eliminate a gross error due to multipath, a high redundancy of range measurements (i.e. more than 5 ranges to each node) is necessary.

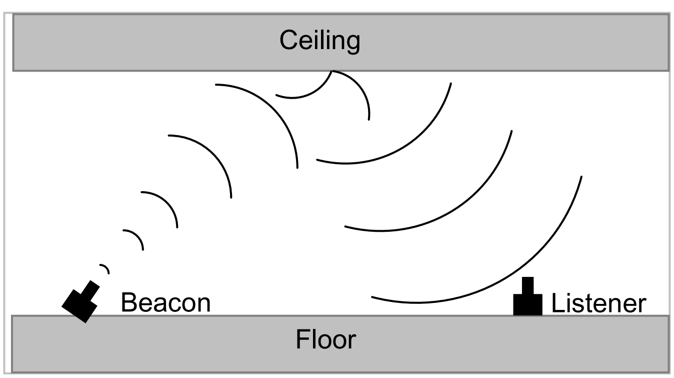

Figure 7: Typical multipath scenario where the signal is reflected at the ceiling

There are several more disadvantages associated with the use of ultrasound. The speed of ultrasound is highly correlated to the temperature. Although cricket units carry temperature sensors on their chip sets, it is hard to obtain an accurate temperature along the path between transmitter and receiver. The speed of ultrasound depends tightly on the speed of wind, which doesn't allow for accurate positioning outdoors. With the ultrasound sender not transmitting omni-directionally, it is impossible to set up a dense ad-hoc network with a large number of Cricket units. In a large ad-hoc sensor network the condition that the nodes face each other is a severe restriction.

Nevertheless, the system has been successfully implemented to obtain full 3D real-time coordinates of a mobile device based on a purpose tailored Matlab program that determines the coordinates by multilateration from range measurements to 3 or more beacons. Figure 8 shows a robot that has been equipped with two Cricket nodes in order to obtain position and heading of a vehicle. While the system works in general, one of the results is that Crickets is only useful as a demonstrator and not suitable for real application due to its prevailing failures and general clumsiness. Mautz and Ochieng (2007) give some details of the implemented positioning strategy and algorithms.

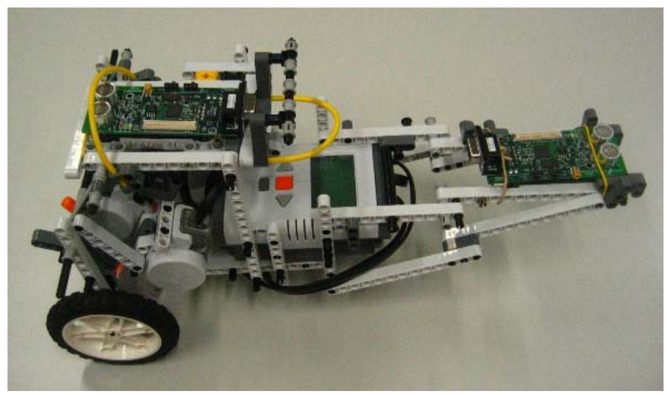

Figure 8: Two Crickets mounted on a robot for positioning and orientation

4.2. Active Bat

The Active Bat System is another ultrasonic positioning system. It is a pioneer work and consists of roaming Active Bat tags, which transmit an ultrasonic pulse, and fixed ultrasonic receivers mounted on the ceiling. The Active Bat system measures the distance between a tag and a receiver based on the time-of-flight of the ultrasonic pulse, and computes each tag's position by performing multilateration. The Active Bat system also provides direction information, which is useful for implementing many ubiquitous computing applications. However, Active Bat employs centralized system architecture and requires a large number of precisely positioned ultrasonic receivers. The system is described by Hazas and Hopper (2006). It was shown to have 2 cm accuracy. The 3D accuracy of a synchronous receiver is better than 5 cm in 95 percent of cases.

4.3. DOLPHIN

Another ultrasonic positioning system is the Distributed Object Locating System for Physical-space Internetworking (DOLPHIN), described in Fukuju et al (2003) and Minami et al. (2004). An accuracy of 2 cm could be reached on a test bed of 3 m in size.

5. CAMERA AND LASER INDOOR POSITIONING SYSTEM (CLIPS)

CLIPS fills the gap that we have identified for an indoor positioning accuracy of better than 1 mm. Clearly, systems that have the capability to provide 3D coordinates with an accuracy of better than 1 mm and even better do exist, but they tend to be complex in their set-ups and require extremely high acquisition costs, see Table 3. These high costs are a result of the requirement for some high precision mechanical parts that need to rotate (total station, iGPS, laser tracker). Some systems such as Locata require the set up a complex sender-receivers structure in order to derive the position from TOF (Time of Arrival) or AoA (Angle of Arrival).

The industry however has a growing demand on precise indoor positioning capabilities – in particular with the upcoming of further automation. Manny applications in tunnels, production facilities and warehouses require a system that can be set-up quickly without lengthy set-ups for the stations and reference points in each room. Therefore we opted for a photogrammetric approach that does not require larger dynamic mechanics but exploits the precise camera and CCD technology that has already reached the level of being readily and cheaply available.

There are various photogrammetric positioning systems on the market already. Most systems however require the installation of reference objects that include the precise determination of their 3D coordinates, such as the Procam from AICON (2009). Some systems use the technique of relative camera orientation from another orientated camera based on homologue points in the scene. The problem here is the reliability and speed of detection of such homologue points. The required software is relatively complex and the success for an orientation depends on the features in the scene. Light projection on objects for the purpose of 3D modelling of an object has also been performed (example), usually in the form of stripes or patterns. Again, elaborate software needs to process the images. The projection is restricted on a certain object and the required laminar coverage of the scene with light affects the object itself. Laser spots have been used by projecting them on a screen or a flat surface. By exploiting the geometric constraints of a planar surface, the outer camera orientation can be determined. However, the strict requirement of such geometric constraints such as plains does not allow the use for any room-geometry.

The key idea of the proposed system is to project well distributed reference points on the walls, furnishings and equipment of any arbitrarily chosen indoor environment. The light source should consist of several laser pointers with focused beams that are being sent out from a static, well defined central point. The camera position and orientation is determined from these tiny spots on the wall, ceiling and various objects in a room. The camera itself – equipped with a probe – will be the actual movable device for 3D real-time positioning.

However, some research issues remain. One problem that needs to be solved is the unique identification of the laser spots. Since we do not restrict the room geometry to be strictly convex, the location of the spots in the image can not be the only basis for their unique identification. In order to be as flexible as possible, we try to avoid bar-coded signals that require a certain spread on the object they illuminate. Instead, we propose a signal coding by time or colour. Practical and technical issues need to be identified and solved.

A second problem that has to be solved is the determination of the scale. The 3D positions of the camera and the laser spots can be not be determined before the scale-unknown is solved. Neither do the image coordinates nor do the angles between leaser beams have the potential to deliver distance information in the scene. We see several options to introduce the system scale, such as taking an image of a norm scale, the use of two laser-beam projection centers or the initialization of the CLIPS system at a known position. These options need to be implemented on a prototype basis and assessed through performance tests.

We also have identified research issues on the computation of the orientation parameters. Even though this computation is a standard task in photogrammetric applications, where the orientation parameters are already approximately known, this is not the case for our purposes. The camera should be initialized at any position and any arbitrary orientation. Just recently an algorithm for the determination of the relative orientation without any a priory information has been developed. Stewénius (2006) uses an algebraic solution based on the minimum number of points.

The system will be designed for indoor engineering surveying tasks, such as industrial measurement of products (e.g. aircraft- and automobile industry) but also geodetic applications in tunnels, production lines, storage handling (guidance of robots). With a proposed update rate of about 30 frames per second, a true real time positioning capability for moving devices will become possible. The goal of the project will be to deliver a prototype with full system performance in the view of industrial production.

Performance parameters and figures are not available at the time of writing.

6. CONCLUSIONS

Judging from the diversity of present positioning systems can be followed that there is no overall solution for positioning yet. While GNSS have become the dominating system for open-sky, several systems share the indoor market; each having its own drawbacks, such as low accuracy, sophisticated infrastructures, limited coverage area or inadequate acquisition costs. Most systems suffer from the multipath problem. The main problem is the direct line of sight that most systems require, but indoor environments hardly provide. The usage of signals that can penetrate building materials may overcome this problem in the near future.

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