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INDOOR POSITIONING – AN AD-HOC POSITIONING SYSTEM

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Abstract. The aim of this paper is to discuss the development of an automatic, low-cost system that exploits current or near future wireless communications technology to enable continuous tracking of the location of devices in all environments. The development of such a wireless sensor network involves system design, digital signal processing, protocol development, extraction of ranges and localisation. This paper focuses on the user requirements, system architecture and network positioning. The user requirements are presented with a focus on applications in geodesy. A high level strategy for the positioning function is presented based on an ad-hoc geodetic network positioning method including issues of accuracy, quality and reliability of the node positions. Results show that it is possible to achieve a position deviation that is of the size of the ranging error.

Keywords: indoor positioning, ad-hoc sensor networks, wireless positioning.

1. Introduction

Indoor positioning systems nowadays become more and more widespread due to the feasibility to build tiny devices cheaply that allow for precise ranging and positioning. With the increase of precision, indoor positioning systems are getting practical for geodetic applications, where requirements for precision and reliability are traditionally very strict.

The aim of this paper is to discuss the current status of the development of an automatic, low-cost system that exploits current or near future wireless communications based on Bluetooth to enable continuous tracking of the location of devices in all environments. Highly accurate, reliable 3D positioning of targets indoors – where GNSS is not available – is a core issue in machine engineering and engineering geodesy. Additionally, other location based services, such as product tracking for industrial applications, will benefit from the proposed system to locate radio enabled devices within ad-hoc networks of static and mobile users and equipment. The 'nodes' of the network could also be mobile phones or portable computers, printers, or simple tags with wireless radio connections that are 'intelligent' enough to be able to connect to the network automatically. The number of nodes in the network should be able to expand and contract 'organically' as devices enter and leave the network, due to radio linkage.

There are a number of high-level drivers of the system.

- The capability to obtain continuous, high accuracy, high integrity and high availability positions in a dynamically changing environment with sometimes hostile characteristics. This depends on the capability to extract high accuracy ranges (distances) between devices from a system that is designed for mobile communications as determined through the requirements capture and analysis.
- The issues of quality and integrity of the location derived from the system are of crucial importance particularly for those services related to expensive or safety of life relevant applications. The expectation in this case is that the system is capable of providing information about its status. It should have a high integrity that allows timely information to the user, if the system is in a bad state and should not be used.
- It is vital that the system has a minimal cost impact on the intended applications and a minimum of dedicated infrastructure, in order to be viable and encourage adoption. It should use existing components with minimal usage of dedicated 'bespoke' technology in the devices or infrastructure. The system should address the limitations of existing and near future space-based positioning systems and cellular phone systems both of which have expensive infrastructure, limited accuracy and availability, particularly in built-up areas and indoors.
- The system should take into account the weaknesses of current wireless ad-hoc positioning methods and algorithms, including the absence of quality and integrity indicators for the positional results, existence of high variances and outliers in range measurements, errors in anchor

nodes or their absence and positioning in low connectivity networks.

Given the background information above, the research to acquire such a system has the following seven objectives: user requirements acquisition, system requirements derivation, extraction of ranges, development of ad-hoc network positioning algorithms, specification of architecture, protocol development, and the development of a demonstration system (prototype). In section 2 the user requirements of such a system are addressed. Section 3 summarises the approach taken for positioning in ad-hoc networks and numerical results are given in section 5. The paper is concluded in section 6.

2. User requirements

As a running mechanism that monitors movement of tunnels, bridges, rocks and devices will contribute to monitoring critical objects and be a means to carry out deformation analyses. Therefore, the "indoor" positioning system should also have the capability to work outdoors. A communication function is required to deliver information to the user immediately and directly, or in some cases to a device holder.

Physical damage of a device should lead to an alarm. This requirement is best achieved by a decentralised network and automatic replacement of destroyed nodes by nearby nodes that take over the communication of the lost network point.

The system should help to locate highly dynamic objects to allow continuous tracking of robots, products and machines in all environments. Therefore, 3-D positioning is of importance within built-up areas, in particular, inside buildings or on roads at flyovers, tunnels and bridges. For a full tracking functionality the import of spatial information is a necessity. Additionally, spatiotemporal data derivatives like the speed, heading or acceleration may support the prediction of movements. In court, the provision of the track of a moving device can be used to build evidence.

Most of the applications would benefit from a service in real-time or near real-time. A concept of automatic detection will be helpful to overcome possible hazards or to timely prevent larger damages on objects. In operation, an interface that allows a device to easily join a network or link two devices to each other in a simple way will support easy handling. In order to keep the system updated in the long term, the functionality should allow the transmission of commands that change the status of single nodes or perform system uploads and upgrades.

Requirements analyses and interpretation

From the summary of the requirements in the previous section, it is clear that precise positioning, tracking, communications, interfacing and integrity (safety and security) are the key drivers to the development of the system. The RNP (Required Navigation Performance) therefore varies according to the application. This is due to the fact that the complex process of fighting crime has no overall solution. The key RNP values depend on the coverage area, e.g. indoor environments require a more demanding accuracy than in urban or rural areas.

In order to accommodate the users request for simplicity, processing and data storage should be performed at a master control centre (MCC). All communication must comprise a two-way data flow. Most of the data flow will be on event or request only. However, if the system is in 'alarm mode', a periodic data rate is required that allows real-time tracking of devices.

The high demand on integrity and security needs to be taken into account by establishing unique ID-numbers for devices and encryption methods in order to protect sensitive data against intruding third parties. In a scenario where the positioning system is ubiquitously available, its vulnerability needs to be mitigated by a decentred system structure. Therefore, the functionality of the MCC will be subdivided physically by establishing several MCCs.

In summary it is clear from above that positioning and tracking in real-time or near real-time are crucial elements of the system.

3. System architecture

A high level system architecture for such a wireless positioning system is illustrated in Fig. 1. The concept is based on the Session Initiation Protocol (SIP), which consists of a SIP gateway, proxy server, redirect server, registrar server and location server. The information of the SIP user, device IDs, access ports, and other ranging information and related time stamp are conveyed to the registrar server. At the location server, this information is to be processed and the device's coordinate position is to be determined by the positioning application and stored on the location server's database. The SIP servers are part of a Master Control Centre (MCC), which is accessible via the internet or alternatively directly attached to the mobile network to avoid latencies and centralisation.

Already existing infrastructure of wireless communication devices (primarily Bluetooth, possibly WiFi, GPRS, UTMS, WiMAX (802.16e)) is used to establish a direct ranging component, that allows for geodetic network positioning. The positioning system uses Bluetooth radios for communication as well as for ranging between devices. Although the Bluetooth radio system is designed for short range voice and data communications, the combination of relatively high received signal power results in the potential to use the system to provide accurate ranging information. This is a particularly attractive prospect in indoor and urban environments. Further detail on the extraction of ranges can be found in Mautz *et al.* (2006).

4. Positioning / network localisation

The localisation strategy can be broken down into three phases.

4.1. Clusterisation

The creation of a cluster is required to compute the positions of vertices in a local coordinate system that is allowed for global translations, rotations and a reflection. The key issue for localisation without the need for refe-

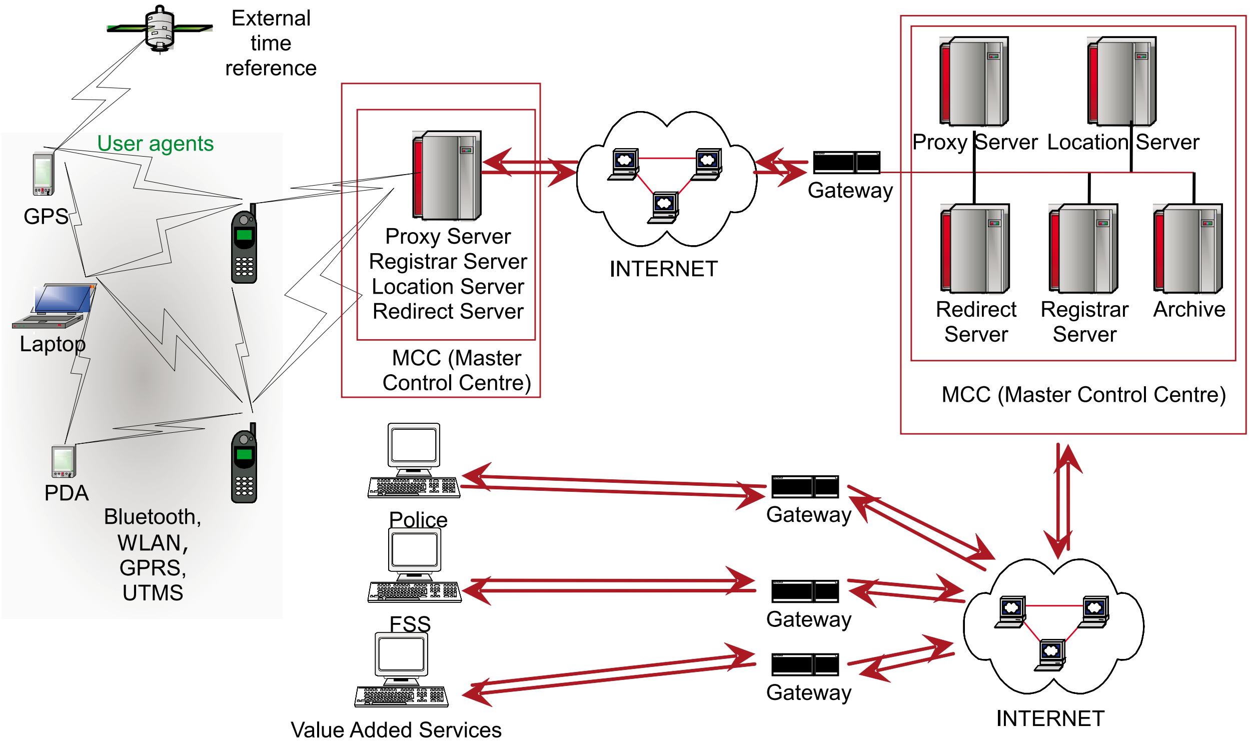

Fig. 1. Scenario for the system architecture

rence nodes is to find a globally rigid graph, or, in other words, a structure of nodes and ranges which has only one unique embedding, but still can be rotated, translated and reflected. In 3D, the smallest graph consists of five fully connected nodes in general position. If one of those 10 ranges had not been measured, say, between nodes 4 and 5, there is an ambiguity problem as there are two different embeddings. As shown in Fig. 2, the nodes 4 and 5 could be on the same side of the base plane or on opposite sides. Only the additional range measurement r_{45} between node 4 and 5 can disambiguate between these two embeddings. As can be seen in the example from Fig. 2, r_{45} is significantly longer than for the reflected case $r_{45'}$, which means that if it is available, the correct embedding can be selected. Consequently, such a set of 5 nodes is rigid in 3D, assuming the nodes are not in a singular position.

If such an initial cluster passes statistical tests, additional vertices are added consecutively using a verified multilateration technique. 'Multilateration' is basically a trilateration technique, where the new node is initially determined from three stations at a time. The remaining distance measurements are used to disambiguate between two different embeddings and to verify the initial computation. Multilateration allows redundant determination of the nodes. The resulting coordinate differences provide essential information to detect false range measurements, e.g. due to multipath effects. The trilateration and multilateration problem considered so far solves for one single unknown point at a time. The sequential accumulation of nodes by multilateration is known as iterative multilateration (Savvides *et al.* 2001). However, this technique is very sensitive to measurement noise. Initially small errors accumulate quickly while expanding the network. Since the scenario we aim for is a large pure distance network with multiple unknown nodes and only a few known anchor nodes, the propagation of errors must be minimised as much as possible. In this case, a free geodetic network adjustment is an essential tool to evenly distribute the errors that have been accumulated during iterative multilateration.

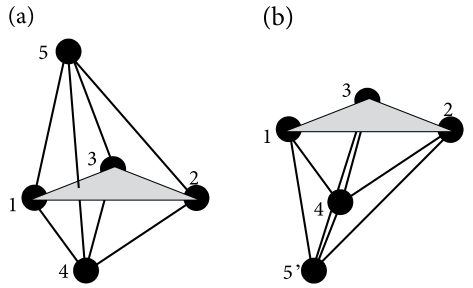

Fig. 2. Quintilateral (a), a version where node 5 has been mirrored at the base plane (b)

4.2. Transformation of the cluster(s) into a reference coordinate system

If the local cluster contains at least four vertices that are also anchor nodes in a reference system, then the cluster is eligible for a transformation into that particular coordinate system. The coordinate transformation used is of 3D-Cartesian type. A closed form solution for the determination of transformation parameters using the 3D-Helmert transformation is given by Horn (1987). Subsequent to the transformation, a fully constrained least-squares network adjustment is performed that permits all of the available anchor nodes and all range measurements to be processed together in order to refine all position approximates simultaneously. Additionally, the mean error in the coordinates is reported by the point confidence ellipse for each node.

4.3. Coarse positioning

Following the procedure described: 1) lateration, 2) free network adjustment, 3) 3D-Helmert transformation, 4) fully constrained adjustment, it is possible to obtain high quality coordinates of devices in the higher reference system. However, in order to accommodate the user requirements for high continuity and availability, a coarse positioning service is introduced for cases where the precise mode fails. Nodes that have not been able to get clustered are now located using the coarse method and also added to the cluster. Coarse positioning exploits connectivity information between nodes when range measurements are not sufficiently available or flagged as unreliable.

The process flow of our localisation strategy is illustrated in Fig. 3.

A detailed description of the positioning algorithm is given in Mautz *et al.* (2007).

5. Experimental results

In this chapter the performance of our localisation algorithm is evaluated. In our simulation, we deployed 100 nodes randomly in a 100 m × 100 m × 100 m test cube. Assuming a maximum observation range of 35 m between the radios, only the distances between nodes with less than 35 m have been recorded into an observation file. After execution, the file contained 570 range measurements. Based on these ranges, the localisation algorithm was supposed to recover the node positions. The algorithm created a 5-node rigid graph, then larger clusters by lateration and cluster merging. Finally, 10 points were chosen randomly to serve as anchor nodes for a 3D-transformation of the local cluster into the original geodetic datum. The results are given in Table.

Comparison of the localisation performance at different noise levels

mean obs. error [m]	0.0	0.1	1.0	10.0
mean obs. error [%]	0.0	0.36	3.6	36.0
nodes participating in the lateration cluster	92	92	85	10
reference mean error of adjusted cluster [m]	0.0	0.1	1.2	8.0
average deviation from ‘truth’ [m]	0.0	0.2	2.2	–
nodes participating in coarse and cluster positioning	99	99	99	99
average deviation of all nodes [m]	1.9	2.2	6.9	32.1

As a consequence to the random deployment of the nodes, one node did not have any range observation to another node in the network. Consequently, only 99 nodes could be located. Additionally, 7 nodes did not have sufficient connections to participate in the lateration cluster, but could be located by the coarse positioning mode.

Four tests at different levels of observation error were carried out. With error free ranges, the positions of all 92 points which participated in the lateration cluster could be recovered exactly. Including the 7 nodes that were located by coarse positioning the average deviation for all nodes between the original positions and the recovered positions was 1.9 m. At a noise level of 10 cm, the same results were obtained with correspondingly slightly higher position errors. However, at the noise level of 1 m (or 4 % of the ranges) the number of nodes participating in the lateration cluster shrunk to 85. This is due to the integrity tests, which prevented non-robust constellations to be formed. The mean position error of these 85 participating nodes is only 1.2 m, which basically means that the network geometry could still be recovered at that noise level. At an average range error of 10 m, only the anchor nodes participated in the lateration network. Even then the coarse mode enabled positioning with an average deviation of 32 m.

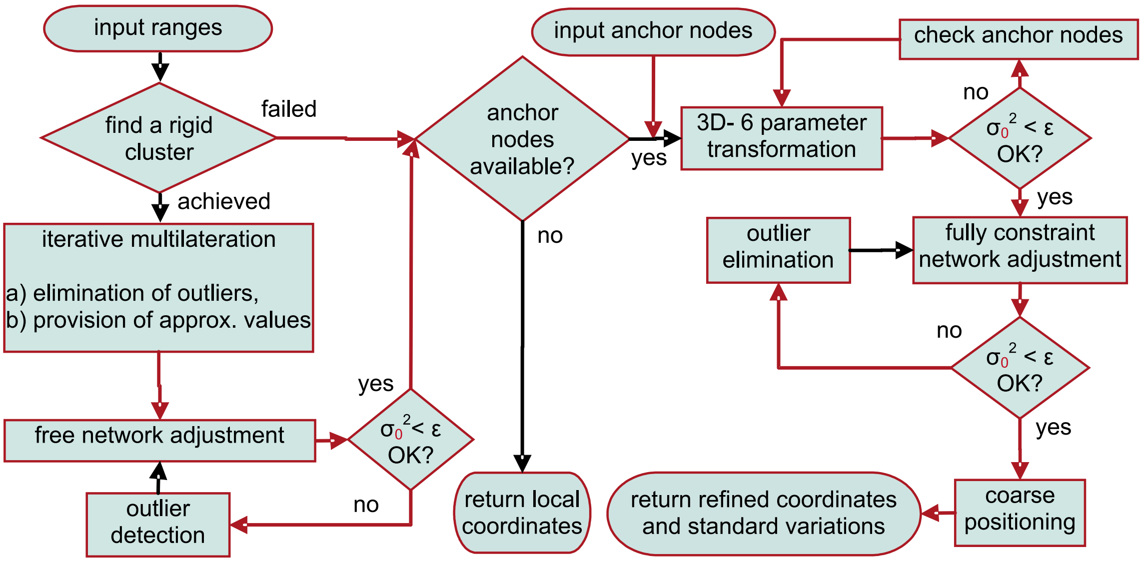

Fig. 3. Start-up of the geodetic positioning mode, which does not require any initial approximate coordinates. σ_0^2 is the a posteriori reference variance, which is compared with a threshold ε

6. Conclusions

The results of the user requirements capture indicate that tracking of devices needs to have full coverage in different environments – indoors as well as outdoors. Consequently, the system should not be denoted as an "indoor positioning system" in order to take into account geodetic applications to monitoring larger natural or man-made structures. The required navigation performance depends on the type of environment. To accommodate these diverse accuracy demands, the system needs a precise geodetic network positioning function as well as a coarse positioning mode comparable to mobile phone localisation schemes.

Requirements for a simple manageable man-machine interface suggest a system architecture that allows the processing to be performed in a master control centre. To further accommodate the call for simplicity the location of nodes needs to be provided within a GIS. Software at the user end needs to be intuitively comprehensible.

With regard to the high demand on integrity and reliability, unique ID-numbers, data encryption and a decentralised architecture need to be incorporated into the system. In terms of positioning outlier detection and quality indicators are essential.

We have studied networks with relatively large errors of up to 10 % of the true ranges and shown that it is possible to achieve a position deviation that is of the size of the ranging error.

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Research interests: positioning in wireless sensor networks; deformation analyses; detection of frequencies in geodetic data; parameter estimation; adjustment computations, engineering geodesy.