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Low Cost Intelligent Pervasive Location Tracking (iPLOT) in All Environments for the Management of Crime

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This paper details the current status of the development of an 'automatic' low-cost system based on wireless communications technology to provide continuous tracking of the location of devices in all environments. This task requires a multi-disciplinary approach combining communications systems design, digital signal processing to extract ranges and, importantly, approaches from the field of geodesy to develop novel network positioning techniques for ad-hoc networks. Such a network will support a number of services relevant to crime management where seamless tracking is required. The paper discusses the process for developing the system, christened intelligent pervasive location tracking (iPLOT), with a particular reference to user and system requirements, and how these have been used to explore a network positioning strategy.

KEY WORDS

1. Ad-hoc networks. 2. Wireless network positioning. 3. Crime reduction. 4. Product tracking.

1. INTRODUCTION. The threat of crime leads to great anxiety as people worry about personal safety and that of their property. Beyond this, crime leads to wider societal consequences including a negative impact on the economy. A variety of methods are employed to fight crime, and are usually formulated by governments and presented as policy statements. With criminals exploiting vulnerability of victims who increasingly possess advanced equipment and devices, technological innovation is now recognised as potentially having an important part to play in the management of crime.

The aim of this paper is to discuss the current status of the development of iPLOT as an automatic, low-cost system that exploits current or near future

wireless communications based on Bluetooth signals to enable continuous tracking of the location of devices in all environments. Accurate, reliable and widely available location of property and people is a core issue in crime prevention and detection. The proposed system will locate radio enabled devices within ad-hoc networks of static and mobile users and equipment. The 'nodes' of the network could 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 iPLOT 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. The requirements for positioning are to be determined through requirements capture and analysis.
- The issues of quality and integrity of the location data derived from the system are of crucial importance particularly for those services related to crime reduction and safety. The expectation in this case is that the system is capable of providing evidence that is admissible in a court of law and can help to convict offenders.
- 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 as far as possible (such as wireless technology) which are required for existing functionality (e.g. communication) 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 and limited accuracy and availability, particularly in built-up areas and indoors.
- Because of the need to determine location reliably and quickly, architectures that are likely to result in 'bottlenecks' due to a large number of users should be avoided. Furthermore, the selected architecture should address relevant privacy concerns.
- The iPLOT 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 iPLOT 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). This paper addresses the first four objectives. Section 2 presents the process followed to capture user requirements and derive system requirements for crime management. Section 3 details a strategy for extraction

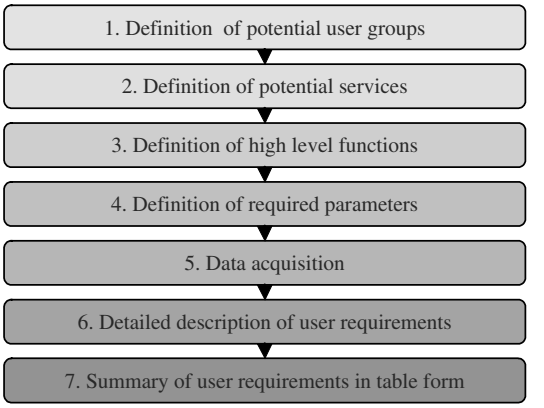

Figure 1. Process for user requirements capture.

of ranges and presents some preliminary results, followed by state-of-the-art research into ad-hoc network positioning methods. The paper is concluded in Section 4.

2. REQUIREMENTS CAPTURE.

2.1. *Process for User Requirements Capture*. Figure 1 illustrates the steps followed to capture the user (service) requirements for iPLOT. Firstly, the potential user groups were identified together with their associated services. This was followed by the definition of minimum high-level functions that the system must fulfil to deliver the services. The functions were then described in detail and the associated list of performance parameters defined and quantified. The next step was to acquire the data. A number of sources were employed including a survey of existing studies, brainstorming sessions, questionnaires and interviews with industrial partners. The accuracy and level of detail with which each service is described will affect how well requirements can be assigned and ultimately how well suited the system design is to the particular application. Finally, for each potential service all the relevant requirement parameters were detailed and summarised in a final step using a concise table format. The high level process given in Figure 1 is expanded in Figure 2 which shows examples of the user groups identified for iPLOT, the corresponding services related to crime reduction, the associated high level functions, and the relevant key performance parameters for positioning.

2.2. *Requirements Summary*. iPLOT is expected to have both a direct and an indirect impact on crime reduction. In crime prevention the system will not be able to physically prevent criminals from getting access to a device. However, it is to be expected that an indirect impact will result when the system will – once installed – have the potential to act as a deterrent. By obtaining reliable and accurate movement detection in all environments, a would-be-thief will be deterred by the awareness that a stolen device is monitored by security personnel.

In order to serve as a deterrent in crime prevention, criminals must consider iPLOT as a continuously operating system that communicates with the authorities and cannot be terminated by the criminal. A tracking feature is needed that allows the setting up of geographic boundaries and automatic receipt of notification when a

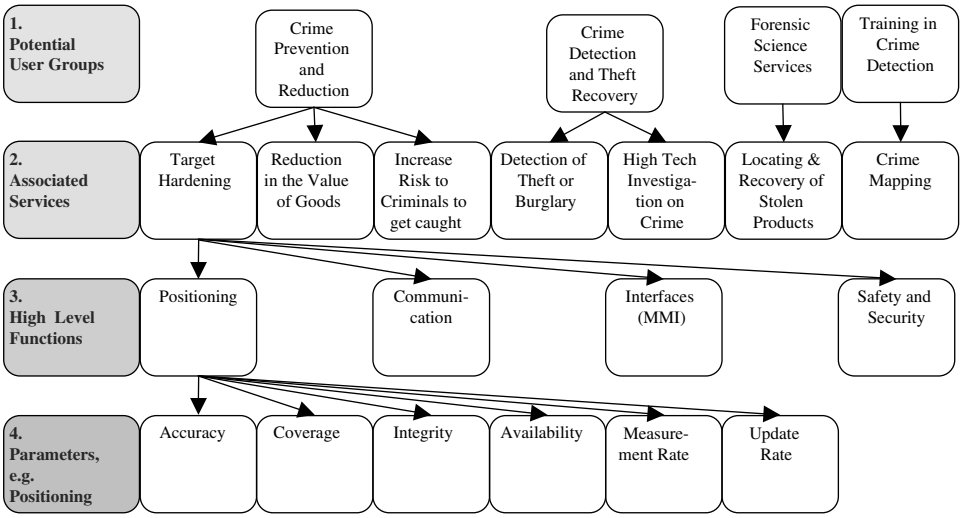

Figure 2. The first four steps of the user requirements capture process.

device enters or leaves those areas. A function that raises an audible alarm in case of an unauthorised exit from the network will prevent criminals from any unperceived misappropriation of iPLOT-equipped devices. On the other hand, ordinary incidents or malfunctions must not lead to an alarm. For instance, if a device's battery is getting low, there is the need for a backup or residual energy resource.

Reduction in the value of assets to criminals is conventionally performed by visible property marking. However, iPLOT will serve as an electronic marker. With the establishment of globally unique identifiers (ID) for iPLOT enabled devices and the iPLOT tracker being intrinsic to a device, its unique identification will contribute to reduction in market value: a stolen iPLOT enabled device will automatically log on the network and send out the device's ID and current location. Certainly, the tracker must not be removable from the device.

A function of iPLOT which disables an electronic device in case of theft will also reduce the value to the criminal. The device may be disabled automatically when leaving a designated area (geofencing). The requirement on the system is that the coverage is such that there will be no gaps within a geofenced area where a node could be undetected. Optionally, iPLOT can send out an email to the owner of a device, notifying him about the restricted or unusual location of the device, simultaneously providing information about its current status, location and predicted position. On the other hand, the device owner may use a secure website and continue to control the lost asset remotely by actively sending requests or commands.

As a running mechanism that monitors movement of assets and devices, iPLOT will contribute to surveillance. A communication function is required to deliver information to the police 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.

Table 1. Importance of iPLOT Functions for Crime Reduction.

Service	Positioning	Communications	Interfaces (MMI)	Safety & Security
Target Hardening Value Reduction	required	core requirement	Database and software required	high demand; core requirement
Increase risk to criminals	required			
Detection of Theft & Burglary	real-time tracking required	core requirement	graphical display with GIS information	high demand; core requirement
Locating of stolen products	tracking required			

In crime detection and recovery iPLOT can help to locate property and provide continuous tracking of people's paths in all environments. Therefore, 3D 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, spatio-temporal 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 a possible scarcity of police resources. 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.

2.3. *Requirements Analyses and Interpretation*. From the summary of the requirements in the previous section, it is clear that positioning (tracking), communications, interfacing and integrity (safety and security) are the key drivers to the development of the iPLOT system. The Required Navigation Performance (RNP) 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 iPLOT data against intruding third parties. In the scenario where iPLOT is ubiquitously available, its vulnerability needs to be mitigated by a distributed system structure. Therefore, the functionality of the MCC will be subdivided physically by establishing several MCCs. Table 1 shows an overview of the key iPLOT functions and their significance to the various services relevant to crime management.

In conclusion, it is clear from above that positioning and tracking in real-time or near real-time are crucial elements of the iPLOT system. In line with the low cost

objective of the research this paper explores the feasibility of exploiting wireless communication and ranging in combination with positioning for continuous tracking of devices in different environments.

2.4. *Required Positioning and Navigation Performance*. The basic positioning function of the final iPLOT system should aim to meet the performance targets under operational conditions as shown in Table 2. These requirements are derived from the perceived needs of crime management. The table presents the RNP requirements for different services in crime management and the data that iPLOT must provide, to enable operations in urban, rural and indoor environments.

3. POSITIONING USING AD-HOC COMMUNICATION NETWORK SIGNALS.

Positioning and tracking require accurate ranging. This section reviews the main issues to be considered in order to determine the distances between iPLOT devices and to use them to determine a position solution.

3.1. *Extraction of Ranges Between iPLOT Devices*. The Bluetooth radio system is designed for short range voice and data communications. The combination of relatively high received signal power (typically greater than −70 dBm in a 1 MHz channel bandwidth) with a symbol rate of 1 Mbps, results in the potential to use the system to provide accurate ranging information. This is a particularly attractive prospect in indoor and urban environments.

Accurate ranging is achieved by satellite navigation systems, as well as those communications systems that have been successfully exploited to provide positioning information such as mobile cellular and digital television (Rabinowitz, 2005), by measurement of the time of flight of the signal (or time differences). However, the Bluetooth system has no method (nor need) to provide accurate synchronisation of transceiver clocks within networks. The measured time of flight between two Bluetooth transceivers is therefore corrupted by the differential clock bias. Hence two-way ranging techniques must be used to cancel this bias and obtain accurate range between two devices. A further issue that must be noted is that as Bluetooth employs a time division duplex (TDD) multi-access system it is not possible to simultaneously range to multiple devices. Two-way ranging to multiple devices must be performed on a sequential basis, with the minimum time possible between range measurements. This has implications for the maximum user dynamics that a Bluetooth-based positioning system can accommodate.

The relatively high-powered Bluetooth Gaussian pulse shaped and frequency shift keyed signals can be processed using a matched filter technique which provides significant spreading gain in order to achieve high resolution range measurements. The maximum spreading sequence length is constrained by the packet length of Bluetooth, which is a maximum of 2745 bits. A classical delay-locked loop tracking process can be employed to provide the range measurement. An assessment of the performance of this technique for a baseband Bluetooth signal operating in the region of the nominal signal to noise ratio (SNR) of 18 dB (0·1% BER), is shown in Figure 3, where the standard deviation of the range measurement is shown for a number of spreading sequence lengths. A high resolution simulation package was written to perform this analysis. As can be seen at the nominal operating point of 18 dB the Bluetooth system has the capability to provide sub-metre ranging. Further reduction of the ranging accuracy can be achieved through averaging of

Table 2. Summary of positioning requirements for each service.

Service	Data Required	Positioning Accuracy (95%) Range: [indoor] [urban] [rural]	Positioning Accuracy (95%) Target: [indoor] [urban] [rural]	Integrity Driver	Integrity Alarm	Integrity Limit	Availability *[maximum allowable continuous outage]*	*Update Rate*	Brief justification
Target hardening	Position, Ranging, Alarm	1–5 m 5–50 m 50–100 m	1 m (P) 5 m (P) 50 m (S)	EF	1–30 s ***10 s***	2–20 m	>95% *[5 min]*	On event, 1 s–10 s	Geofencing, e.g. device is leaving office.
Reduction in the value of goods	Alarm	no positioning	–	EF	30 s–1 h ***30 s***	–	>95% *[1 h]*	On event or request	Disabling of devices, electronic marker.
Increasing the risk for criminals of getting caught	Position Ranging, Movement, Alarm	0·5–1 m 1–5 m 50–100 m	0·5 m (P) 2 m (P) 50 m (S)	EF	1–30 s ***1 s***	2–20 m	>95% *[1 min]*	On event in event: 1 s–10 s	Motion detection in offices, surveillance on roads and crime hotspots
Instantaneous detection of theft or burglary	Ranging, Position, Speed, Heading, Track	0·1–1 m 1–5 m 5–100 m	0·1 m (P) 1 m (P) 10 m (S)	EF SOL	1–10 s ***1 s***	1–2 m	>99% *[1 min]*	On event, in event: 1 s–10 s	Movement detection in offices, tracking on streets and roads.
Locating and recovery of stolen products	Ranging, Position, Track	0·5–5 m 5–100 m 1–50 m	0·5 m (P) 1 m (P) 10 m (P)	EF	1–5 min ***60 s***	5–10 m	>99% *[5 min]*	On event, on request	Trajectory of movements, locate stolen products in all environments
High tech investigation on crime	Position, Track	5–10 m 5–20 m 10–50 m	5 m (P) 5 m (P) 10 m (P)	EF	1–5 min ***60 s***	10–20 m	>90% *[5 min]*	On request	Crime scene recovery. Locate mobiles on roads.
Training in Crime Detection	Position, Time	5–10 m 5–10 m 50–200 m	5 m (P) 5 m (P) 100 m (S)	EF	–	–	>90% *[60 min]*	On request	Identification of crime hot-spots, support briefings

P denotes the primary operating environment, S denotes secondary, e.g. crime is mostly concentrated in urban areas, but it may be also required in some rural areas. EF represent economic factors. The time-to-alarms in bold type have been adopted for the project.

multiple measurements, although this will impact upon the maximum tolerable user dynamics.

There are however a number of key technological issues that will determine if the full potential of high accuracy ranging using Bluetooth can be achieved. These issues, which are the subject of continued research, include the effects of multipath and interference, the effects of modulation and demodulation distortions within the low cost transceiver technology used, the effects of modulation and demodulation distortions due to the Bluetooth signal definition itself, i.e. variable range of Bluetooth products, frequency deviations, frequency drift during packets due to frequency modulation being employed, the group delay variation across the frequency hop range employed. A ranging demonstrator based upon commercial qualified Bluetooth devices is under development to evaluate practically the impact of these (and other) factors.

3.2. *State of the Art in Applied Positioning*. It is well known that GPS coverage has limitations when used in certain environments. Signals from GPS satellites or other space-based systems can be significantly attenuated or even blocked by infrastructure within the built environment. For example, GPS works generally well outdoors but provides little to no coverage indoors where people and equipment are most likely to be found. The inadequacy of GPS in terms of integrity monitoring has been identified by Ochieng et al. (2003). Moore et al. (2004a) use real world data to simulate future scenarios for future satellite positioning systems (the proposed European Galileo system and the Modernised GPS) in order to predict the accuracy and reliability of a real time positioning service. That paper concludes that even for the projected combined service the local topography in gorges will prevent visibility of satellites. The strict user requirements in terms of iPLOT service coverage rule out a pure usage of GPS.

Another system that is widely used for positioning is the Global System for Mobile Communication (GSM). Inherently GSM is used for data communication, but the study of De Groote (2005) shows several positioning methods including Global Cell Identity (GCI), Timing Advance (GCI + TA) and Uplink Time Difference of Arrival (U-TDOA) methods that make use of the system's capabilities to deliver positioning accuracies of more than 100 m for GCI as well as for GCI + TA in urban areas and less than 35km and 550 m for GCI and GCI + TA respectively in the countryside. The GSM positioning accuracies will not support the 1 m – 100 m accuracy range required by the iPLOT users.

There is also a trend of combined usage or integration of different positioning technologies. Examples here include the integration of GPS with deduced reckoning sensors including inertial navigation systems (INS), and the use of cellular communications networks to assist GPS receivers in difficult environments. The latter is commonly referred to as Assisted Global Positioning Services (A-GPS), where GPS is integrated in a mobile network and the computation task is now partly done by the network. According to Darnell and Wilczoch (2002) positioning accuracy of 15 m outdoors and 50 m indoors can be reached with A-GPS. De Groote (2005) estimates the A-GPS accuracy of 20–30 m in urban and 3–10 m in rural areas because in highly agglomerated places, as towns generally are, the GPS signals are biased. A-GPS is not an option for iPLOT due to its poor indoor positioning accuracy.

Positioning techniques in difficult environments using pseudolites (terrestrial GPS signal generators) have also been investigated. However, in addition to being

expensive, they also suffer from some operational weaknesses including the near-far problem.

Chey et al. (2004) exploit the proliferation of wireless networking hotspots that can provide positioning comparable to GPS in urban settings and also function indoors where GPS does not. A database of all the WLAN (Wireless Local Area Network) access points in the world will allow clients to compute their own positions using Received Signal Strength Indicator (RSSI) values in a multilateral fashion. Since the strength of the signal decreases (at least quadratically) as the distance increases, it is possible to calculate the range from the signal source. However, this method has a very low level of reliability because signals are vulnerable to attenuation and distortions by obstacles such as walls, furniture and even human bodies. Although their test experiment indicates achievement of 2–3 m accuracy inside buildings, the usage of RSSI for iPLOT is inappropriate due to strict requirements on reliability and integrity. In addition, the necessary set up of a propagation model is elaborate and does not meet the requirements of low-cost.

Thongthammachart and Olesen (2003) focus on issues of positioning in different wireless short range technologies using GCI techniques. The predicted accuracies depend on the cell sizes which are 35–50 m for 802.11 WLAN standards and 10–30 m for Bluetooth. They conclude that both technologies will take advantage of the user's position when the mobile terminal is connected to the Internet Protocol (IP) network when the mobile core networks have changed to the Internet Protocol Version 6 (IPv6). However, GCI methods cannot be used for iPLOT because most potential services require metre level position accuracy.

Melnikov (2004) also studies and compares current positioning strategies (GPS, WLAN, GSM, UMTS) and their combinations. He concludes that different technologies cover different levels of accuracy and availability and therefore should be used in combination. He also sees WLAN as a possibility for positioning at an accuracy of 2–10 m in urban and indoor areas using RSSI methods. Due to a lack of overlap, additional WLAN access points and repositioning of existing ones are required. Signal-strength mapping or propagation path mapping for each room is also required, which does not meet the low-cost requirements for a seamless, ad-hoc system such as iPLOT. Melnikov mentions Bluetooth as an alternative for WLAN, but focuses on the widespread WLAN IEEE 802.11 technology in the 2·4 GHZ band, where more research has been carried out.

The location tracking method proposed in this paper should overcome many limitations of the current systems which are critical to several location based services such those relevant to security, crime reduction, emergency services and many more. First of all iPLOT will make use of TOA (Time Of Arrival) to derive accurate ranges rather than using unreliable RSSI or imprecise GCI methods. Secondly, the mobile devices themselves will partially replace necessary infrastructure such as anchor or access points.

A possible absence of fixed anchor nodes is proposed to be dealt with by setting up free local networks based purely on ranges. In case anchor nodes (control points) are available the local coordinates are transformed to the desired reference system. Since in reality anchor nodes are not perfect, an error propagation model will take into account the position errors of anchor nodes. Multipath effects appear in a set of ranges as outliers; therefore outlier detection will be implemented at different levels within the localisation application. High levels of noise in range measurements will

be taken into account by an iterative multilateration technique. Non-localizable nodes whose positions cannot be determined uniquely are generally ignored in current localisation algorithms. However, our approach includes a coarse positioning mode that seamlessly returns positions and variances for all nodes. Further details are given in section 3.4.

3.3. *Determination of Single Points.* A straightforward method to determine the position of an object based on simultaneous range measurements from three stations located at known sites is called trilateration. The system of observation equations of a 3D-trilateration

$$(x-x_i)^2+(y-y_i)^2+(z-z_i)^2=r_i^2 \tag{1}$$

has to be solved for, where $\mathbf{P}_i=(x_i, y_i, z_i)$, $i=1, 2, 3$ are the known coordinates of station I, and r_i is the range measurement associated with it. This problem is equivalent to finding the intersection point(s) of 3 spheres in R^3. Such an interpretation allows an easy geometric proof that usually there will be two points of intersection, because, if $\mathbf{P}$ is a solution to the problem, then clearly the reflection of $\mathbf{P}$ in the plane defined by the 3 given points will also be a solution. The ambiguity may be solved when the location of $\mathbf{P}$ is approximately known a priori. But this may not be the case in automatic ad-hoc networks. In any case, trilateration is too sensitive to outliers in range measurements to be used in positioning when high standards of integrity are demanded. However, trilateration can be a useful tool that can efficiently provide rough position estimates. Manolakis (1996), and Thomas and Ros (2005) provide fast algebraic and numeric algorithms for tracking a single moving object such as a robot. Coope (2000) shows that the effect of errors in the range measurements can be particularly severe when the required point is close to lying in the base plane or the three stations are nearly aligned. An iterative least-squares solution procedure for these ill-conditioned trilateration problems is provided by Murphy and Hereman (1995).

In order to solve for the mirroring ambiguity and assess more reliably the effect introduced by errors we suggest using $n>3$ measured distances – when available – and solving for the resulting over-determined problem by non-linear least squares techniques. The so-called multilateration method may still not be reliable in situations where the constellation of the anchors is unfavourable. In an ad-hoc scenario the location of nearby devices is arbitrary and situations of bad geometry are likely to occur, e.g. when all devices have approximately the same height. Since difficult constellations will be unavoidable in iPLOT, it is essential to attach coordinate outputs throughout with variances and reliability information based on the redundancy and the PDOP (Position Dilution Of Precision). In cases where the time offset has to be determined due to clock synchronisation, the GDOP (Geometric Dilution Of Precision) is required.

3.4. *Ad-hoc Network Positioning.* The trilateration and multilateration problem considered so far solves for one single point whose coordinates are unknown. The scenario of ad-hoc positioning consists of a large pure distance network with multiple unknown nodes and some known anchor nodes. Geodetic network adjustment algorithms provide coordinate estimates of several unknown nodes thereby improving the reliability of the quality indicators as determined a posteriori, see Grafarend and Sanso (1985). The theory of linear Least-Squares (LS) adjustment can be found in Grafarend and Schaffrin (1993). Although LS adjustment

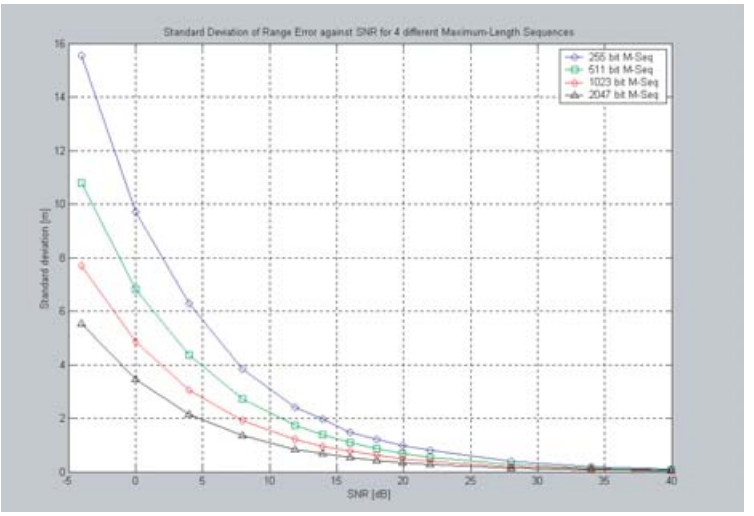

Figure 3. Standard deviation of range errors against SNR for 4 different maximum-length sequences.

is a powerful tool for the positioning task, the following issues need to be taken care of:

- The observation equations (1) are non-linear, but the adjustment is based on linear equations that require their linearisation. The standard least-squares adjustment uses the Gauss-Newton method to iteratively achieve a solution. The iteration can only converge and provide the global solution for the unknown coordinates under the assumption that good quality approximation values for the unknowns are provided initially. Bad initial values may cause the algorithm to diverge or converge into a sub-optimal local minimum. Additionally, side effects due to linearisation may also contribute to divergence.
- Outlier observations distort the network but they cannot be isolated by performing a least-squares adjustment and analysing the residuals. Thus, outliers need to be removed in a pre-analysis before the network is adjusted.

Both issues are accommodated by performing an anchor free start-up functionality that provides local approximate coordinates and pre-analyses of the observations for outliers. The proposed start-up function exclusively uses range measurements to calculate the positions of the nodes. The key issue for an anchor free localisation is to find a globally rigid graph, or in other words, a structure of nodes and ranges which has only one unique embedding up to rotation, translation and reflection. In 3D for instance, a graph of four nodes in general position which are all connected to each other by ranges is such a globally rigid structure. Aspnes et al. (2004) provide the theory of rigid and non-rigid point formations in 2D and 3D.

Based on the three ranges r_{12}, r_{13}, r_{23} between the nodes P_1, P_2, P_3, a local coordinate system is defined where the coordinates read

$$P_1{:}(0,0,0),\ \ P_2{:}(r_{12},0,0),\ \ P_3{:}\left(\frac{r_{12}^2+r_{13}^2-r_{23}^2}{2r_{12}},\sqrt{r_{13}^2-\left(\frac{r_{12}^2+r_{13}^2-r_{23}^2}{2r_{12}}\right)^2},0\right). \quad (2)$$

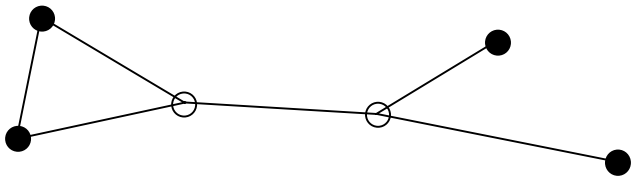

Figure 4. Collaborative network topology.

The fourth point is added to the network by 3D-trilateration thereby arbitrarily choosing one of the two solutions for further processing and discarding the other. The remaining nodes are added to the core network (as a rigid structure) individually using 3D-trilateration from three stations at a time. This procedure allows repeated determination of the same point using different combinations of nodes. The resulting coordinate differences provide essential information to detect false range measurements e.g. due to multipath effects. After all significant outliers are removed from the data set, multilateration is performed whenever more than three ranges are available. However, Moore et al. (2004) show that there is the probability of incorrect realisations of a graph when the measurements are noisy. For instance, if a new node is multilaterated from points located closely to one plane and the ranges are affected by errors, a flip ambiguity may occur due to the mirroring effect of that plane. These incorrect graph realisations can be avoided by identifying weak tetrahedrons with volumes smaller than a threshold which is determined by the estimated noise in the ranges. Only tetrahedrons passing the test of robustness are further considered or otherwise discarded. This step eliminates the mirroring ambiguity of nodes added to a rigid structure and improves accuracy measures. Once a node's position is determined, it serves as an anchor point for determination of other unknown nodes. This way, starting from the initial anchor points the position information iteratively spreads through the whole network.

However, limited availability or unfavourable deployment of anchor nodes may bring iterative multilateration as – described above – to an undesired halt or may even inhibit the algorithm to start. Figure 4 shows such a topology where the determination of both unknown nodes (open circles) cannot be achieved iteratively. Location information over multiple hops is needed. Savvides (2001) provides a recursive algorithm to check the feasibility for a graph to be determined collaboratively. Collaboratively solvable graphs such as shown in Figure 5 can be determined using global optimisation techniques. Although global optimisation is computationally expensive, its usage can be justified for a network start-up.

After completion of this step, approximate values of all coordinates are available. If the network has adequate redundancy and geometry, a free minimally-constrained least-squares adjustment can be performed with P_1, P_2, P_3 introduced as fixed points according to (2). A free network adjustment is ideal for looking at the internal consistency of the measurements. The outcome of a free adjustment shows only the errors in the measurements without adding in any potential errors as a result of inaccurate anchor coordinates.

Most applications require the network nodes to be tied in a coordinate system of higher order. With a minimum availability of three anchor nodes, the local coordinates can be transformed into the relevant target system. This can be achieved

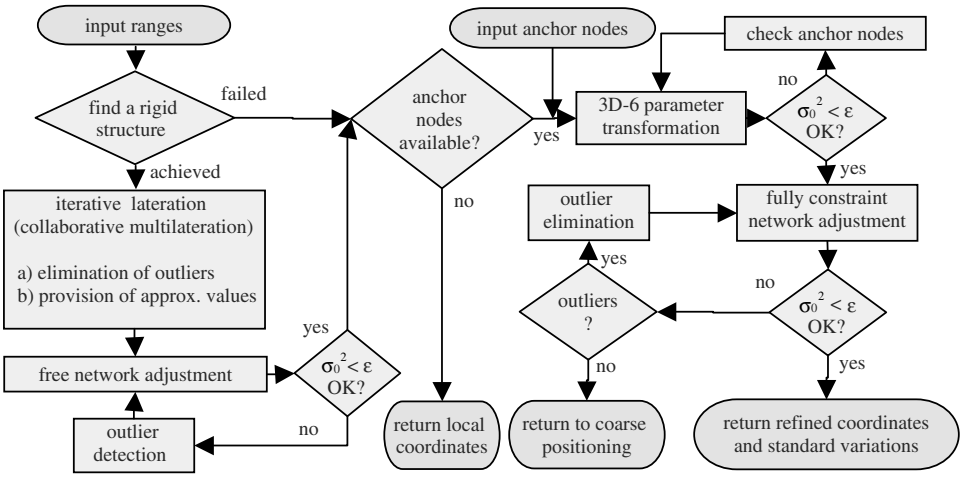

Figure 5. Start-up of the geodetic positioning mode (does not require any initial approximate coordinates. σ_0^2 is the a postiori reference variance, which is compared with a threshold ε).

by a 3D-Cartesian coordinate transformation (Vanícek, 2002). A closed form solution for determination of transformation parameters using the 3D-Helmert transformation is given by Horn (1987). Subsequent to the transformation, a fully constraint LS 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 point.

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, there will be the prospect of having to deal with incomplete or badly conditioned networks either as a result of in-situ conditions or in the event that range measurements are identified as outliers and removed. Scenarios range from a single node not being able to participate in localisation due to a lack of range measurements up to a situation where the complete network adjustment fails due to different possible reasons. However, users do demand positioning even under these circumstances.

To accommodate the user requirements for high continuity and availability, a coarse positioning service is used for cases where the geodetic network fails. Coarse positioning exploits connectivity information between nodes when range measurements are not available or flagged as unreliable. The simple fact that a node is connected to a fixed neighbour encloses its position within a sphere of maximal signal range. Although the sphere is the smallest envelope that encloses a set of possible locations, a cuboid along the coordinate lines is used which encloses the sphere as a bounding box. Bounding boxes are advantageous from the computational point of view, i.e. when intersecting the boxes for unknown points with multiple connections. The final coordinate estimate of the unknown point is simply the centre of the box with errors the size of the extent of length of the edge.

In case some ranges are available but do not fulfil the requirements for a geodetic network adjustment, anchor based localisation methods such as those of

Savvides et al. (2003), Savarese et al. (2002) or Niculescu and Nath (2001) can be used. All methods commonly start with estimating the distances between unknown nodes and anchor nodes, then evaluate a rough position and finish with an iterative refinement of the positions. The key issue is to find rough estimates of the distances between unknown nodes and some anchor points, which are preferably located at the edges of a large distance network. Savarese addresses that problem by finding the shortest path to each anchor point and then counting the number of hops on that path. Multiplying the minimal hop count by the average hop-distance of the network gives a rough estimation of the actual Euclidian distance. Savvides follows the same approach but replaces the average hop-distances by the measured distances between nodes. Since neither approach works very well in irregular networks, Niculescu's distance determination makes use of the local geometry around the anchor points. The algorithm aims to set up triangles from the distance measurements thereby facing the problems of mirroring and existence of flat, ambiguous triangles. Once either of these algorithms has been used to determine the distances to the anchor points, lateration or bounding-box methods can be used for an approximate positioning. Langendoen and Reijers (2003) compare some decentralised anchor based localisation methods showing that each strategy has its pros and cons depending on the conditions. Furthermore, geodetic network approaches developed for incomplete networks can be employed (Ochieng, 1990).

3.5. *Tracking and the Determination of Movement*. Tracking of devices is based on the fact that some nodes in the network have moved and some have not. The output of two geodetic network adjustments may be compared, using two sets of observations measured at different epochs. Within a deformation analyses function, a change detection test is performed as a two-sided cusum test which uses the likelihood ratio for testing between the no-change hypothesis and the change hypothesis. Those nodes detected for movement get flagged as 'on the move', and their displacement vectors are calculated. Repeated determination of displacements enables 'tracking' and allows estimation of higher temporal derivatives such as speed, acceleration and heading. The speed v can be estimated with $v = \Delta s/\Delta t$, if at least two measurements are available that differ by Δs in position and Δt in time. The estimation of acceleration a requires a minimum of three measurements and is determined by $a = \Delta v/\Delta t$ making use of the change in velocity Δv between two epochs which differ by Δt in time. With the coordinate differences Δx and Δy the heading can be determined using the expression $\mathrm{ArcTan}(\Delta x/\Delta y)$.

However, just for the purpose of tracking a least-squares adjustment of the whole network is computationally inefficient with a complexity in the order of $O(n)^3$ with n being the network size. On the other hand, the system latency is critical for large real time ranging networks. In order to overcome the latency problem, an efficient algorithm must be used, that allows quick position updates for single nodes. One approach is to make use of tracking techniques based on trilateration (Thomas and Ros, 2005) that do not require recalculation of the network. Once tracking is initialised by a significant displacement of a node, the position of the moving object is updated at the highest possible rate and its track (that is a series of positions and associated time stamps) are stored at the location server.

Moreover, the historical profile of a device is not just considered as a pure geometric series of positions that can be displayed graphically. An extended position track provides information about the travel behaviour. When the position tracks

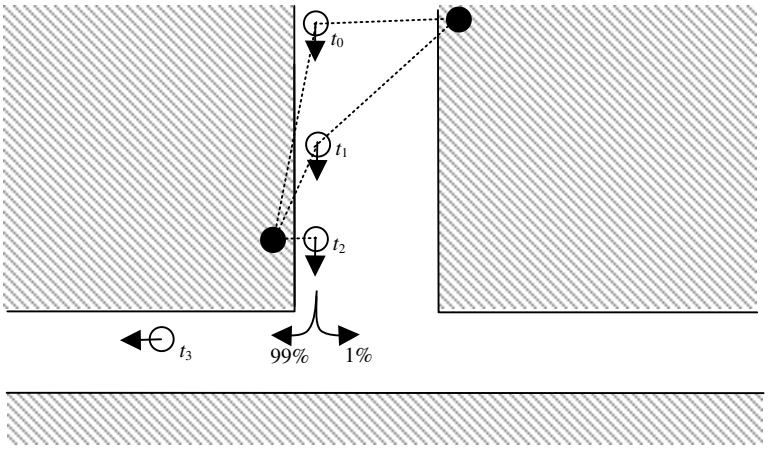

Figure 6. Various supports for positioning.

are used together with a travel behaviour model (Polak and Nakayama, 2001) unusual activity may be detected automatically. Travel can be predicted in short term with the help of speed, heading and the recent track, while a long term prediction can be made using the travel behaviour model.

On the other hand, in case of an ill-conditioned network solution the trajectory information may support positioning. As a novelty, the spatial and temporal derivatives such as speed and heading provide additional measurements to extrapolate the current position and thereby stabilise the positioning algorithm. The prediction is additionally complemented by constraints from a GIS as well as usage of historical data from a travel behaviour model. Figure 6 shows a scenario, where the shortness of anchor points requires sticking to these data sources. At the time t_0 and t_1 the position of a node is determined accurately by range measurements from two anchors. At t_2, one range and previous speed and heading pinpoint the location. Finally, at t_3 all ranges are lost. The position is marked down by the constraints of GIS (spatial database) and the travel behaviour model, which implies a 99% probability that the object has turned to the right. Clearly, the position accuracy and reliability needs to be adjusted accordingly.

4. CONCLUSIONS AND FURTHER WORK.

The results of the user requirements capture indicate that tracking of devices needs to have full coverage in different environments. The required navigation performance depends on the type of environment. To accommodate these diverse accuracy demands, iPLOT needs a precise geodetic network positioning function as well as a coarse positioning mode.

Requirements for a simple manageable man machine interface suggest a system architecture that allows the processing to be performed at a master control centre within iPLOT. To further accommodate the call for simplicity the location of nodes needs to be provided within a GIS. Software at the users 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 iPLOT. In terms of positioning outlier detection and quality indicators are essential.

Even though network adjustment has been used in GPS or triangulation networks to deliver positions of network nodes including their quality indicators, additional functions are required in order to establish ad-hoc networks. Future work will focus on an automatic start-up function for the system that eliminates outlier observations, sets up a free distance network and transforms the coordinates into a targeted reference system. A major challenge will be a positioning functionality for ill-conditioned networks that makes best use of available range measurements, connectivity information, temporal-spatial derivatives, travel behaviour and GIS data. In addition, the protocol development for communication is a major task which has not been the subject of investigation in this paper.

Although the iPLOT system is being developed to satisfy crime management requirements, it will have the potential to support many value added services such as fleet management, emergency and incidence response management, research and product tracking for factories on large industrial sites.

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REFERENCES AND BIBLIOGRAPHY

Aspnes, J., Eren, T., Goldenberg, D., Morse, A., Whiteley, W., Yang, Y., Anderson, B and Belhumeur B (2004). A theory of network localization. *IEEE Transactions on Mobile Computing, July 2004*.

Chey, J., Lee, J., Jee, G., Kim, W and Park, J (2004). Indoor Positioning Using Wireless LAN Signal Strength of Reference Points. *International Symposium on GNSS/GPS, Sydney, Australia 6–8 December 2004*.

Coope, I (2000). Reliable computation of the points of intersection of n spheres in n-space. *ANZIAM Journal*, Vol. **42**(E), pp. C461–477. 2000.

Darnell, C and Wilczoch, C (2002). Real Time Positioning., Construction and implementation of a GPS-Communicator. *Master's thesis in Control and Communication*, *Report no. LITH-ISY-EX-3246-2002*, *Linköping University, Sweden*.

Grafarend, E and Sanso, F (Editors) (1985). Optimization and Design of Geodetic Networks. *Springer-Verlag*.

Grafarend, E and Schaffrin, B (1993). Ausgleichung in linearen Modellen. *Wissenschaftsverlag, Mannheim, Leipzig, Wien Zürich*.

De Groote, A (2005). GSM Positioning Control, in: Seminar MOBILE BUSINESS. *Information Systems Research Group, Department of Computer Science*, University of Fribourg, Switzerland, January 2005.

Horn, B (1987). Closed-from solution of absolute. orientation using unit quaternions. *Journal of Opt. Soc. Amer.*, vol. **A-4**, pp. 629–642. 1987.

Langendoen, K and Reijers, N (2003). Distributed localization in wireless sensor networks: a quantitative comparison. *The International Journal of Computer and Telecommunication Networking*, **43**(4):499–518, November 2003.

Manolakis, D (1996): Efficient Solution and Performance Analysis of 3-D Position Estimation by Trilateration. *IEEE Aerospace and electronic systems*, Vol **32**, No. 4, Oct. 1996.

Melnikov, H (2004): Open solutions for location based services in WLAN environment. MSc Thesis. *Tampere University of Technology, Department of Information Technology*, 2004.

Moore, D., Leonard, J., Rus, D and Teller, S (2004). Robust distributed network localization with noisy range measurements. *Proceedings of the ACM Symposium on Networked Embedded Systems*, 2004.

Moore, T., Hill, CJ., Noakes, CJ., Hide, CD (2004a). Simulation of future LBS. *European Navigation Conference GNSS*, *Rotterdam*, The Netherlands, May 2004.

Murphy, W and Hereman, W (1995). *Determination of a position in three dimensions using trilateration and approximate distances*. Department of Mathematical and Computer Sciences, Colorado School of Mines, Golden, Colorado.

Niculescu, D and Nath, B (2001). Ad-hoc positioning system. in:*IEEE GlobeCom*, 2001.

Ochieng, W., Sauer, K., Walsh, D., Griffin, S and Denney, M (2003). GPS Integrity and Impact on Aviation Safety. *The Journal of Navigation*, **56**, 1–15.

Ochieng, W. (1990). Wide Area Differential GPS and Fiducial Network Design. PhD Thesis. University of Nottingham.

Polak, J. and Nakayama, S. (2001). Models of Learning and Day to Day Adaptation in Travel Behaviour. *Working Paper, Centre for Transport Studies*, Imperial College London.

Rabinowitz, M and Spilker, J (2005). A New Positioning System Using Television Synchronization Signals. *IEEE Transactions on Broadcasting*, Vol. **51**, No. 1, March 2005.

Savarese, C., Langendoen, K and Rabaey, J (2002). Robust positioning algorithms for distributed ad-hoc wireless sensor networks. in: *USENIX Technical Annual Conference*, Monterey, CA, 2002, pp. 317–328.

Savvides, A., Han, C and Strivastava, M (2001). Dynamic Fine-Grained Localization in Ad-hoc Networks of Sensors. *Proceedings of ACM SIGMOBILE 2001*, Rome, Italy, July 2001.

Savvides, A., Park, H and Srivastava, M (2003). The n-Hop Multilateration Primitive for Node Localization Problems. MONET **8**(4): 443–451.

Thongthammachart, S and Olesen, H (2003). Mobile location services over the next generation IP core network. *Proceedings of the 10th International Conference on Telecommunications 2003*,Volume: 1, 2003, pp. 324–329.

Thomas, F and Ros, L (2005). Revisiting Trilateration for Robot Localization, IEEE Transactions on Robotics, Vol. **21**, No. 1, pp. 93–101. February 2005.

Vanicek, P., Novak, P., Craymer, M and S. Pagiatakis (2002). On the Correct Determination of Transformation Parameters of a Horizontal Geodetic Datum. *Geomatica*, Vol. **56**, No. 4, 2002.