# High-Precision Ad-Hoc Indoor Positioning in Challenging Industrial Environments

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## 1. Abstract

This paper addresses the problem of providing high-precision positioning in industrial environments. Such environments are extremely challenging due to the adverse effects of multipath fading caused by the abundance of metallic objects, the physical layout of the environment which is often complex, and the lack of fixed positioning system infrastructure. Several technologies are assessed with regard to these challenges and their shortcomings are outlined. A solution based on an ad-hoc system is outlined in which we propose the use of an ad-hoc multimodal positioning system to achieve our goals.

## 2. Introduction

An Irish engineering company called ProsCon [19] offer a 3-D laser scanning service that can be used to survey and map complex structures relatively quickly and easily. Sample environments include chemical plants and oil or gas rigs. These surveys are typically turned into CAD diagrams which are then used in the prefabrication of machinery and parts. Accurate prefabrication offers significant advantages since parts merely need to be directly fitted rather than adjusted on the factory floor. This minimises the time that a given piece of machinery must be inoperational and is therefore of great benefit to the customer.

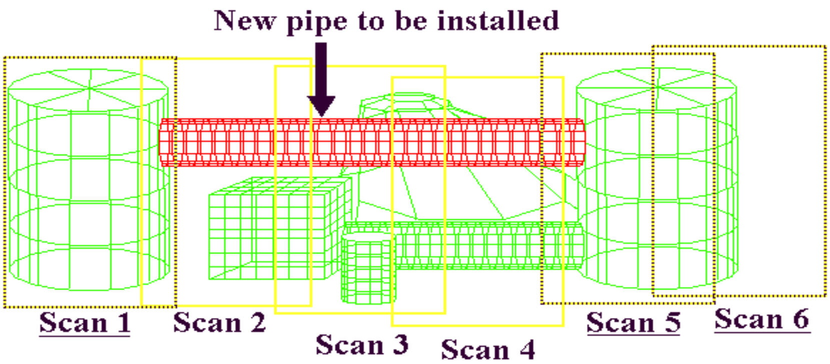


**Figure 1** shows a series of scans to be stitched together. Only scans 1, 5 & 6 are of interest.

There are two main difficulties involved with the scanning process as it currently stands.
Typically only a small area can be mapped in a single shot so it is usually necessary to take a selection of shots and "stitch" them together to form a larger image. To create a full 3-D image of a large and complex structure it is necessary to move the rather bulky laser scanning device to multiple locations and stitch entire selections of images together. Scans are currently stitched together manually, which is a labour intensive process.
Another problem arises when only a partial scan of two or more disconnected objects is required. In order to map these objects together in 3-D space it is necessary to connect them using a continuous scan (Fig. 1). This means that superfluous scans are made and need to be stitched together. In addition, objects causing blockages and walls bisecting the survey area necessitate the inclusion of yet more scans.

These problems could be alleviated by having knowledge of the exact position of the laser scanner when a scan is being made. This can be achieved with the use of a high-precision positioning system. The benefits of such as system would be a marked decrease in the number of scans taken, and hence the time, storage and expense required. It would also be expected to facilitate a faster, more automated approach to the stitching process.

## 3. Requirements

Such a positioning system is required to:

- have accuracy to within 10mm ideally
- work in a hostile environment consisting of multiple levels, complex geometry, metallic obstacles and possible electric and magnetic fields
- have no fixed infrastructure
- use relative positioning rather than absolute

These factors will cause problems for positioning technologies that use radio propagation methods, line-of-sight methods and magnetic fields in order to calculate position.

## 4. Existing Positioning Systems

The combination of accuracy requirements and hostile environmental conditions means that no current positioning system is able to fulfil the requirements for such a system. Indeed, the majority of positioning system are designed for use in an outdoor setting where blockages are infrequent.

An example of an outdoor system is Differential GPS (DGPS). DGPS offers good potential in terms of accuracy but unfortunately does not work indoors. Most other outdoor positioning systems offer low precision positional estimations and are thus unsuitable.

There are several positioning systems designed for indoor use but such systems typically target office environments rather than industrial plants. Accuracy is also an issue since for the target applications of these systems high accuracy is not a necessity. The use of a significant amount of fixed infrastructure also makes these solutions unsuitable for industrial environments. Systems such as Active Badge [2], which is based on the detection of infrared signals emitted from the "Badge", are content with detecting proximity to a sensor rather that establishing where an object is in relation to it. Indeed such a system is ideal for office type scenarios where information about which room a person or object is in is perfectly sufficient for most needs.

A more ambitious system is Active Bat [1] which uses ultrasound in order to perform time-of-flight lateration in order to calculate the 3-D position of a "Bat" which can be worn on a person or object. One of the problems with Active Bat with regard to this project is that, aside from the accuracy, Active Bat requires a vast amount of infrastructure. Receivers need to be placed in a square grid 1.2 meters apart and connected by a network of cables. This level of infrastructure is infeasible for the system we require.

The Cricket [3] system is somewhat similar to Active Badge in that it uses ultrasound as a basis for time-of-flight lateration. It requires less infrastructure that Active Badge but as a result suffers a loss in accuracy. Active Bat is accurate to 9cm whereas Cricket is accurate to $4ft^2$ ($1.22m^2$) regions.

Some positioning systems function in an ad hoc manner without the need for any infrastructure. An example of such a system is SpotOn [4] which uses radio signal strength information in order to estimate the distance between two SpotOn tags. A collective algorithm enables a network of SpotOn tags to estimate the relative position of the nodes in the network. Although SpotOn's ad hoc nature is a beneficial trait in our target environment, the use of perceived radio signal strength, which is typically less accurate than time-of-flight as a means of performing range estimation is not suitable for the target environment, nor would it produce the accurate positional estimations that are required.

Developmental systems include Ultra Wideband (UWB) ranging [7], [8], [16], [17] and [18] and spread spectrum ranging [5] and [6]. UWB in particular has received a great deal of attention. Advantages of UWB positioning include resistance to multipath (or Raleigh) fading and penetration of walls and other solid objects. Proponents of UWB also claim that it is capable of interoperability with other radio based systems. Experimentation shows that while UWB signals may be able to penetrate solid objects, metallic objects cause a UWB signal to be reflected. This means that in the target environment even a UWB signal will suffer reflections and multipath effects. UWB also faces several regulatory hurdles in regard to interoperability.

Spread spectrum ranging has received much less attention than UWB and few experimental systems have been implemented. Spread spectrum has many of the favourable characteristics of UWB such as resistance to multipath.

While both UWB and spread spectrum, offer the potential for high accuracy ranging, no system has as yet been developed that offers sub-centimetre accuracy in working conditions.

## 5. Proposed Solution

A solution to the problem must address a number of difficulties in order to succeed. Firstly there is a lack of infrastructure. This means that an ad hoc network of positioning nodes must be deployed in order to provide coverage and positional estimations. Secondly a coordinate system must be established so that all positional estimations have a common frame of reference. Thirdly we must address the fact that no single technology offers the required accuracy needed.

An ad hoc network of positioning nodes will eliminate the need for fixed infrastructure and also provide a great deal of flexibility when deployed. In a high multipath environment accurate ranging measurements can only be obtained where a line of sight exists between the node involved in the ranging process. The deployment of ad hoc nodes can be used to navigate around blockages in the environment, creating an unbroken chain of line-of-sight nodes, and eliminate dead spots.

Several papers propose methods and techniques for resolving positional estimates in a network of ad hoc nodes. Most of these papers propose the use of iterative lateration or the generation and solving of a constraint based positional model [9], [10], [11] and [12]. The problem with these approaches, from our perspective, is that an ad hoc network needs to be seeded with position aware nodes in order to function. These position aware nodes must be either manually placed or get their position from another positioning technology such as GPS. A novel approach is suggested in [14], which proposes the establishing of a local coordinate system within the ad hoc network without position aware nodes. Of concern, however, was that upon the merging of two local coordinate systems errors tend to propagate. This is an undesirable feature that must be remedied. Savvides et al [13] suggests the use of laser range finders or long range ultrasound in order to accurately form large area local coordinate groups thus minimising the amount of merging that is required.

### 5.1 Local coordinate system formation & merging

In order to form a coordinate system at least three nodes (A,B,C) which have known distances with respect to each other, are needed. These three nodes must form a triangle and cannot be co-linear. One of these nodes, chosen at random, say A, will form the origin of the coordinate system (0,0). The line between the origin and another of the nodes, also chosen at random, say B, becomes the x-axis. Thus, B has coordinates (0,AB). C then has coordinates (AC cos $\alpha$, AC sin $\alpha$). The angle $\alpha$ is given by the standard formula:

$$\alpha = \text{arcos}\,\frac{AC^2+AB^2+BC^2}{2\ AC\ .\ AB}$$

It is worth noting that at least one distance measurement is needed in the formation of local coordinate systems, as angle measurements merely describe the shape of the triangle and the ratio of the length of its sides to each other. As a result it is impossible to form local coordinate systems using angulation alone. Once the basis for the coordinate system is formed it is then possible to add any nodes within range in order to form a local coordinate group.
We propose the use of laser rangefinder nodes, or supernodes, to form a larger scale local coordinate system and to participate in the resolution of positional estimations for other nodes in range. Thus, the principal role of the normal nodes is to cover areas which are not covered by the super nodes. Clusters of normal nodes shall be deposited where necessary and these groups of nodes will form their own local coordinate groups. The existence of common members in two coordinate groups allows the groups to be merged into a common coordinate group. Such a technique is described in [14]. Several operations need to be carried out during the merging process. It may be necessary to flip one coordinate system about an axis in certain situations. It will then be necessary to rotate the coordinate system until all axes are pointing in the same direction. Finally the two groups can be merged by adjusting one of them by some vector.

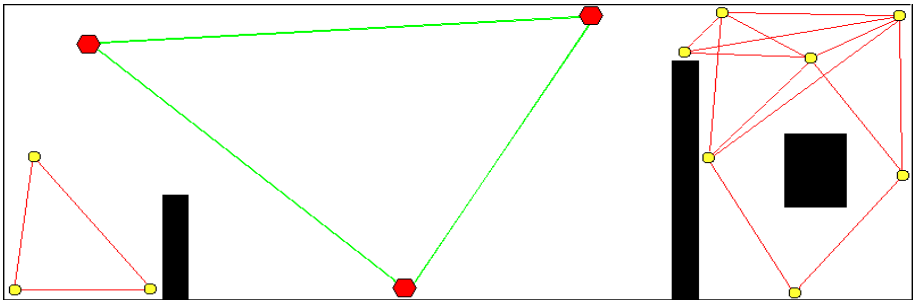

**Figure 2**. A large scale coordinate system is formed by the laser range finders (represented as hexagons). Normal nodes are deployed to cover other areas and form local coordinate systems of their own. These will later be merged into a common coordinate system.

Verification of positional estimations can also occur when a supernode is available to do so and positional estimations can be iteratively recalibrated in order to minimise error accumulation. For example, in Figure 2 above the leftmost supernode (shown as hexagons) can verify the relative positions of the nodes (shown as dots) involved in the leftmost coordinate group. This information can be transmitted to this coordinate group so that it can fine tune its position estimations before merging.

## 5.2 Increasing accuracy

In order to improve the overall accuracy of our system we propose the use of multimodal sensing nodes which will use a constraint based model to solve unknown positions. Nodes would be endowed with both UWB ranging ability, which would provide low precision positional estimation to within 10-15cm, and a high accuracy laser angulation device. UWB, while useful as a ranging tool, is also useful as a communications medium because of its resistance to multipath effects. Having found the approximate location of neighbouring nodes using UWB ranging and a few iterations of the constraints model, each node pair will begin a search pattern with its laser pointer. Laser technology is well developed and angulation offers excellent positional information without the need for high resolution clocks and avoids clock synchronisation issues.
Described in [9] are methods involving the use of angular measurements to achieve positional estimations. One of the methods called DV Radial assumes the existence of a compass in some or all of the nodes. The use of compasses allows the DV Radial method to generate more accurate

estimations with a decrease in the amount of signalling necessary. This method however would not be appropriate for industrial settings as metallic objects and magnetic fields would render the compasses used ineffective. An alternative method called DV Bearing functions without the use of compasses but suffers a decrease in accuracy and an increase in signalling. It is assumed that each node has a principal axis against which angular measurements are taken and that at least some of the nodes are aware of their orientation. Nodes can deduce, from the latter, their orientation, and other nodes can learn from them their orientation until all nodes know their orientation, and bearings, to their neighbours with respect to some common direction.

A node will be able to detect when another nodes laser is pointing at it via some laser sensitive receiver. The receiving node can then send a message to the scanning node in order to let it know that the correct angle has been achieved. When this process is completed for all nodes an elimination process can begin. Nodes that do not meet certain criteria, due to being collinear, an outlier or non line of sight, can be eliminated from the constraints model and accuracy can be further improved.

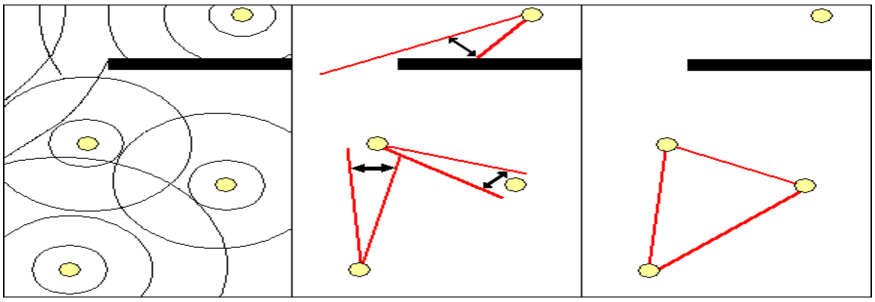

**Figure 3:** UWB ranging is performed followed by a search using a laser pointer. If the search is unsuccessful then it is likely that the UWB signal arrived via reflection and is thus dropped from the constraints model.

Several constraints models perform reasonably well such as the Kalman filter described in [13]. However, such systems have no means of removing error causing nodes and hence suffer a decrease in accuracy. Our system, with its tiered approach, offers an opportunity to do this and is one of the benefits of choosing a multimodal positioning system.

## 6. Conclusions and Future Work

In order to address the problem posed by the accuracy requirements of the application, and the difficulties faced in the target operating environment we considered several technologies. A solution was proposed that addresses the requirements and has a high potential for success. Future work will consist of simulation, evaluation of the Cramér-Rao Bound [15] in order to determine possible accuracy, and development of the appropriate algorithms involved followed by a real world trial of a prototype positioning system.

## 7. Acknowledgements

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