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Autonomous Navigation using Ad-hoc Networking

by

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J. Treurnicht
2008 March

AUTHENTICITY

Declaration

I, the undersigned, hereby declare that the work contained in this assignment/thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Date:...29 February 2008...

ABSTRACT

A solution for autonomous navigation is described and demonstrated using simulations. The novelty is to use a set of interconnecting nodes with self-locating properties for navigation. This work defines the error propagation algorithm used for a single node solution and then expands the application thereof for solving a network of interconnected nodes.

Simulated results show that the navigational solution is a strong function of the geometry of the nodes. The results for a single node solution and for a set of interconnected nodes are presented. A navigation solution is demonstrated using a simulated mission planner with a selection of paths constructed by using these nodes as waypoints.

Implementation issues are discussed regarding the feasibility of executing the navigation solution on a platform with wireless Ad-hoc networking capabilities.

SAMEVATTING

Die oplossing vir ‘n outonome navigasie netwerk word beskryf en gedemonstreer deur middel van simulasies. Wat die betrokke oplosing uniek maak is dat dit gebruik maak van ’n stel gekonnekteerde netwerkpunte met die eienskap om hul eie posisie te kan bepaal. Die eienskap word dan aangewend om ’n navigasie oplossing te bewerkstellig. Die proses wat gevolg word is om ’n fout propagasie algoritme te gebruik wat eerstens die posisie van ’n enkelpunt nodus oplos en dit dan uit te brei om meervoudige punte se posisie en posisie foute te kan bepaal.

Gesimuleerde resultate toon aan dat daar ’n streng verband is tussen die posisie fout en uitleg van die aanvangsnodus posisies wat in so ’n oplossing gebruik word. Resultate vir die oplossing van ’n enkelpunt nodus en ook vir ’n stel nodusse word getoon. Die oplossing vir die navigasie probleem word gedemonstreer met behulp van gesimuleerde missie planne waarin ’n aantal navigasie roetes gekies word deur van die nodus posisies gebruik te maak.

Praktiese aspekte en die doenbaarheid van ’n navigasie oplossing word bespreek. Beskikbare hardeware vir draadlose ad-hoc netwerke dien as ’n platform waarop die navigasie algoritme as toepassings sagteware uitgevoer word.

ACKNOWLEDGEMENTS

"It you don't see beauty in your equation it is not worth publishing"...

(Anonymous)

My inspiration came from many sources; Mark Weiser (July 23, 1952-April 27, 1999), chief scientist (Engineer) of Xerox PARC reprimands us to design calm technology, while Norman promotes simplistic design concepts. Using these guidelines as a yardstick goes a long way towards defining simplistic solutions and complex technology as building blocks.

Thanks to the CSIR that gave me the opportunity to do something worthwhile. My sincere thanks go to my family and friends for their support and motivation that helped me to see this task through until the end.

The praise and glory belongs to my Creator for keeping me humble and strong through my life's journey. I hope that this work may inspire others to take their challenges head on, remembering not to rush in (only fools may) but first to enjoy the scene. The journey is not a burden but a privilege to improve our world.

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ACRONYMS

AHNN	Ad-Hoc Navigation Network
ANMP	Ad-Hoc Management Protocol
AoA	Angle of Arrival
DARPA	Defence Research
DGPS	Differential Global Positioning System
DOP	Dilution of Precision
ECEF	Earth Centred Earth Fixed (Coordinate reference system)
EPA	Error propagation algorithm
FoM	Figure of Merit
GLONASS	GLobal Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning Satellite/System
IMU/IRU	Inertial Measuring Unit or Inertial Reference Unit
IN	Intelligent Node
INS	Inertial Navigation System
ITAR	International Traffic in Arms Regulations
LAN	Local Area Network
LORAN	Long Range Navigation
MEMS	Micro-machined Electro Mechanical Systems
MoC	Mote on a Chip
NN	Navigator Node
OEM	Original Equipment Manufacturer
ON	Ordinary Node
PAN	Personal Area Network
PNT	Positing, Navigation and Timing
PNTMT	Positing, Navigation, Timing, Mapping and Tracking
QoS	Quality of Services
rad	radians
RTK	Real Time Kinetics
SLN	Self Locating Node
SN	Smart Node
SNMP	Simple Network Management Protocol
SoC	System on a Chip

SPA	Self Positioning Algorithm
TDoA	Time Difference of Arrival
ToA	Time of Arrival
TSMP	Time Synchronized Mesh Protocol
TTFF	Time to First Fix
WAAS	Wide Area Augmented System
WAHNN	Wireless Ad-Hoc Navigational Network
WAN	Wide Area Network
WGS	World Geodetic System
NLOS	Non-Line-of-Sight
LSA	Least Squares Adjustment

NOTATION

λ	Latitude (m)
φ	Longitude (m)
A, B	Vector notation
a, b, i, j, k	Unit vector notation
▯, θ, β, Φ, φ, γ	Angles (scalar values)
σ^2	variance
x, y	coordinate
μ	micron (scaling unit)
$\mathfrak{R}$	Real number
τ	Time delay (unit in s, μs, ms)
υ	Residual (error)
ω	Angular rate
$\hat{e}$	Expected value
s	seconds

Chapter 1

1 INTRODUCTION

Unlike animals mankind has technology to serve the basic need of knowing "where am I?" or "where I'm going too?" Animals (birds, tortoises, fish, hamsters and the like) are well equipped with biological navigation systems (bio-nav). Animals use the complex mechanisms of Path integration, Visual Landmarks and Cognitive Maps [4, 12, 21, 60] for their survival. Humans do not have genetically engineered navigational capabilities but use their innovative minds and technology to enhance own positioning and orientation functions. To this effect the Global Navigation Satellite System (GNSS) was developed to provide absolute position, anytime and anywhere using ground based receivers [14, 31, 34, 46]. The market sectors for the military [32], aviation, and civilian have many applications with a wide selection of available products and many more to come. As the demand for higher performance systems increases further, innovative solutions are developed such as augmented or GPS aided systems [30], Differential Global Positioning Systems (DGPS) [17, 29] and Real-time Kinematics (RTK) systems all examples of high end performance products. Some challenges still remain because the above-mentioned technologies need favourable environmental conditions for signal transmission. The abundance of network technologies with its connectivity, mobility and communication functions are enabling alternative positioning solutions.

The feasibility of implementing these highly complex systems using handheld devices is supported by the latest technology trends. A few examples of these technology developments are;

- Single chip solutions for powerful embedded control and signal processing;
- Recent developments in artificial intelligence (i.e. SWARM, Fuzzy Logic and Neural Networks) for autonomous operations
- Advantages in high-density energy sources (Li-Ion batteries) and on chip power management.
- On chip sensors using MEMS technology and
- Robotics [56]

Innovative programs with objectives to spur further interest in using these technologies are the focus of current research programs; examples such as the DARPA urban challenge [67] and the Autonomous Lawnmower competition [65]. A particular challenge for autonomous navigational systems is the capability to remain functional for extended periods when the Global Positioning System (GPS) becomes unavailable. The autonomy for this type of system is classified as such because it does not use GPS as the primary sensor. The feasibility of implementing autonomous navigational systems on handheld or portable devices demands extensive use of a combination of all these latest technology trends.

Chapter 1 presents the introduction with an historic overview of navigation and wireless networks as background knowledge. The navigational problem and an overview of the proposed navigational network concept solution are broadly defined. The literature study in Chapter 2 discusses vector theory and recent technology advancements in wireless networks and navigation systems with the objective to create a framework for application development. Chapter 3 gives detailed description of the proposed network concept as an alternative navigational solution. The Ad-Hoc navigational solution is developed based on its error propagation model and the error sensitivity is studied using both Monte Carlo simulations and an analytical model. Chapter 4 defines the experimental work followed by the analysis and evaluation of the experimental results. The focus is to demonstrate how network geometry and the number of propagations influence the overall positional accuracy of these self-locatable nodes. Chapter 5 demonstrates a typical example of a navigational network and its effect on path planning. Conclusive remarks, recommendations and proposed future work are addressed in Chapter 6.

1.1 Historical overview

Since early days when man started to circumvent the globe a need for navigation was born. This was not an easy task and involved many risks that required courage and willingness to explore unknown territory. The knowledge of ones position in terms Latitude and Longitude was not accurate at all and very much depended on personnel skills or a priory knowledge of the surrounding landmarks. Latitude determination was of lesser complexity as the techniques to determine the north south latitude by means of the sun and stars positions were developed much earlier. Only since the eighteenth century, when John Harrison invented the chronometer, seafarers were able to compute longitudes as well. Since then position and location determination has become part of our everyday life. Making use of the latest innovations (i.e. GPS, RTK, DGPS) we are able to know our exact position with varying degrees of accuracy and certainty.

1.2 Motivation

Autonomous navigation inside buildings, tunnels, caves, canyons, tropical forests or urban environments with high rising buildings are a challenging task. A typical system capable of knowing its position under all conditions is yet to be designed. GPS solutions are but part of the solution and a basic requirement of an autonomous system are to integrate seamlessly with GPS signals without any user intervention.

Accurate positioning in areas that lack the infrastructure to support location-based services is problematic. The widely reported Non Line of Sight (NLOS) problem typically experienced in radio communications is also true for all terrestrial and satellite based positioning system solutions using electromagnetic signals [64]. The root cause relates to the operational and/or environmental conditions that either attenuates, interferes, scatters and/or reflects (i.e. multi-path phenomena) radio frequency (RF) signals. The resulting poor signal reception degrades the performance with respect to positional accuracy and the integrity of a navigation system.

The generic solution for this NLOS problem is to use augmented navigation systems. This type of solution utilises complementary aspects of sensors (hardware) and absolute position systems using signal processing (software). This requires an in-depth knowledge of sensor system theory and the availability and/or access to Original Equipment Manufacture (OEM) type hardware. This substantially increases the complexity and cost of these solutions. A developing country, like South Africa has additional problems because most of these high performance inertial sensors (i.e. navigational grade) require ITAR approval.

Technologies such as “Systems on a Chip” (SoC) or Micro machined Electro Mechanical Systems (MEMS)) sensors are commonly used for positional updates in signal restricted environments. Current studies show promising results but the requirements for absolute position updates to compensate for sensor drift still remains. This study proposes an alternative concept that makes use of ad-hoc networks as pseudo-lites. The concept is to extend the availability of GPS signals inside these restricted areas using a network of self locating nodes. Once the Ad-hoc network is established a navigational solution can be provided by defining a path with the node positions as the waypoints. Preconditions are that the nodes remains connected and that the node density is sufficient to provide a self locating solution in order to provide position updates for the user. In this thesis an algorithm to demonstrate a concept for dynamic node localisation is developed. This algorithm or method is then used to investigate how the error propagates as a function of the number of nodes and the geometry thereof for a network navigational solution.

Network routing protocols are defined as being optimal using the shortest possible route as reference. The efficiency of directing data using path-aware protocols optimises the network latency and minimises network congestion by avoiding busy network nodes once the shortest path between the originator and destination point has been resolved. To establish the path requires a navigation capability after which effective data transfers are possible once this optimal route has been identified. The user/client does not necessary remain at a fixed location, a typical example is to provide Email services to a travelling salesman. Using dynamic path finding algorithms a message can be forwarded efficiently if the locations of both entities (originator and receiver) are known at any instance. This has additional benefits because the store and forward method currently used for sending and receiving e-mail requires that multiple copies of that message be stored on different mail servers as opposed to sending them directly to the end user.

Traffic control is another example that can benefit from using network based navigational techniques. Traffic flow is very dynamic and demands on the fly (ad-hoc) methods to redirect/reroute individuals. This is a dynamic type of navigation solution that can be solved using networking navigational techniques. In this scenario the dynamic node becomes the current location of the motor vehicle while the desired/planned destination is the end waypoint node. The individual may change his destination based on his current position as a suggested optimum route may invoke additional requirements that may need on the fly route planning to include "what if" scenarios.

Network based navigation systems poses many advantages for military use. Secure communication of which the encryption and decryption is based on the space-time knowledge of the source designated position of secure data, battlefield situational awareness, location based surveillance for target tracking and target designation purposes are but a few examples that relate to network navigation and location awareness. Urban warfare demands that operators are to be alerted at all times, while situational awareness with quick reaction tasks translates into requirements for accurate positional information of both friend and foe. These typical operational conditions, classified as close combat scenarios, have the friendly forces on one side of a wall and the enemy on the other side of that same wall. In this type of scenario the requirement for absolute position is in the order of 0.5 m accuracy.

When considering the specifications of available technologies with sub meter accuracy without using any infrastructure, it is concluded that such systems are not presently available (2007) as turnkey systems. The influencing factors are the level of maturity of the technology used or intended to be used, the extent of collaboration between different disciplines and the extremely high costs vs. risks for using new technology for application developments.

Current efforts are to develop high bandwidth network roaming accessibility for the mobile market. Many problems still need to be solved but off the shelf turnkey solutions are becoming available that are fairly reliable and robust products. This is mainly due to the explosion in the communication markets (i.e. cell phone, wireless internet, laptops) pushing manufactures to produce products that are small, powerful and affordable. Chip manufactures have only but started to produce systems that are able to comply with man portable systems using SoC and MEMS technologies.

1.3 Problem definition

Autonomous navigation that is man portable in areas deprived of GPS signals is problematic. The use of inertial sensors is not particularly suited to man portable applications. This Inertial Navigation System (INS) has many practical limitations mainly due to the availability of portable high accuracy sensors, the required complexity of alignment and calibration processes for these sensors. This contributes to an additional burden on the overall weight and power budgets for man portability and has a subsequent increase in cost. Further complications are ITAR (International Traffic in Arms Regulations) restrictions regarding export licences for navigation grade type sensors. This limits easy access to the technology and support for these types of sensors to foreign countries such as South Africa.

1.4 Summary

Global navigation services have become ubiquitous for everyday use. Wireless networks are available in many different forms; either using cell phones or wireless networks for LAN, WAN or WAAS applications, laptops or the Personal Digital Assistant (PDA's). Many interoperable issues still need to be addressed but recent developments for example the Software Defined Radio (SDR) and its applications look very promising.

Although these different systems and their applications still lack location based services it is fast becoming the norm. By example, the E911 regulation which is known being implemented makes use of the enabling technology developments for location-aware protocols. These trends will continue to support autonomous navigational solutions utilising all available network points of which the location is known. According to Akyildiz, {2005(530)} [1] many problems such as scalability and security still remains to be solved. Although many researchers are currently addressing these issues, no articles could be sourced where a study was made on how consecutive errors propagate within the network environment.

Chapter 2

2 LITERATURE STUDY

Autonomous navigation requires background knowledge in geometry, vector mechanics, networking and navigational theory and its practices and probability theory. Geometry and vector mechanics are the applied theory in the fields of land surveying, mapping, cartography and GIS. Navigational principals, networking, communication, control and signal processing theory are useful from a system perspective to deal with the complexity of finding the optimal solution. Implementation issues require an assessment of the latest development trends in sensors, robotics, and wireless technologies. Essential theories and technologies are described in some detail. The objective is to provide better insight in the role and function of each of these in an autonomous navigational network. The system approach is seen as an effective problem solving technique including an appreciation of how these different aspects interact.

2.1 Navigational systems

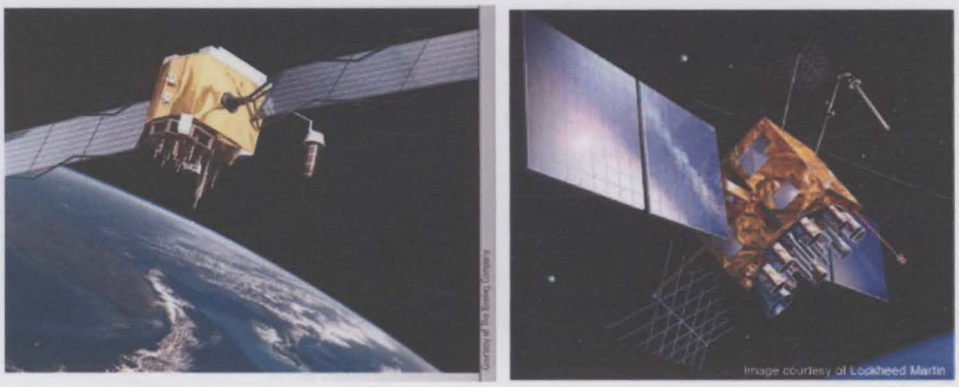
Navigational solutions fall into one of the following categories:

- **GNSS:** Global Navigation Satellite Systems
- **Inertial sensors:** Platform mounted sensors that senses gravitational fields and/or inertial forces (acceleration or gyroscopic rates)
- **Network based:** Making use of exciting wireless networks or ad-hoc sensor networks.
- **Vision based:** Using maps or visual presentations with a priory knowledge of the area or location that are to be navigated.
- **Augmented systems:** A combination of more that one of the above methods and commonly referred to as augmented systems.

2.1.1 GNSS

The global world has become very much depended on GNSS type solutions for almost all its positing, navigation, timing, mapping and tracking (PNTMT) applications. The ever increasing costs in keeping the traditional, local radio navigation type systems such as DECCA or LORAN operational, the advantages in satellite based applications and a demand for a global positioning capability is the driving force behind many of these solutions. The point has been reached where the historical radio navigation systems are either being phased out, or are considered to be phased out in the near future to be replaced by the much cheaper and ubiquitous global navigational systems, like GPS, GLONAS or Galileo.

Most navigational application products and systems have integrated global positioning receivers (GPS, operated by NAVSTAR) with total reliance on this satellite-based solution. The USA has developed its GPS for military applications but due to the many benefits of having a global positioning system it was soon released into the public domain. Since then GPS has become a very popular and affordable system solution that gained a wide civilian user base. To a lesser extent the GLONASS (Russian) system followed similar routes but is hampered by limited funds since the cold war has ended.



(a) (b)

Figure 2-1: Old (a) and new (b) generation GPS satellites.

Until recently the USA and Russia were the only suppliers of global positioning systems. The European consortium plans to start operating the GALILEO positioning system by 2011-12 [70], followed by China with the COMPASS (preciously BEIDOU (big-dipper) positioning system. In terms of global navigation on Sea, Land and Air it is almost unthinkable what would happen if GPS or GLONASS were not freely available any more. Although costly, most first world countries do build a business case to manage and control there own positioning systems. For strategic reasons many 1st world countries opted for their own independently operated satellite systems i.e. GALILEO (Europe) and COMPASS (China). Although these systems are not operational as yet, it will elevate the perceived problems with current operational systems that may become unreliable for many reasons (i.e. to costly, politics, terrorism or global disasters). To this extent many of the current research focus is based on getting these alternative systems into operation. This research has many commercial benefits as the market for GPS receivers are well established with an ever-increasing client and application base.

In 1964 the US launched the TRANSIT system [55, 72] that used Doppler and knowledge of the satellite positions to determine ones local position. This was replaced by the NAVSTAR system (operational since 1978) that used atomic clocks to synchronize timing between receiver (ground based segment) and transmitter (space based segment) to accurately measure distance using a common reference time. The GPS system as operated by NAVSTAR is widely in use today and is currently being upgraded (Block III, constellation 24+ satellites, 2011) with improve services. Supplementary systems such as GLONASS (Russia, 18 satellites by 2008), Galileo (Europe, a constellation of 24+, satellites expected to be operational by 2013/5) and Compass (previously called Beidou, operated by China, with a planned constellation of 35 satellites at a yet to be announced date) are progressing with planned operational dates in the near future as indicated in brackets. All these use very similar principals to calculate a user's local position via ranging (distance measurements) and the satellite positional data through triangulation algorithms. This is all good news but as Figure 2-2 indicates the frequency bands are becoming very crowded. This problem is currently been addressed by GNSS. In addition the problem of getting a suitable parking space for geostationary satellites is also becoming very problematic.

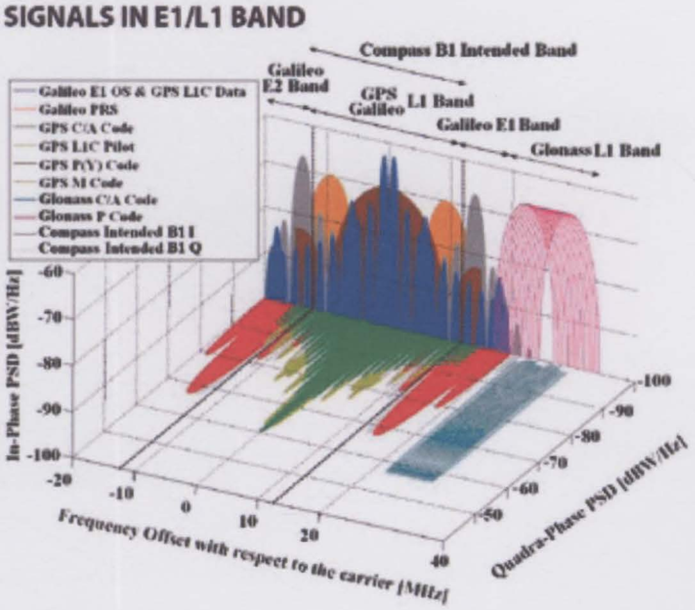


Figure 2-2: Spectral band usage of the E1/L1 frequency for GPS, Galileo, GLONASS and Compass systems (Source: ION News).

The United States plans to launch the next generation GPS block III satellites by year 2011. According to GPS world [22] this system "will address the challenging military transformational and civilian needs across the globe, including advanced anti-jam capabilities, improved systems security, accuracy and reliability". GPS receiver technology is becoming more complex with increased performances. Of special interest are the higher sensitivity receivers (< -155dBm) for indoor applications, typical examples being; SuperSence (u-blox) and NavSync, shown in Figure 2-3. Unfortunately these positioning systems do not solve the problems associated with applications that provide accurate and reliable positioning updates in urban, bush and indoor environments.

A common factor that limits the performance is the very weak GPS signal and multi-path phenomena. Alternative solutions are to make use of inertial sensors. The availability of all these alternatives is very promising in terms of satellite redundancy, alternative backup systems and improved global positional coverage with associated services. Unfortunately the problem remains that these GPS receivers all require a RF signal to operate. This signal is not available inside buildings, canyons, tunnels or dense foliage with the effect that the overall positional accuracy is degrading due to a weak signal or no fix can be obtained due to signal loss.

»LOCATION-BASED SERVICES

Galileo-Ready Chip

The u-blox 5 is a GPS- and Galileo-ready chip with less than 1 second acquisition. It has a 50-channel engine, power consumption of less than 50 millwatts, and an acquisition and tracking sensitivity of -160 dBm that enables indoor coverage using SuperSense weak-signal technology. SuperSense has algorithms that enable superior acquisition and tracking sensitivity at low-power consumption, higher terrain coverage, excellent dynamic responsiveness, and higher flexibility with antennas. The chip is designed for GPS-enabled mobile phones and other battery-operated portable devices that operate in indoor environments. **u-blox**, *www.u-blox.com*

Figure 2-3: New generation GPS receivers for indoor navigation.

2.1.2 Inertial sensors

Recent advantages in Micro-machined Electro Mechanical Systems (MEMS) technology enabled the use of inertial sensors for indoor applications. Traditional inertial sensors are not suitable for man portable applications because these systems are large in size and consume too much power. For the time being this will remain the case for all high performance type system requirements. Recent technology advantages, in particular MEMS type sensors, used in combination with increased signal processing power and algorithms have created new opportunities. Strap down inertial platforms avoid the many pitfalls of mechanical gimbals by implementing the required functions using software processing techniques. Inertial sensors have the advantage that they can operate without any man-made infrastructure but a disadvantage is long term stability due to drift and sensor bias.

2.1.3 Network based navigation

Network based solutions for navigational purposes are a fairly new concept under development. Although the solution and method in itself is not new, it is due to the enabling technologies having reached higher levels of maturity that now allows for the exploration of wireless network concepts for navigation. This is achievable by a combination of meshed and/or ad-hoc networks with localization capabilities, lately a subject of intense studies. Research challenges are discussed by Akyildiz [2] and Lee [43] while advanced research work is done by Beutel [5] and Langedoen [40].

2.1.4 Vision based

The possibility of navigating using visual cues has a long history. It is quite easy to find a know location by recognising landmark features. Humans and animals do this intuitively without even realising that visualisation is an optimal navigational solution. The unfortunate condition is that a-priori knowledge is required for this to have any affect. With the latest developments in mapping techniques i.e. GIS, Digital terrain mapping, remote sensing and an abundance of visual sensors this method allows for very effective means to find a position using a-priori information network. A typical example is research work done for DARPA's MARS2020 for autonomous vision based localization (i.e. without GPS) as described by McHenry [47]. Robotics research is using vision-based systems for collision avoidance and navigation studies with regard to implementing autonomous navigation concepts on mobile platforms in the Urban Grand Challenge [68] and Lawnmower research programs [66]. Some of the enabling technologies are the availability of more powerful Digital Signal Processors allowing for implementing Artificial Intelligence (AI) and Pattern recognition algorithms on embedded systems.

2.1.5 Augmented systems

Augmented navigation system solutions have become the order of the day. Realization of these highly integrated systems is possible with ever increasing processing power using reduced chip sizes that consume much lesser power. The benefits of sensor fusion are examples of advanced developments with well documented theory, a subject of several publications [19, 39].

Augmented systems integrate GPS receiver technology, inertial sensors and a Kalman filters to optimise the positional solution. For navigational purposes the augmented solutions give the better of two worlds as the GPS provides optimal position updates for low frequency position updates while the inertial system has a higher update rate to address the issues of high dynamic platforms. The additional costs and system complexity is offset by the many advantages of solving unique problems. The typical, commercially available GNSS only solutions falls in the prize range of R3k (off the shelf GPS receiver) and R150k for a top of the range DGPS system used for land surveying applications. Augmented system solutions differ substantially in prize and depending on the quality of Inertial Navigation Sensors (INS) used the cost can vary between R70k, for a commercial grade INS up to R2M, for a navigational grade INS.

Major disadvantages of inertial sensors are the requirement for frequent positional updates due to gyro and accelerometer drifting errors. Using navigation grade sensors as opposed to commercial type inertial sensors cuts down on the frequency of positional updates but cannot avoid this problem as the requirement for position updates still remains. Navigational and Tactical grade sensors are expensive and normally not easily available in developing countries (like South Africa). The errors caused by drifts can be bound by using GPS to provide an absolute position from time to time. Accepting the fact that the position error will increase when GPS is not available some alternative solutions are considered. Due to its availability and relative acceptable performance specifications MEMS technology has made an enormous impact as it is now possible to use these miniaturized sensors for man portable applications.

2.2 Synchronised Time

Accurate and stable timing do play an important role in any navigational solution. Typically a clock uncertainty of ±1 s per day was required for crossing the Atlantic in 1750, first demonstrated by the Harrison chronometer that allowed for such accurate navigation [13]. Continuous technology achievements as depicted in Figure 2-4 enabled the many techniques that require accurate distance measurements based on the time of flight or travel time of a electromagnetic pulse between two entities. This is achievable by using two different but synchronised clocks. An electromagnetic pulse only needs 3.3ns to travel a 1mm distance and it is obvious that these clocks need to be of high quality and extremely accurate in order to synchronise the two events that are spaced apart in space-time. Miniature atomic clocks are currently being developed with timing resolutions of 1x10^{14} ppm/day using the recent advantages in MEMS technology. Figure 2-5 is an example of such a MEMS clock that is more affordable and available in reduced chip sizes.

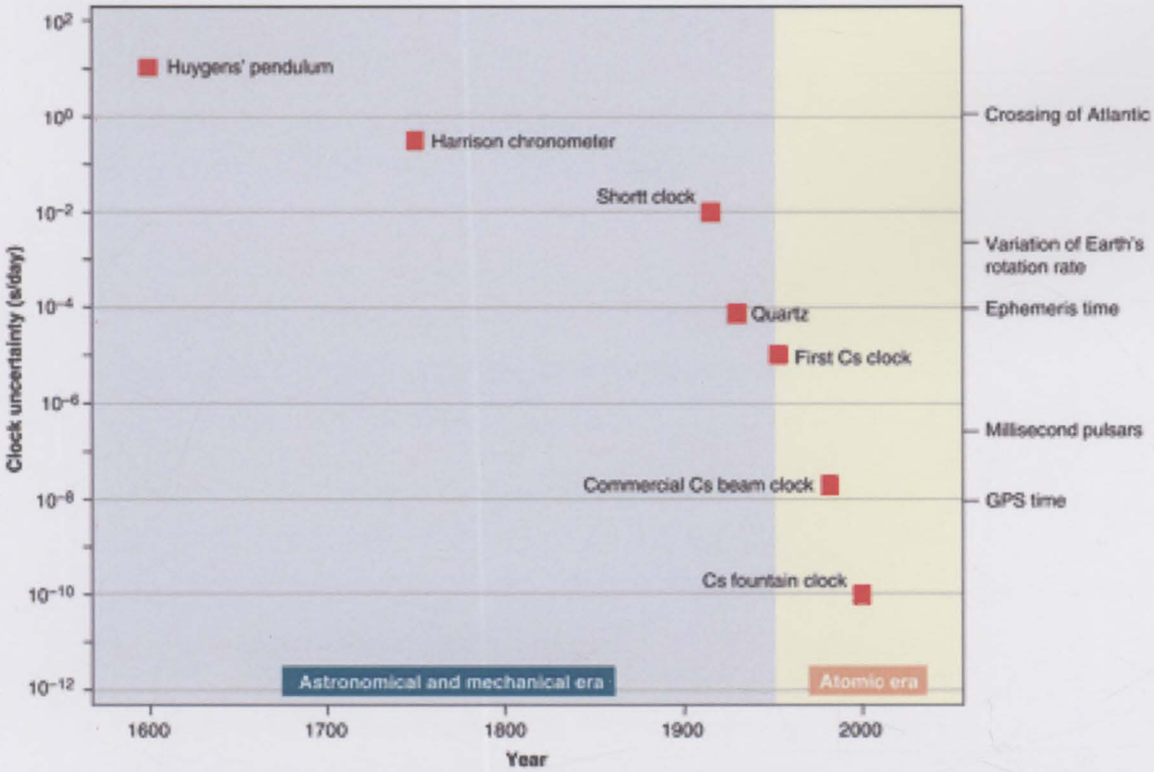


Figure 2-4: Some of the major milestones in the improvement of clocks over the past 400 years.

(Source: Science {2004,1318})

Figure 2-5: Miniature atomic clock (Sandia National Laboratories)

2.3 Definitions

2.3.1 Vectors

Vector mechanics and vector algebra is used to describe the observation equations and the geometry of the network structure. It is thus important to define both a coordinate system and a reference system. The notation is depicted in Figure 2-6 using the right handed Cartesian system and associated orientation and rotation angles for an orthogonal coordinate system.

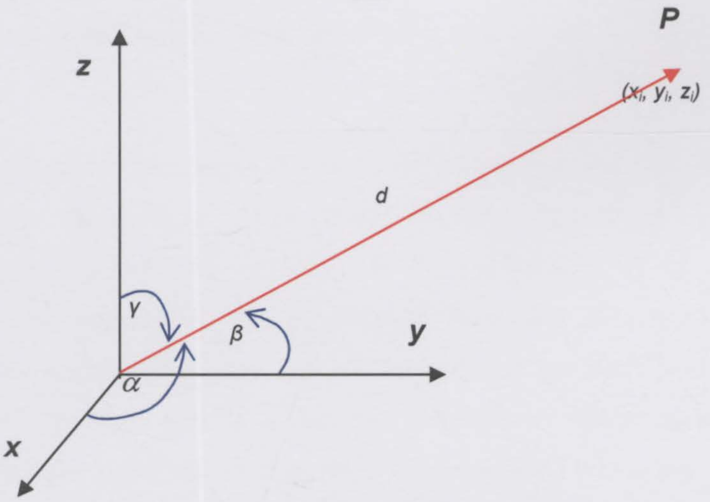


Figure 2-6: Cartesian coordinate system using a right-handed rule

The WGS84 reference system is defined for this navigational system. The network of navigation nodes relates to absolute global positioning systems, as it is initialised using either GPS, mapping and/or geodetic information services. Most of these services have already converted to the WGS84 standard for their positional coordinates.

Additional information regarding the fundamental vector laws and the vector algebra rules are defined in Appendix A.

2.3.2 Accuracy and precision

Accuracy is defined as the absolute nearness (correctness) of a measured quantity to its true value. The true accuracy is always an unknown quantity as this “true value” can never be determined [61]. It is convenient to introduce a term called the “value of uncertainty” that can be used to describe and model system errors. The usefulness is apparent because once the main error sources have been identified and modelled, their independent influences can be studied using different mean and standard deviations. A systematic approach is required, based on reasonable assumptions necessitated to reduce the model complexity. A typically assumption is that errors are independent and can be modelled as separate entities to be added at a later stage using a define process i.e. least squares models, linear or non-linear methods.

Precision is defined as the degree of consistency between measurements based on the uncertainty within the data set. The extent to which this degree of precision can be attained is depending on the stability of the environment (during the time of measurement), the quality of the equipment used for the measurement and the performance and adequacy of the algorithm used to perform the observation[15]. A convenient way to explain this is to use the example of throwing darts. Accuracy is defined as hitting the bulls eye (if that was the intention) while precision is defined as how close the three darts are grouped inside the bulls eye or for that matter any place on the dart board independent of the intension to hit the bulls eye.

Navigational solutions use positional accuracy as one of the key performance parameters. Throughout the process of knowing a current position with a margin of uncertainty they continue getting updates in order to determine a new or changed position. The accumulated errors are a function of the sensors, methods and environmental conditions. To achieve optimum navigational performance requires in-depth knowledge of positional accuracy and the error coupling mechanisms. Farrell [16] identifies the error sources as Systematic, Instrument Computational, Alignment and Environmental errors while Wolf [61] use a slightly different classification of

Instrumental, Natural and Personal type errors. A further distinction is made for positional solutions as either being an absolute or relative position.

A relative position is defined between two users as the degree of precision to which the position of the other user can be determined when at a different location but in synchronized time. For this type scenario any agreed upon coordinate reference system or frame may be used as long as both users make use of the same frame or have the means to translate the information into the accepted reference framework. Not all applications do require absolute positioning and many solutions may only need relative positioning to fit the bill.

The overall definition of accuracy is a bit controversial using the example of GNSS accuracy measures illustrated in Table 1 below. This table is useful to relate between different error models. It is not so much the theory that is to blame but most likely the incorrect application of the statistical models. A typical example would be using a 2D model instead of a 1D model for a 1D application. From this table it is clear that the difference is significant using for example; the 1-D_{rms} = 1 (in 1D space) value equates to 2-D_{rms} = 1.41 (in 2D space) [23].

Table 1: Accuracy measures for circular error probability (CEP), rms and Gaussian error distributions (percentiles)

CEP➔	1-D_{rms}➔	2-D_{rms}➔	67%➔	95%➔	68%➔	98%➔	
1	0.85	1.19	1.26	2.08	1.28	2.37	CEP
1.18	1	1.41	1.49	2.45	1.51	2.80	1-D_{rms}
0.84	0.71	1	1.06	1.74	1.07	1.99	2-D_{rms}
0.79	0.67	0.95	1	1.64	1.01	1.88	67%
0.48	0.41	0.58	0.61	1	0.62	1.14	95%
0.78	0.66	0.93	0.99	1.62	1	1.85	68%
0.42	0.36	0.50	0.53	0.88	0.54	1	98%

2.3.3 Error propagation analysis and corrections

We need to consider how errors propagate within a network of nodes and its contribution to the final error. The assumption is that these errors have normal distribution i.e. Gaussian and can be modelled with probability theory. Wolf and Ghilani [62] postulate that thumb rules can be avoided using more optimal solutions like LSA (Least Square Adjustments) instead. It is also conclude that the LSA process has some additional advantages when correcting surveying errors as it is based on a rigorous adjustment method. Using modern computers these adjustments are easy to apply, enabling post-adjustment analysis and pre-survey planning. Planning a navigational mission can benefit from pre-survey task analysis and is thus an important input for optimal network design and for predicting navigational errors for a chosen geometrical layout. A typical example would be to study how the system accuracy can be improved by using properly defined weights based on system geometry or to progressively improve accuracy by increasing the precision of the measurements at distances further away from the smart or Anchor nodes. The novelty of LSA is that the integrity of the process can be checked based on proper statistical analysis after adjusting the data. This is a useful method to verify that the error margin stay within the expected boundaries. This process can be automated, a recommended task as part of further work to follow.

Statistical methods are used to improve positional accuracy and to determine the integrity of a location using some form of verification method. A covariance matrix is calculated for each coordinate using the standard deviation to determine error estimates in the reference axis direction. The importance is to realise that each error has a cardinal direction pointing in a direction towards the largest uncertainty. For two jointly distributed variables x and y the positional error at each node follows a bi-variant normal distribution [52] observable as an elliptical shape. This error ellipse is depicted in Figure 2-7. The $<x, y>$ coordinates are the system reference axis while the $<u, v>$ coordinate system is defined by angle t being a clockwise rotation starting on the y-axis

The "degree of freedom" is determined by the number of redundant measurements (i.e. distance or angle). This allows for the use of statistical methods to either verify measurements or make adjustments that decrease errors.

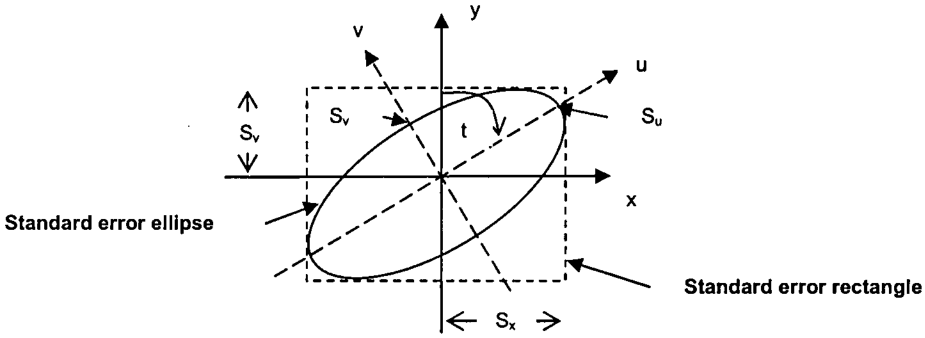


Figure 2-7: The standard error ellipse defining symbols and coordinate system

The errors in distance measurement between nodes can be presented by the error ellipse or as a circular error. The error ellipse is more complex to implement but extensively used by surveyors because it is more accurate. This error model is based on the assumption that the error leans more towards a direction collinear to the line that connects the two nodes (u) while an angle measurement error is perpendicular to this connecting line (v). The spread is typically Gaussian as several distance measurements are made to obtain an average value with a certain variance.

2.4 Sensitivity analysis

The variance-based technique is used for analysing model sensitivity because it is defined as the basis for creating good models.

The measurement of sensitivity is defined as an output variable (Y) due to a variation of a single input variable (X_i). The value is expressed as the expected amount of variance $V\,[E(Y\,|\,X_i)]$ as a contribute to the total output variance, given the condition that the true value of X_i is known. This, so called, main effect is defined as a probability value of knowing X_i within its uncertainty range. The first order sensitivity index (S_i) is obtained using the following definition:

$$S_i = \frac{V[E(Y\,|\,X_i)]}{V(Y)} \qquad 2\text{—}1$$

$V(Y)$ is the total unconditional variance. This sensitivity index is a measurement of the relative importance of the individual value X_i in driving the uncertainty and very useful to direct optimisation efforts. Sensitivity theory also defines two-way or multi-way interactions by evaluating the sensitivity index for a combination of these input variables. This functional expression is referred to as a high dimensional model representation (HDMR) with terms that are decomposed with increasing dimensionality:

$$f(X) = const + \sum_{i} f_i(X_i) + \sum_{i<j} f_{ij}(X_i, X_i) + \sum_{i<j<k} f_{ijk}(X_i, X_j, X_k) + \ldots. \qquad 2—2$$

for which we define

$$f_i(X_i) = E(Y \mid X_i) - E(Y)$$

$$f_{ij}(X_i, X_j) = E(Y \mid X_i, X_j) - f_i(X_i) - f_j(X_j)$$

$$f_{ijk}(X_i, X_j, X_k) = E(Y \mid X_i, X_j, X_k) - f_{ij}(X_i, X_j) - f_{ik}(X_i, X_k) - f_{jk}(X_j, X_k)$$

with $f_i(X_i)$ the main effect and $f_{ik}(X_i, X_k)$ the two-way interactions between pairs.

This decomposition is not unique, as an infinite number of ways exist to combine arbitrarily selected variables. If each individual term in the HDMR is chosen to have a zero average it is proven that the specific selection is orthogonal or independent in which case the additive and scaling laws are applicable as for linear systems.

By dividing each of the individual sensitivity indices (S_i) with the system sensitivity index (S_T) the sum of all individual sensitivities then become normalised i.e. $\sum S_i \leq 1$. This is a useful tool to compare different scenarios using the individual sensitivities. The sensitivities are obtained by a partial differential with respect to each of the input parameters as explained in Chapter 3.

2.5 Technology Applications

2.5.1 Wireless networks

Networks have become part of the way we do our day-to-day business. Each network connection has a specific location with a structured configuration that provides some or other service i.e. a database or mail server. Normally these servers are fixed in a location and thus defined, as beacon or anchor nodes if their location is know. Mobility requirements for handheld and portable devices need additional features such as; self-locating, dynamic reconfigure-ability and distributed control for interconnected nodes. By implication this requires a navigation capability of knowing the exact present location and a future next location in order to use or ignore network nodes on the fly. This is typically the definition of Ad-hoc Wireless Networks (AHWN). Any mobile or stationary node with “node-aware” capabilities is able to navigate or participate in a network navigation scheme. Wireless Ad-hoc application developments are a subject of intensive research with objectives to define network localization algorithms, to define routing protocols [11, 51] to improve Quality of Services, to increase the positional accuracy, to develop communication schemes and to optimise power.

The Internet has influenced how information is exchanged and affected our everyday life. The most significant impact is on the accessibility of information regarding both the quality and quantity of available data. This is further more enhanced by innovations in services such as the powerful search engines (i.e. Google and Yahoo) that accelerated all aspects of distributing information in a global market.

Wireless networks are an extension of the Internet that enable mobile users to have access to information and data regardless of their location. This had a profound impact on implementation hardware and protocol development. These associated problems are systematically addressed leading to the development of a wide range of new IEEE 802.xx standards. Typical challenging problems are mobile address ability and the inefficiency of static transport and application layer protocols. The history and development of these standards and feasible solutions are discussed in length by Perkins [54], Murthy and Masnoj [48].

The types of wireless networks are depicted in Figure 2-8 and subdivided in the following wireless network groups [1]:

- Packet radio networks (GPRS)
- Wireless/Mobile Ad-hoc network (i.e. BAN, PAN and LAN)
- Scatter nets
- Meshed networks (i.e. BAN, PAN and LAN)
- Multi-hop networks (i.e. PAN, LAN)

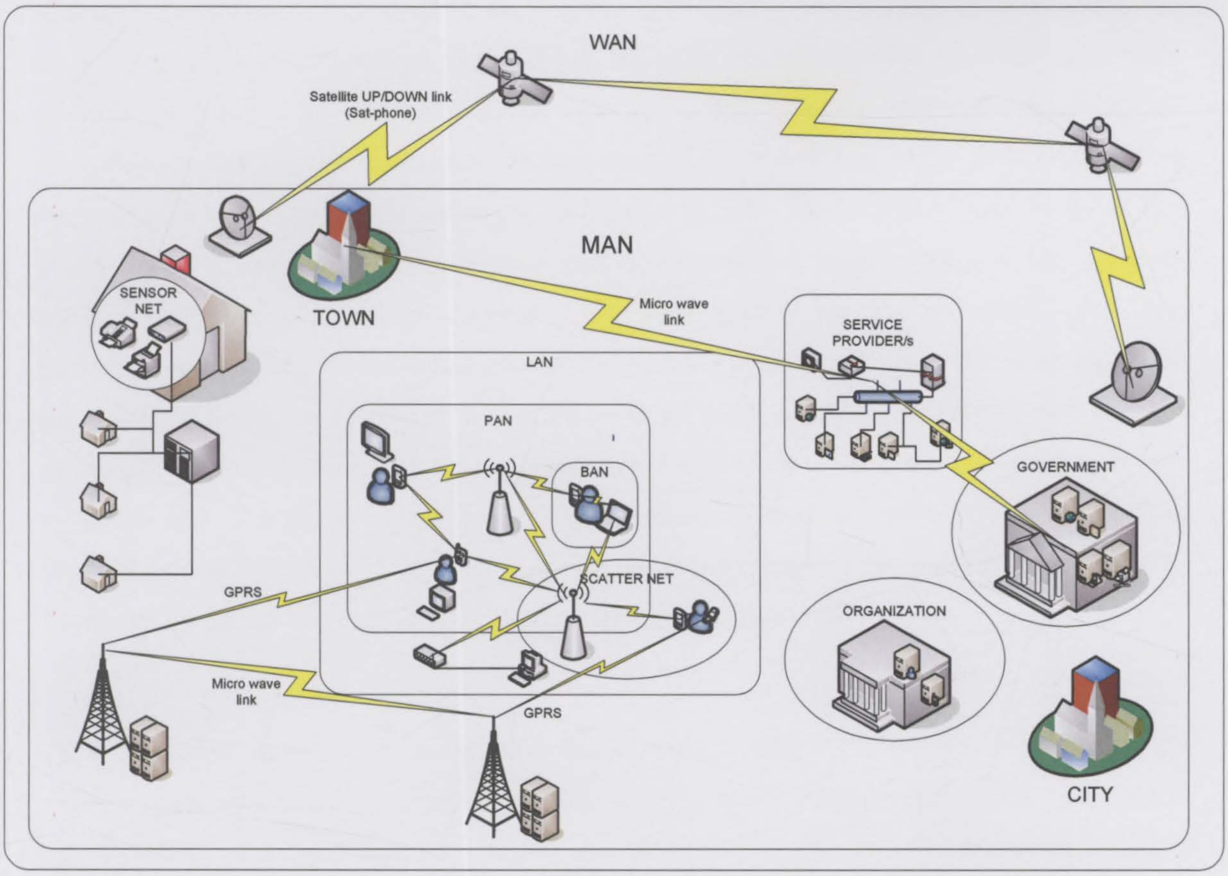


Figure 2-8: Network hierarchy

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[1] **NOTE:** Figure 2-7 show examples of wireless links that can function as an Ad-Hoc Network (i.e. infrastructure-less)

2.5.2 Ad-hoc networks

Ad-hoc networks are best described as a multi-hop relaying concept. This innovative communication scheme was devised by king Darius from Persia and used since 522-486 B.C. King Darius made use of a line of shouting men to send messages over long distances all across his empire. Native tribes in Africa, New Guinea and tropical America used talking drums in similar fashion to telegraph or relay messages by replacing the physical layer in the ad-hoc network with the beating drum instead of the shouting voice. A major technology breakthrough took place since Norman Abramson from the University of Hawaii invented ALOHAnet (1970). What started as a single-hop wireless network that used a common resource to negotiate among a set of uncoordinated nodes for message delivery, was developed into the Ethernet (by Robert Metcalfe) and the packet wireless network (PRNET) under sponsorship by DARPA for military applications. According to Murthy the significant change came when these concepts evolved into distributed multi-hop wireless communication systems that could operate over large geographical areas [49, 53]. The Ad-hoc network design makes provision to self-organize, self-configuring and auto detect the radio link that allows operating in a dynamic infrastructure-less environment. This type of environment has many issues to deal with including the establishment and maintenance of the network topology, error handling and managing the flow control for the wireless link. The network needs to be reconfigured on the fly because path breaks may arise at any time due to node mobility. Further issues to be dealt with are the processing and storage capability of each node, which node needs to be fitted with what type of sensors and how to share the distributed channels? Many of these problems were addressed by the DARPA sponsored, SURAN (1983) program, that investigated the survivability of radio networks using ad-hoc packet forwarding techniques.

The proposed network navigational solution utilises the advantages of a collaborative Ad-hoc network (AHN) with wireless connectivity that is self-configurable. The AHN function is the backbone system used in the navigational solution to execute application software in this distributed processing environment. The application software performs the initialisation functions such as the self-locating of nodes and information sharing by connecting with other nearby nodes. Once the navigational network has completed the initialisation tasks the individual nodes become positional referencing points for other nodes providing the navigational solution.

Several efficient Ad-hoc Wireless Network (AHWN) communication protocols are under development that supports the strategies discussed above. This is a subject of intense study judging from the numerous publications under the titles “New MAC Protocol for Wi-Fi Mesh Networks” [57] and “ANMP” [9]. The process comprises of an initiating request by any node that needs to resolve its own position. This request is a set of random events that are broadcasted within a cell of nodes. The application software manages these events as computational threats by generating the messages and commands while using the backbone communication system functions as provided by the selected wireless ad-hoc network protocol [10, 35].

The solution to the navigational problem needs to be optimised to resolve conflicting demands such as for low power consumption, wireless link reliability, Quality of Services (QoS) and collision avoidance for the typical infrastructure-less environment. Once established the communication link between two or more close by nodes are used to exchange navigational information. Position coordinates are to be defined as absolute positions in accordance with the WGS-84 standard. The integrity of the positional accuracy must be maintained and be verifiable thought out the operational exercise.

2.5.3 Mesh networks

Murthy and Manoj [50] describe Meshed networks as a sub-category of Ad-hoc Wireless Networks (AHWN). It makes use of the multi-hop radio relay mechanism but with all nodes in a fixed location. Some nodes act as gateways to the wired Internet. The mesh network is aimed to provide high-speed Internet access to residential areas. Traffic is routed using multiple hops up to a gateway that connects to the Internet. The mesh network can also provide fast and low-cost access for mobile users, due to the presence of multiple gateways, thus selection of the correct gateway and routing of data packets is problematic. A typical example is a hotspot region close to a gateway that becomes congested resulting in packet losses.

2.5.4 SWARM or Collaborative Networking

The clustering of network nodes is what intuitively comes to mind when researching ways and means to solve the ad-hoc network connectivity problem. A set of nodes that are able to communicate and collaborate can function as a SWARM by distributing functions among the participating nodes. This SWARM behaviour is described as "animals, particularly those of relatively social species, often communicate to coordinate their activities. Moreover, when competing they often negotiates resolution of their differences" by "interacting for mutual advantages" in order to "cooperate." [58] Animal behavioural studies and birds in particular, demonstrate that the complex task of information sharing requires information discovery, followed by acquiring that information (data acquisition) and then exploiting it. Data dissemination needs to be cognitive of the circumstances (environmental impacts) and contextual issues at the time when the information was made available. Very simplistic behavioural signals are used (interact, attack, escape...) with supplemental information (Probability, Intensity, direction (how to use)). Non-behavioural information or attributes (location and identity) is also exchanged in conjunction with the external stimuli (food resources, predators) that initiated the signal/message [59].

2.5.5 Distance measurements

Several methods for distance measuring or ranging are available. This thesis focuses on developing suitable algorithms for network navigation purposes and the feasibility thereof. The feasibility depends on the practical issues for implementing the uncounted number of distance measurements techniques and methods currently being development. Ranging techniques and concepts are defined and the practical limitations when using available sensor technologies are discussed.

The criteria for selecting and optimisation of an Ad-hoc localization method involves trade-off studies to select between the listed parameters. (Refer to Appendix D for a more detailed discussion). These criteria are:

- Optimal Power consumption
- Optimal communications
- Node density (Network size and distance between nodes)
- Reliability
- Redundancy
- Robustness
- Deploy-ability
- Technology utilisation
- Application and mission requirements

2.5.5.1 Triangulation or Angle of arrival (AoA)

The triangulation method is the most popular solution for determining node positions. Although many variances are reported the basic concept comprises the measuring of the Angle of Arrival (AoA) or heading between nodes and then resolving the observation equations. A direction sensor estimates or measures the angle of arrival (AOA) of the received signal. A numerical method is used to resolve the observation equation to deduce the position of the node. A theoretical definition is presented in Chapter 3.

2.5.5.2 Signal strength (RSSI)

Received Signal-Strength-Indicator (RSSI) signal methods use the power of a received signal to estimate the distance between two nodes. This method is discussed by □apkun [8] using signal strength measurements supported by theoretical or empirical models.

These signal strength measurements are done by the hardware as a built-in function for many RF front-ended chip solutions. Typical multi-hop methods utilize average distances between hops as some means of obtaining distance.

The efficiency of a Wireless radio link is a function of the transmitted power of the carrier wave based on the assumption that the modulation and demodulation methods are optimised for a given application. The transmitted power is attenuated being a function of the distance. If the environmental conditions are favourable for direct line of sight communications the received signal strength measured at the receiver can be used to measure distance. For this technique to work properly the transmitter must either transmit with constant signal strength or the transmitted power needs to be send as part of a message to the receiver.

2.5.5.3 Time of Arrival (ToA) and Time Distance of Arrival (TdoA)

Timing-based (TOA, TDOA) methods estimate distance between nodes by timing the flight of a communication signal. The node position is resolved using a set of linear observation equations for which a closed form solution is found.

2.5.5.4 Multi-lateration (or Multi-hop)

Hop-based (DV-HOP, Hop-TERRAIN) is when position-aware anchors broadcast their locations. Each node maintains a minimum hop count to these different anchor nodes within the network. The distance to anchors is estimated as being the product of the number of hops (i.e. the hop count) with the average distance between hops.

2.5.5.5 Self-Positioning Algorithm (SPA)

The Self Positioning Algorithm (SPA) uses a set of randomly distributed nodes for which the distance between nodes is measured in order to define a local reference relative to all other nodes within its reach. This is a basic requirement for all types of network localisation methods. □apkun et al. [8] describes a GPS-free positioning algorithm with this classification (i.e. SPA) as an extension of some previous work done by them. Time of Arrival (ToA) methods is used to measure the distance. □apkun refers to several papers that discuss the influences of the error in the distance measurement. Typical applications are mentioned such as geodesic packet forwarding and location aided routing in order to increase network efficiency.

2.5.6 Mapping techniques

Mapping techniques relates to physical means used to measure distance by mapping an area with any type of imaging method. Similar methods are used by animals such as echolocation (i.e. Dolphins), electro-location (i.e. Sharks and Eels), and RF-location (i.e. Bats) for this purpose. The sensor needs to provide both distance and directional information to be able to construct a map of the surrounding environment.

2.5.7 Power usage

This typical scenario is also recommend by [3, 44] as these studies prove optimal power and bandwidth usage. Jordt [37] makes the observation that energy conservation during the localisation process is futile as the power budget for even the most expensive configurations is < 0.4% during this stage. Although this contradicts many of the current efforts used to conserve energy as the means to prolong node durability other secondary objectives would still require that computational and communication functions are to be optimised.

2.5.8 Secure communications

Secure communication between nodes is also a subject of intense study as the wireless networks make exclusive use of the license free 2.4 GHz bands. Typically these problems can be avoided with additional cost by using suitable/applicable licensed bands i.e. Military wireless bands operate in the 4 GHz region or by applying network secure type protocols with resulting lower bandwidth as the penalty.

2.6 Navigation

2.6.1 Ranging methods

Triangulation ranging techniques that utilize non-contact ranging sensors are:

- Angle of arrival (Triangulation)
- Time of flight
- Phase-shift measurement (CW)
- Frequency modulation (CW)
- Interferometry
- Swept focus
- Return signal intensity

The sensors categories are either passive or active and commonly referred to as RADAR (Radio Direction and Ranging), SONAR (Sound Navigation and Ranging) or LIDAR (Light Direction and Ranging). Each of these deploys one or more of the techniques listed above with the specific sensor selected based on the application, cost and performance requirements.

2.6.2 Navigation Means

Grewal {2001, 1} [28] identifies the five basic forms of navigation:

- ***Pilotage:*** Older than mankind but essentially relies on the recognizing landmarks to localise oneself.
- ***Dead reckoning:*** Dead reckoning starts from a known location and use heading and speed estimations for positional updates.
- ***Celestial navigation:*** The time and angle measurements between a local vertical (the reference) and a celestial object (e.g. sun, moon or stars) are used to determine local position. Note that this concept requires some a-priori information consisting of accurate mapping of the trajectories of these celestial objects.

- ***Radio navigation:*** Radio navigation uses radio frequency signals to estimate pseudo ranges and for communication purposes to determine a local position. This requires an expensive capital investment for the establishment of the infrastructure (terrestrial (LORAN), or satellites (GNSS)) and additional operating cost for maintenance.
- ***Inertial navigation:*** Like dead reckoning inertial navigation requires initialisation with a known position, velocity and attitude (orientation). Own position is calculated using inertial measurements such as angular rates, acceleration and inclination (magnetic direction) without the need of external references.

Using a combination of these forms of navigation has become common practice especially if the synergy between different systems can be exploited. This is typically done using the popular Kalman filter solutions. A Kalman filter has the desired property that exploits statistical information within error signals with the objective to optimise errors for complementary systems. A typical example is the augmented system that combines Global Positioning System (GPS) and an inertial navigation system (INS). The short term position error for an INS is relatively small but degrades without bound over longer time spans. GPS short term performances are not as good but do not degrade over time.

2.6.3 Reference systems (Coordinate and Frames)

A reference system plays an important part in any navigational solution. Sensors and positioning systems differ substantially when deployed or used in applications. The dynamics of the platform on which these navigational systems need to function require different sets of reference systems. The coordinate system and or reference frame do play an important role during the design and implementation of a navigational system. It is therefore necessary to understand why different coordinate systems and reference frames are necessary in order to use these reference systems within the correct context. This knowledge is used extensively to compute navigational solutions and may require several transformations and translations for converting between different frames or coordinates. Several coordinate systems and/or frames are defined by Grewal {2001, 328-345} [27] and Farrell {1999, 21-25} [18]:

- **Coordinate Frames**
    - Inertial
    - Geographic
    - Geocentric
    - Local geodetic or tangent plane
    - Body or vehicle Platform frames
    - Instrument frames

- **Coordinate Systems**
    - Earth-centred earth-fixed (ECEF-rectangular and ECEF-geodetic)
    - Cartesian and Polar
    - Celestial
    - Satellite Orbit
    - ECI
    - Local tangent plane coordinates (LTP)
    - RPY
    - WGS-84 (GPS)

The literature provides comprehensive definitions for each of these coordinate reference systems. By default this study uses a Cartesian coordinate system for node orientation and the WGS-84 global grid (i.e. GPS Coordinate system) for local and global positioning.

2.6.4 Sensors

Sensor technologies are classified according to Table 2 below.

Table 2: Inertial Navigation sensor technologies and performances

Classification by type	Performance range	Unit
Mechanical Gyros (Spinning Mass)		
Single Degree of Freedom (DoF), rate-integrated	0.1 - 3000	deg/hr
Two DoF, dynamically tuned	0.001 - 10	deg/hr
Flex gyroscope	1 - 5	deg/hr
Dual-axis rate transducer	0.1 -0.4	deg/hr
Magneto-hydrodynamic	0.05 - 5	deg/sec
Electrostatically Suspended Gyro	0.001	deg/hr
Vibratory sensors (Coriolis induced acceleration)		
Hemispherical resonant gyros	0.05	deg/hr
Tuning fork (quartz or silicon)	10 - 100	deg/hr
Optical Gyros		
Ring Laser Gyro	0.001 - 10	deg/hr
Fiber Optic Gyro	0.01 - 50	deg/hr
Accelerometers		
Force feedback pendulous	1 – 30 10 – 500	mg *ug*
Quartz vibrating beam	0.1 - 1	mg
Silicon micro-machined	1 - 20	mg

(Courtesy: NavtechGPS Tutorials, Sept 24-25, 2007)

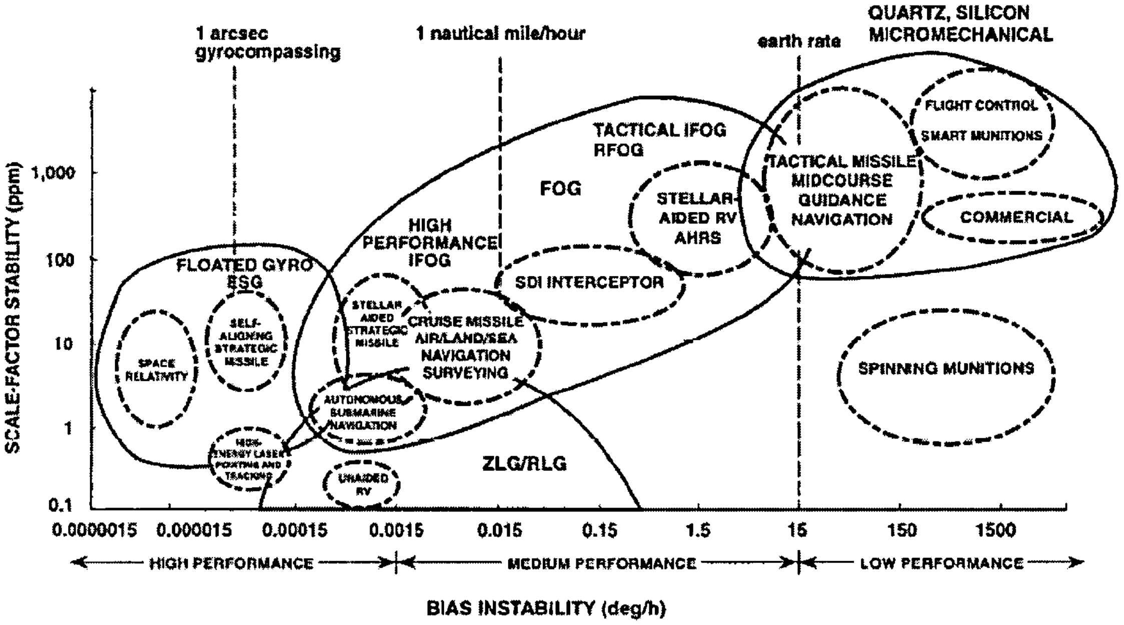

Figure 2-9: Future Gyro Technology Applications (Source: Greenspan [24])

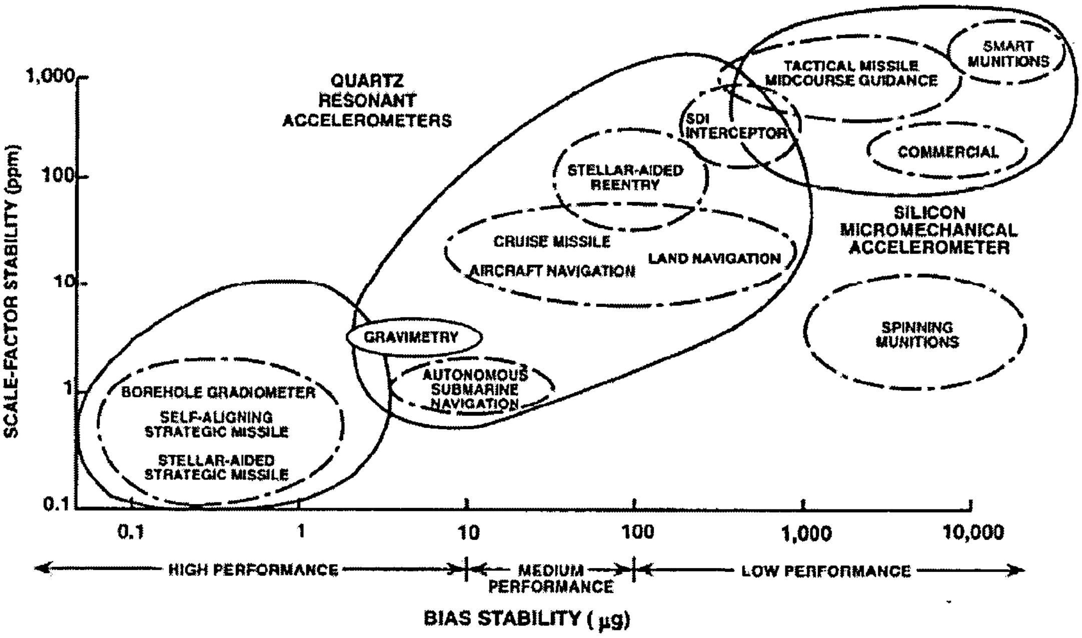

Figure 2-10: Future Accelerometer Technology Applications. (Source: Greenspan [24])

2.6.5 Processing

The processor is essential to finding the navigational solution as almost every aspect of the implementation is done by software. The software algorithms and processes are executed on powerful processing platforms. Several aspects need to be considered for practical reasons, which include processor power, memory usage, processing speed, the development environment and the footprint of the embedded operation system. Several embedded processors are suitable for navigational type applications in the categories Digital Signal Processors (DSP), Micro controllers (PIC, 8051), AVR and/or ARM processors. The latest developmental trends in FPGA technology that combines both logic and software functions (with embedded Core processors) is very advantageous for single chip solutions.

2.6.6 Augmented systems

Augmented systems are defined in a broader sense to include all types of aided systems and system of systems. Although the current focus is to integrate Global Positioning Systems (GPS) with Inertial Navigation Systems (INS) other work that involves assisting or adding some or other sensor using a different technology or sensor can also be classified as such. Typically the following are identified as possible candidates:

- GPS/INS integration
- Tightly coupled systems (GPS+INS+KALMAN)
- WAAS (GPS + Ground station)
- DGPS (GPS + Communication Satellite Network)
- RTK (DGPS + Local reference station)
- Location Aided Routing [38] or Geodesic Packet forwarding [7]

2.7 Sensor network simulations tools

The ad-hoc or meshed network concepts are front-end research with a long list of demonstrator models and devices to choose from. These products range form the Smart Node (SN) and can be configured by adding more sophisticated sensors, obviously adding to its cost and consuming more power. Although essential for accurate navigation some means needs to be developed to understand and predict the behaviour of the proposed navigational solution (i.e. network based). This is done by means of a mathematical model that is used to simulate different scenarios with the objective of providing answers in terms of the optimal number of Smart Nodes and Ordinary Nodes required for a given coverage and distribution. This navigation algorithm is being developed to study effects such as node distribution, network coverage, error propagation, initialisation parameters, power usage, bandwidth and sensor accuracy in order to make recommendations regarding the optimal use of the different nodes that constitute the Ad-Hoc sensor network. The overall performance criteria will be based on how accurate a mobile node can navigate between any two waypoints using the Ad-Hoc network for a specific mission scenario and typical operational environments.

This simulation work needs to be extended to model and predict the overall network performance. Several tools are available that can be used for this purpose i.e. OPNET, ns2, OMNeT++ and GloMoSim. These graphical presentations are tools useful in simulating large-scale networks with the focus on network communication solutions. This environment is extensively used to develop new network protocols and to implement algorithms.

2.8 Wireless developmental kits

The Zigbee alliance is a group 100 companies [74] and/or vendors with the objective to design and manufacture interoperable Zigbee certified devices. This alliance has already published the Zigbee version 1.0 standard that runs as application software on top the MAC and PHY layers defined by the IEEE 802.15.4 standard. The Zigbee 1.0 standard is specifically targeting wireless personnel area networks (PAN) for commercial applications with some examples of certified devices with network and location capabilities shown below. These products comprise of hardware with embedded software operating systems (TinyOS) and are used as development platforms to test and evaluate navigational algorithms by several researchers [6].

- **Motes (MICAz from Crossbow™)**

The MICAz [73] wireless measurement system is a 2.4 GHz, IEEE 802.15.4 compliant (See Zigbee), Mote module used for enabling low-power, wireless sensor networks. The MICAz Mote features several new capabilities that enhance the overall functionality of Crossbow's MICA family of wireless sensor networking products. These features include:

- IEEE 802.15.4/ZigBee compliant RF transceiver
- 2.4 to 2.4835 GHz, a globally compatible ISM band
- Direct sequence spread spectrum radio which is resistant to RF interference and provides inherent data security
- 250 kbps data rate
- Runs TinyOS 1.1.7 and higher, including Crossbow's reliable mesh networking stack software modules
- Plug and play with all of Crossbow's sensor boards, data acquisition boards, gateways, and software

Figure 2-11: Mote (MICAz, from Crossbow) and the interface board (MB600CA)

TinyOS is a small, open-source, energy-efficient, software operating system developed by UC Berkeley for supporting large scale and self configuring sensor networks.

- **TinyNode**

The TinyNode provides a platform for both academic projects and industrial applications. The TinyNode 584 [71] core module is a low-power sensor node with an array of hardware options for connectivity, storage, energy and interfacing functions. The development kit comprises of TinyNode 584 nodes (3x), its accessories, the installation software and the TinyOS environment along with demo applications and protocol software.

Figure 2-12: Processor (TinyNode 584) and a developmental kit from Stockfish SA

- **DUST networks**

DUST networks supplies wireless mesh networking systems for solution providers, integrators and OEMs for enterprise-class monitoring and control applications. These Zigbee compliant devices use the standard 802.15.4 radios coupled with the Time Synchronized Mesh Protocol (TSMP). Typical products are the a) SmartMesh™ Network (M2135), b) WirelessHART™- DN2510 Mote-on-Chip™ (MoC) and the c) SmartMesh® Evaluation Kit depicted in Figure 2-13 [69]. These products combine sophisticated mesh networking software and low-power wireless nodes to provide a reliable, manageable and an ease installable network.

a) SmartMesh™ b) Mote-on-Chip™ (MoC) b) SmartMesh® Evaluation Kit

Figure 2-13: Product examples from DUST Networks

Chapter 3

3 IMPLEMENTATION

System implementation issues are discussed followed by the algorithm definition for a simulation model used to demonstrate the functions of an Ad-hoc Navigation Network (AHNN). The navigation network is defined as a system with the objective to identify the key aspects. This sets a framework for possible future development work of which the navigational model is but the initial step. This study focus on how the navigation error propagates within a network as one of the key aspects, with absolute positioning accuracy which is the primary requirement for any navigational solution. The model comprises of first solving the position of a single node (Cell node). This single cell solution is then used as a modular building block and subsequently used in solving the position of an arbitrary chosen number of unknown positional nodes. In addition an analytical model is proposed with the objective to predict error growth based on an intuitive hypothesis. This section concludes with issues regarding the verification of the simulation model and a discussion on the validity of the analytical model.

3.1 Autonomous network navigation

A distributed network of interconnecting cells is constructed to implement a navigational capability. Typically, a cell comprises of several nodes in a defined area that are within the communication range of any randomly selected node. Cells may purposely overlap to enforce redundancy; to improve connectivity; or to allow for a different geometrical structure of these nodes within the network. The interconnected nodes function as a collaborative network that share and/or relay information in order to provide a navigational solution. The quality of the navigational solution is a function of how well the network covers the area of interest. The attributes that govern network coverage is node density and the extent of nodes overlapping (redundancy). The specified values for these attributes are dictated by the navigational system requirements for accuracy, reliability and availability. The environmental constraints and the operational requirements do enforce different types of network structures and a variety of different configurations.

3.1.1 Functional description

The system diagram in Figure 3-1 presents an AHNN comprising of sets of smart, ordinary and navigator nodes. Collectively these nodes are defined as intelligent nodes.

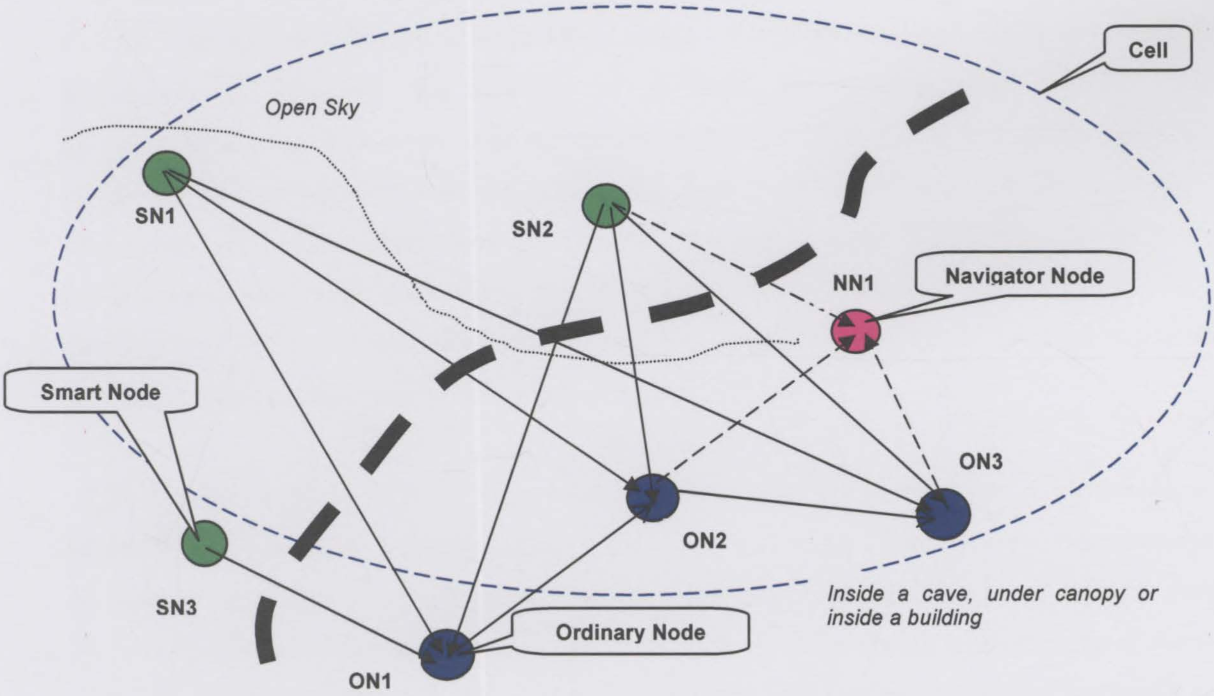

Figure 3-1: System diagram for a collaborative network (dotted lines show communications boundaries)

Smart Nodes (SN) determine their own location without the need to communicate with any other nodes. The SN node has two operational modes defined as the mobile or the static mode. SN nodes are fitted with positioning sensors that are able to do frequent absolute position updates. This feature is important when the SN operates in the mobile mode in order to get regular position updates because a change in its own position has an impact on the dynamics of the complete network affecting all dependent nodes within that cell. This is typically the case when a SN is configured with robotic functions that allows for the reposition of itself in order to optimise system performance to compensate for changing environmental conditions.

When the SN node is in the static mode its location is fixed. During initialisation this positional sensors function is to determine the nodes own position (self locatable node) and thereafter for monitoring the integrity of the navigation network. This static SN may also be referred to as an anchor or beacon point.

An Ordinary Node (ON) does not know its own position offhand and needs to determine the position by communicating with other nodes. For 2-dimensional (2-D) solutions an ON needs to measure the distance to at least three other nearby nodes and simultaneously retrieve their node position coordinates. The nodes within this cell can either be SN or another ON for which the positional coordinate has already been calculated. It is thus clear that an iterative solution is required that starts with an initialisation step and ends when reaching a satisfactory level of performance. The detail of how ON positions are calculated and the associated errors are the subject of this work and will be addressed in following sections.

The Navigator Node (NN) is a portable device carried by (a man) or mounted on (a robot) for a particular application. The Navigational Node allows autonomous navigation in areas deprived of any of the traditional positioning type sensors and therefore sometimes referred to as a GPS-less system. The design architecture of these navigational devices is more complex and thus more costly when compared with ON or SN due to the requirement of having to perform more functions. Typical functions are a user interface (touch screen display), motion sensing (INS, pressure sensors, compass...), more powerful processing and additional communication means (i.e. voice, for remote control and/or telemetry). The navigational solution is executed using the onboard application software and therefore the requirement for more computational power. The typical NN can be described as an augmented system (i.e. integrating INS and GPS using a Kalman filter solution), but in addition assisted by the AHNN for navigating in areas without GPS. The navigational network provides position updates independent of any other positioning sensors using pseudo-like positioning signals obtained from communicating with ON and/or SN within a network cell. The NN require larger energy resources to comply with the higher demand in power consumption.

A Smart Node may also be classified as a NN if fitted with robotic functions and inertial sensors. This has added benefits for use in special circumstances for autonomous inspection of inaccessible remote areas or danger zones during rescue operations.

3.1.2 Functional Constraints

Node distribution needs to be done very effectively by considering the following conditions:

- Nodes are randomly distributed but with sufficient density that ensure high reliability communications and robust connectivity between all nodes within a cell with a guaranteed connection path between two arbitrary chosen endpoints in the area of interest. Typically these endpoints shall be selected based on map coordinates as part of a planned mission or can be randomly allocated for a scenario where nodes are added to navigate in previously unknown areas.
- The geometric composure (structure) of these nodes is important because they impact on the positional accuracy of resolving node locations that are within the cell.
- The system performance specifications dictate requirements for node architectural design. Functional requirements such as redundancy, the accuracy of the distance measuring sensor (an onboard node function) and the survivability of a node may be different for each sensor depending on its operational use, environmental conditions and deployment issues.
- Management functions are distributed among nodes and govern the computational power and memory usage for each node.
- Power optimisation issues need to be considered in order to provide sustainable services for the above mentioned for a specified period of time.
- Optimal communication is required to minimise bandwidth usage and power consumption due to excessive communications.

- Smart nodes (SN) are position-aware and typically scattered around the perimeter of the navigational network and/or placed in spots where external position sensors can function. The SN maintains its positional accuracy with regular updates using any available but external resources like GPS, survey points, beacons or mapping coordinates.

Power restrictions require optimal use of the communication link while secondary requirements such as the need to avoid detection, will further enforce minimal communication events. The process used to create the navigational network is dynamic because any number of different node configurations may be added or removed in an ad-hoc fashion. This is why the ad-hoc sensor network concept was chosen as it automates the process that will maintain connectivity given these dynamics. The distributed control strategy will manage change as a ripple effect through out the navigational network. Affected nodes will update their position as soon as a verifiable change is reported using other or newly added nodes that are within range.

3.1.3 AHNN states

The functional role of defined intelligent nodes is described using the configuration depicted in Figure 3-1 (above). The objective is to illustrate the functioning of the different nodes using a typical example of a collaborative network that consists of all the different nodes, i.e. Smart Node, Ordinary Node and the Navigational Node. This process used to provide a navigation solution is explained. The state diagram in Figure 3-2 depicts the process that creates an ad-hoc navigational network using different states to describe it. These states are:

Scatter state: The physical task of placing these nodes. Typically this operation involves designing the layout of the network and the planning of how the nodes are to be distributed. SN is placed in ideal positions i.e. high visibility to any external type of positioning systems.

Link state: Once the nodes are placed in position the ad-hoc network is initialised to create on the fly connectivity. Not all nodes are linked and the wireless protocol needs to configure the network to optimise connectivity and robustness of the connections. This is done using several optimisation loops.

Anchor state: The anchor process is continuously executed and runs independently of any other processes. Smart nodes perform the function to initialise their own absolute position. Once initialised this node functions as an anchor used as a reference to other nodes within the cell to determine their own position. The positioning process is continuously executed until the positional accuracy meets the required speciation using averaging and least square measurements to optimise the positional error. Power considerations are seen as the limiting factor and thus it is managed to extend the operational life of a SN.

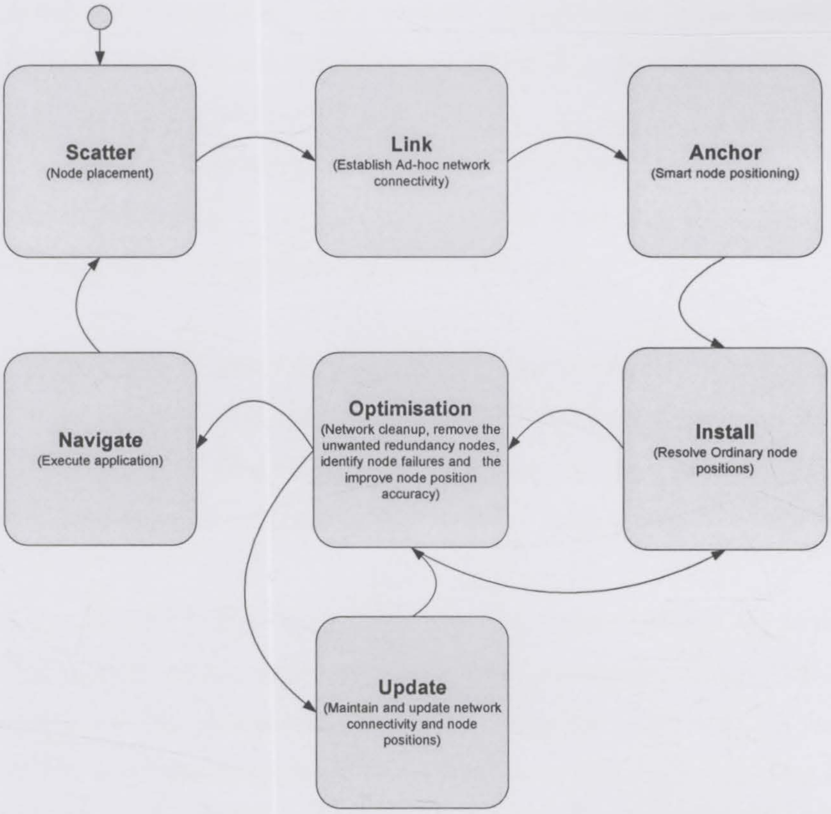

Figure 3-2: Process flow diagram for the AHNN.

Install state: Installation is the application of the developed algorithm described in section 3.2 that resolves the ordinary node positions. This iterative process ends the loop when all node positions are resolved as a first order approximation. In this process each node is tagging including those that could not be resolved or potentially has a bad solution (i.e. large mean or variance). Further optimisation is needed to improve the accuracy and to eliminate nodes that do not contribute to the navigational solution maybe being redundant or due to node failure.

Optimisation state: The optimisation loop follows the installation process with the objective to refine the positional error for each individual ON as the initial position was determined as a rough first order estimate. The method is not unique with Langendoen doing related work [41]. The optimisation process also utilises different node geometry options to improve dilution of precision (DOP) and/or by adding more nodes (by expanding the observation equations), if and when other nodes are available that contribute towards the solution. This process needs to be time limited to prevent continuous optimisation loops and is based on a best effort approach.

Update state: The process work in conjunction with the optimisation loop but tasked with maintenance functions. Periodic checks are done on the network health to maintain the navigational status of the network solution.

Navigate state: The required function is performed when a user enters the area of interest that is covered by the navigational system. Location-aware-data is communicated to the user to enable other functions i.e. decision making, providing location based information or to indicate that a device is on track.

During initialisation all nodes communicate within their own cell group within range but typically not more than the so called “single hop” distances. Using the time of flight and compensating for the delays caused by SN response time and the environmental conditions the ON are able to estimate the distance to the anchor node. This random request is repeated until the ON is able to calculate its own position using information from at least three other anchor nodes. If more than three anchor nodes are available an optimal solution is calculated using the best combination of all the available information. Once the position is known the status of the ON is upgraded to become an anchor node. This anchor node status implies that the node performs the function of a transponder (i.e. RFID tag) and will only reply when interrogated. This process continues until all node locations have been resolved or if the process has reached its timeout limit.

An anchor node is allowed to issue its own position request if the integrity of the known position is expected to be lower than a predefined threshold level. In addition a secondary request can be repeated from time to time as part of a scheduled maintenance strategy with the objective to maintain or optimise the network topology. Nodes have limited power and as expected they will become dysfunctional or may fail due to obscure or unpredicted events. The assumption is that the navigational network has sufficient coverage and overlapping redundancy to compensate for node failures.

For the time being the assumption is made that all nodes are stationary and their absolute positions are known. This network defines an area in which navigational nodes are all interconnected, functional and able to provide local positioning data that meets the required specifications. This assumption is required to avoid unlimited communication loops once all the nodes have resolved their own position by meeting the required position accuracies. The objective is to keep the network topology as static as possible to the extent that no positional updates are required until something changes (i.e. a new node is been added to expand the network or to replace a node that has failed or due to an interference causing a breakdown in network communication signals). The next step is to add a mobile node to this distributed network. This, so called, Navigational Node (NN) obtains positional updates while it navigates through the meshed network. To compensate for these types of events regular updates are inevitable. It should also be noted that this is an interactive network due to the nature of managing distributed connectivity and even the NN plays an important role in updating or to improve node positions when the need arises.

An anchor node (i.e. Smart node or an Ordinary node that has already resolved its own position) responds by transmitting a unique identity number (i.e. MAC address, IPv6 or a secure code), its coordinates and its current onboard clock timing information. To resolve an unknown position a node needs a minimum set of at least three vectors that comprises the responding message from anchor nodes. The navigational message is the same for all nodes and has the following structure: “NAV_MSG = [Node identification tag, Lat (x), Long (y), Altitude (z), Time (t), V_x, V_y, V_x] [2]". The distance between nodes is measured by some means such as, Time of arrival (ToA), Angle of Arrival (AoA) or Time over Distance (ToD), depending on the type of sensor configuration for the node in action.

The onboard processor resolves and updates the node position using either the triangulation (i.e. AoA) or, the preferred method, of multi-lateration (i.e. ToD or ToD) type algorithms. Some of the important aspects for consideration are the amount of energy consumed during this process and the cost of the navigational system. Typically the faster processors consume more power while excessive communications have similar effects. This enforces very effective protocol and algorithm design efforts that minimise processor and memory utilisation as the available power drives node durability. Adding more sensors to increase node functionality impacts both the cost and energy budgets.

The major advantage of this concept is that these positional updates are all absolute positions referred to a nearby GPS signal. This is a substitute for GPS signals when radio signals from the satellites start to degrade or are lost due to environmental conditions. For mobile nodes different strategies can be used such as adding an INS. This augmented system provides autonomous navigation and compares to or mimics the much larger systems like WAAS, DGPS and RTK using ad-hoc sensors that are cheap and easy to deploy in a large distributed area without the supporting infrastructure. This concept idea for a Wireless Ad-Hoc Navigational Network (WAHNN) has many advantages for instance adding mobility to a Smart node allows optimisation of it absolute position when the DOP for GPS satellites becomes unstable. This is done before repositioning itself for better visibility and improved DOP.

An AHNN becomes stable when all nodes have been localized to be within the specified accuracy range. In addition the performance criteria have to guarantee that the navigational integrity and expected accuracy remains intact thought out the operation. This statement can only hold true for an un-deterministic period of time, a function of the extent to which the positional signal integrity can be assured. This is managed by increasing the density of the network nodes (i.e. adding more ON or SN) to improve performance (i.e. increased accuracy) or to allow for a higher level in redundancy. This

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[2] NOTE: This message structure is for a 3-D solution but the study only utilises the 2-D information.

increases the robustness of the network and, depending on the requirements and the density, overlapping of nodes may vary from application to application or sometimes be forced to overcome the restrictions due to unfavourable environmental conditions.

A generic functional description of an intelligent node is defined in the Figure 3-2 below. The node is an electronic devices with sensory and communication capabilities. The definition of the intelligent node is generic containing all possible functions. The proposed Ad-Hoc network would most likely compromise of several nodes with limited functions. Typically an ON is not configured to have a GPS sensor while the NN is configured with all the functions. A network will comprise of a few SN and an abundance of ON. The Navigator Node (NN) is typically the device carried by the user that allows autonomous navigation in any area for which an Ad-hoc network has been established.

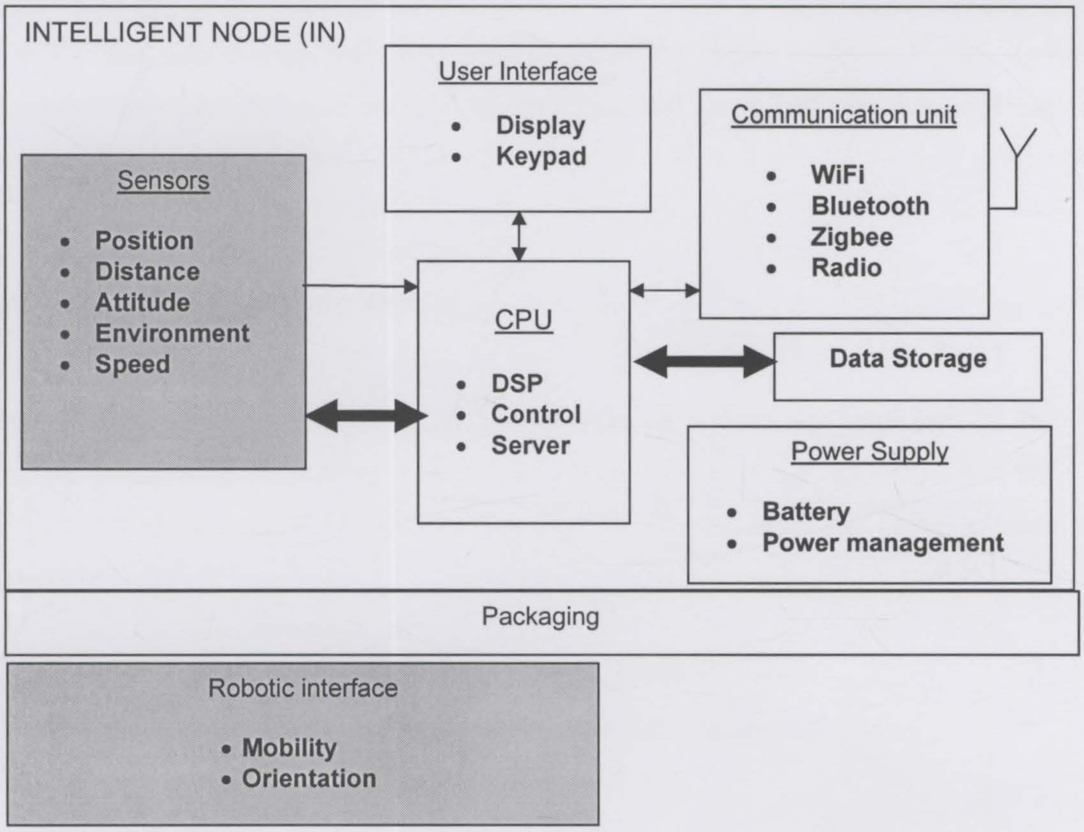


Figure 3-3: Functional block diagram for a smart mote

The different sensor technologies were identified and described in Chapter 2. The Intelligent Node (IN) is a modular device that consists of a basic platform with a:

- Processing device (DSP or Micro-controller),
- Power supply and management unit,
- User interface,
- Storage unit and a
- Communication unit

Depending on the application this defined platform is configurable by adding modular units and sensors. These add-on features and functions is what classify the node as being a Smart (SN), Ordinary (ON) or Navigator (NN) node.

Node mobility is an optional feature that allows nodes to reposition themselves to a different location using robotic functions, making Smart Nodes, even Smarter. Obviously this adds cost and complexity and thus used as a last resort for optimisation reasons previously explained.

3.2 Node Positioning Model

A theoretical self locatable node (SLN) algorithm is developed considering two possible positioning algorithms. Both these SLN solutions are described but only the Tri-Lateration Algorithm (TLA) was selected for implementation using a three-step approach:

- Solving for a single node position (Section 3.2.2)
- Performing sensitivity analysis (Section 3.2.2) and
- Implementing and verification (Section 3.2.3)

The following theoretical algorithms were studied and evaluated before selecting the tri-lateration as the preferred solution:

- Triangulation method (Using angle measurements)
- Tri-lateration method (Using distance measurements)

3.2.1 Triangulation method

The triangulation method comprises of angle measurements. Wolf [63] and Pagès-Zamora [50] propose alternative methods (a numerical and a closed form respectively) based on a classical procedure developed by Torrieri [1984]. The numerical solution entails the expiation of non-linear observation equations with Taylor approximations. Initial attempts to find a close form solution for node position *(Ux, Uy)*, based on the Cosine, Sine or Tangential Laws were not successful. While a closed form solution is a novelty the accuracy thereof as reported by Zamora [50], is not satisfactory (i.e. <10m (~1□) and <20m (~2□) for angle measurement accuracies of □i = 87.3 mrad).

Figure 3-4 constructs the proposed solution for a 2-dimensional space with the angles defined in the x-y plane.

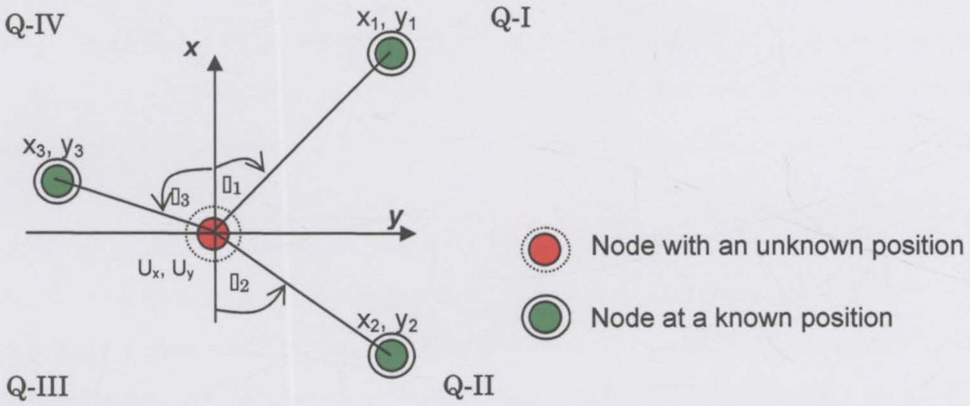


Figure 3-4: Triangulation construction using azimuth as reference.

Node position *(Ux, Uy)* is found by writing the observation equations for the azimuth angle (□i);

$$\alpha_i = \tan^{-1}\left(\frac{y_i - U_y}{x_i - U_x}\right) \qquad 3\text{—}1$$

with i = 1,2 and 3 as :

$$\alpha_i + C = Az_{ui} + \upsilon_{Az_{ui}} \qquad 3\text{—}2$$

with Az_{ui} the measured azimuth angle and $\upsilon_{Az_{ui}}$ the measurement error. C is a constant to correct for the sign of the azimuth angle being measured in different quadrants. See Table 3 below:

Table 3: Relationship between quadrant, C and the azimuth; Wolf [1997, 250]

Quadrant	Sign $(x_u\text{-}x_i)$	Sign $(y_u\text{-}y_i)$	Sign □i	C	Azimuth
Q-I	+	+	+	0°	□
Q-II	+	–	–	180°	□+180°
Q-III	–	–	+	180°	□+180°
Q-IV	–	+	–	360°	□+360°

Equation 3-1 is non-linear thus solved with a numerical method, in this case using a Taylor approximation. These equations are not expanded. Further interested parties may read the reference material.

The triangulation method is seen as limiting because it required additional tests to check the sign and the validity of the angle used in the calculation. Table 4 shows the checks for sign determination. The tangent function is problematic for large angles close to 90°. These computational intensive calculations are an additional burden on already limited processing and power supply resources for nodes. The Tri-Lateration method, avoids similar problems by using distance measurements. For these reasons the Triangulation method is reserved for special cases when distance measurements are not possible.

In practice it is much easier to measure distance as opposed to angles by using one of the ranging techniques described in section 2.6.1. Angular sensors typically make use of readily available cameras (i.e. 2-D imaging devices) but do require much more processing power to extract angular information from these images.

3.2.2 Tri-Lateration algorithm

The Tri-Lateration Algorithm (TLA) is defined using the notations in Figure 3-5. The properties of this method have many advantages:

- It is easy to implement on low performance processors due to its simplicity. A 2-D solution for an unknown node requires at least three other nodes to be visible and the ability to measure in between distances.
- The algorithm is scaleable and thus capable of solving higher dimensional problems. For instance, a third axis (z-axis) is added by expanding the observation matrix, and then used to solve the 3-Dimensional (3-D) space problem with the same algorithm.
- In addition the algorithm is not limited in terms of the number of observation equations that can be written for each visible node. This last property is important giving flexibility between the required accuracy in determining a node position and the available processing power. Although this feature is not addressed in this study it is recommended for future study (see 7.2.4).

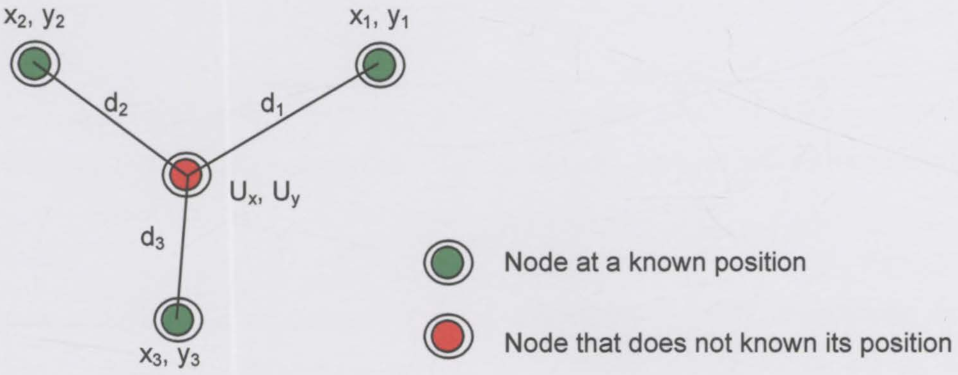


Figure 3-5: Notations for a Tri-Lateration method in 2-D space

The observation equation describes the node positions in two dimensions as a function of the distance (d_i) between nodes, with one node at a known location $<xi, yi>$, and the other at the unknown location $<U_x, U_y>$. For position $P = f(d, x, y)$ we have:

$$d_i = \sqrt{(U_x - x_i)^2 + (U_y - y_i)^2} \qquad 3\text{—}3$$

Using a closed form solution and solving for U_x and U_y in equation 3-3 provides the coordinates, <x, y> of the unknown node position in terms of an arbitrary chosen, Cartesian reference frame.

The true position of a node is not exact and a statistical model is used to express the uncertainty. Almost all types of experiments that use statistical measurements as a basis for collecting empirical data have a normal distribution. The Gaussian curve is modelled with a mean value and variance to model the uncertainty. This is also expressed as the expected value *E[P]*, defined as the probability of that position (waypoint or node) being within a certain range i.e. 1σ, 2σ. Using these terms the position of the unknown node, ***P*** is re-defined as:

$$P = E[P] = \hat{p} + \Delta p$$

including the uncertainty (Δp).

For an unambiguous solution in 2-D space a minimum set of three (x3) distance measurements to three (x3) remote position coordinates (i.e. 3 nodes at remote locations) are required.

The closed form solution for equation 3-3 for 2-dimensional (2-D) positioning is obtained by subtracting the equations from each other to obtain the linear equations of the form:

$$aU_x + bU_y = c \qquad 3\text{—}4$$

$$dU_x + eU_y = f \qquad 3\text{—}5$$

The node position is solved for x and y using the matrix algebra notation presented in equations 3-4 and 3-5.

$$U_x = \det\frac{\begin{bmatrix} c & b \\ f & e \end{bmatrix}}{\begin{bmatrix} a & b \\ d & e \end{bmatrix}} \qquad 3\text{—}6$$

$$U_y = \det\frac{\begin{bmatrix} a & c \\ d & f \end{bmatrix}}{\begin{bmatrix} a & b \\ d & e \end{bmatrix}} \qquad 3\text{—}7$$

and defining ;

$$\begin{aligned}
&a = 2(x_1 - x_2);\\
&b = 2(y_1 - y_2);\\
&c = d_{2u}^2 - d_{1u}^2 + x_1^2 - x_2^2 + y_1^2 - y_2^2;\\
&d = 2(x_3 - x_2);\\
&e = 2(y_3 - y_2);\\
&f = d_{2u}^2 - d_{3u}^2 + x_1^2 - x_3^2 + y_1^2 - y_3^2;
\end{aligned}$$

The MATLAB™ function x = $A\backslash B$ is very useful for solving these type of equations. This function makes use of a useful property of least square approximations when A cannot be inverted. Given the condition that the set of equations is linear and of the form $Ax = B$ the solution is:

$$\hat{x} = (A^T A)^{-1} A^T B \qquad 3\text{—}8$$

This is achievable by rewriting equations 3-4 and 3-5 to obtain;

$$A = \begin{bmatrix} a & b \\ d & e \end{bmatrix} \text{ and}$$

$$B = \begin{bmatrix} c \\ f \end{bmatrix};$$

and then solving for x using equation 3-8.

3.2.2.1 TLA properties

The following aspects have a significant influence on the performance of the Tri-Latertion algorithm:

- Residue
- Initialisation node accuracy
- Node dynamics

3.2.2.1.1 Residue

The TLA solution fails when the A matrix is non-invertible. Using the MATLAB™ function (i.e. $x = A \backslash B$) do provide some guarantee that a best solution would be found irrespective this being the case. Langendoen {2003, 504} [42] proposes a sanity check by computing the residue (Δx) between the measured distance (d_i) and the estimated location ($\hat{x}$) with equation 3-6:

$$\Delta x = \frac{\sum_{i=1}^{3} \sqrt{(x_i - \hat{x})^2 + (y_i - \hat{y})^2} - d_i}{3} \qquad 3\text{—}9$$

If the magnitude of the residue is larger than a predefined node cell range the solution is inconsistent and rejected. It is worth noting that this residual error is nothing other that the Dilution of Precision (DOP), a metric used by the GNSS community that is very effective in indicating the integrity of a GPS solution. The problem though, is that a solution or an estimated solution needs to be determined first before the sanity check can be used. It is thus possible to use this as a refinement method once a first order or course estimated solution for a node position has been found.

3.2.2.1.2 Initialisation

A systematic error caused by the uncertainty of knowing the true position of the initialisation nodes (i.e. Smart Nodes) needs to be taken into considered. These errors degrade the absolute position of the navigational network, observable as a shift in the absolute position of the complete navigational network. This local effect is not addressed by this study other than this reference. This is not an uncommon problem and several methods and or techniques are available to compensate for this apparent shift. Error correction is possible using typical land surveyor methods such as post-processing of data or by back-propagation for real time compensation if conditions are favourable.

3.2.2.1.3 Node dynamics

The positional coordinates for randomly positioned nodes are obtained from map coordinates, GPS positions, fixed terrestrial beacons or previously determined node positions within the defined navigational network. The position of a specific node holds true as long as the surrounding positional nodes used in that particular positioning calculation also remain static for the time being. The assumption that the nodes remain reasonably static is not unrealistic and is to a certain extent linked to the uncertainty of the distance measurement. This is modelled as a random positional shift that takes place during the time when the information was requested and when the distance measurement was executed. During this sample interval a limited amount of movement can be tolerated as long as it remains within the specified standard deviation (□) for the position of that particular node. Any significant change in the position of the initialisation nodes will affect the accuracy (Δp) of all newly calculated positions, as this error is propagated throughout the network of inter-dependent nodes.

3.2.3 Error sensitivity

The sensitivity function is defined by partial differentiation of all the variable parameters. The overall sensitivity is evaluated at each point of interest by including the associated uncertainties obtained from a statistical evaluation (i.e. sensor variance as obtained from a datasheet or from empirical measurements).

$$S_i = f(x_i, d_i, y_i)$$

Sensitivity is evaluated for each axis using the following

$$\begin{aligned}S_x &= \frac{\partial U_x}{\partial x_1}\Delta x_1 + \frac{\partial U_x}{\partial x_2}\Delta x_2 + \frac{\partial U_x}{\partial x_3}\Delta x_3 \\ &+ \frac{\partial U_x}{\partial y_1}\Delta y_1 + \frac{\partial U_x}{\partial y_2}\Delta y_2 + \frac{\partial U_x}{\partial y_3}\Delta y_3 \\ &+ \frac{\partial U_x}{\partial d_{1u}}\Delta d_{1u} + \frac{\partial U_x}{\partial d_{2u}}\Delta d_{2u} + \frac{\partial U_x}{\partial d_{3u}}\Delta d_{3u}\end{aligned} \qquad 3-10$$

$$\begin{aligned}S_y &= \frac{\partial U_y}{\partial x_1}\Delta x_1 + \frac{\partial U_y}{\partial x_2}\Delta x_2 + \frac{\partial U_y}{\partial x_3}\Delta x_3 \\ &+ \frac{\partial U_y}{\partial y_1}\Delta y_1 + \frac{\partial U_y}{\partial y_2}\Delta y_2 + \frac{\partial U_y}{\partial y_3}\Delta y_3 \\ &+ \frac{\partial U_y}{\partial d_{1u}}\Delta d_{1u} + \frac{\partial U_y}{\partial d_{2u}}\Delta d_{2u} + \frac{\partial U_y}{\partial d_{3u}}\Delta d_{3u}\end{aligned} \qquad 3-11$$

The generic form for the sensitivity equation is denoted in equation 3-12 below.

$$S = \Sigma S_{ij}\Delta \qquad 3-12$$

with

$$S_{ij} = \frac{\partial\left[U_x \quad U_y\right]^T}{\partial(x,y,d)} = \begin{bmatrix} \frac{\partial U_x}{\partial x_1} & \frac{\partial U_y}{\partial x_1} \\ \frac{\partial U_x}{\partial x_2} & \frac{\partial U_y}{\partial x_2} \\ \frac{\partial U_x}{\partial d} & \frac{\partial U_y}{\partial d} \end{bmatrix}^T$$

a [2x9] matrix and Δ a [9x1] vector.

The total sensitivity in *x* and *y* is calculated using perturbation values for each of the input parameters. Typical values for sensor accuracies are specified in data sheets or can be measured using empirical methods. These statistical error values are expressed as 1σ

(68.26%), 2σ (95.44%) or 3σ (99.73%) values [20]. For example the GPS positional accuracy is 7m (a 2σ value) meaning to say that 95.44% of all GPS solutions are within ± 7m. The uncertainty for distance measurements is based on instrument measurements normally expressed as rms values. The relationships between measured (1-D_{rms} or 2-D_{rms}) and the statistical values (σ-values) are discussed in Chapter 2, Table 1.

> **Example**: Some practical results for the overall sensitivity are obtained using typical values. The uncertainty for positioning systems is expressed in meter (units) as 2σ values. The distance measurements are 2-D_{rms} values and indicated below:

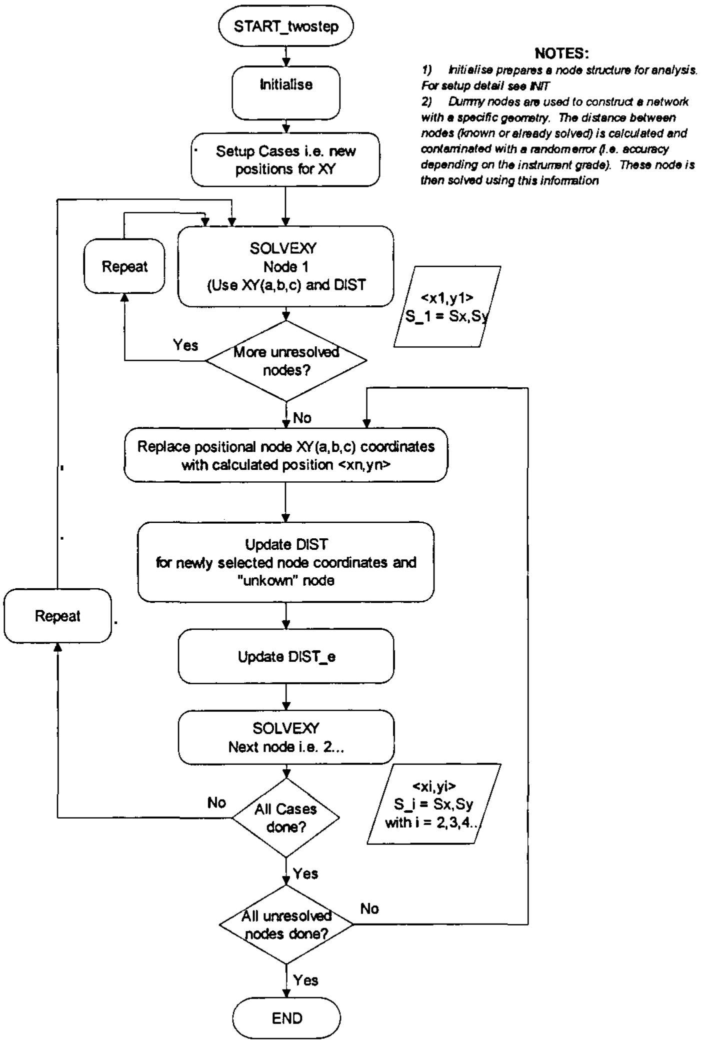
$$\Delta = \begin{bmatrix} 7 \\ 7 \\ 7 \\ 7 \\ 7 \\ 7 \\ 0.1 \\ 0.1 \\ 0.1 \end{bmatrix} = \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \\ \Delta y_1 \\ \Delta y_2 \\ \Delta y_3 \\ \Delta d_{1u} \\ \Delta d_{2u} \\ \Delta d_{3u} \end{bmatrix}$$

This sensitivity matrix (*S*) presents the magnitude contributed by each parameter in the final solution at a specific nodal point i.e. coordinate <*x*, *y*>. The sensitivity was evaluated for the navigational network using several test cases defined as part of the experiments and discussed in Chapter 4. The program that implements the localisation algorithm includes the sensitivity analysis and is discussed in the next section (i.e. section 3.3).

3.3 Single Node Implementation Software

The algorithm was implemented using MATLAB™ script language (netnav_v2.m) following a two step process. Position-aware nodes (x3) are used as the initialisation step to solve for an unknown node position via the tri-lateration method (see section 3-2-1 above). The method used is to assign true positions to all nodes, with the first three defined as the initialisation nodes. The true distance is then the calculated value between all nodes, but the measured value is diluted using a random error model with a non-zero mean as a bias value and a variance to model the instrument uncertainty. A normally distributed error is added to the true distance using a *randn()*[3] function in order to simulate typical measurement errors. In a second step one of the initialisation node positions is replaced by the calculated node position and used to determining a second unknown position.

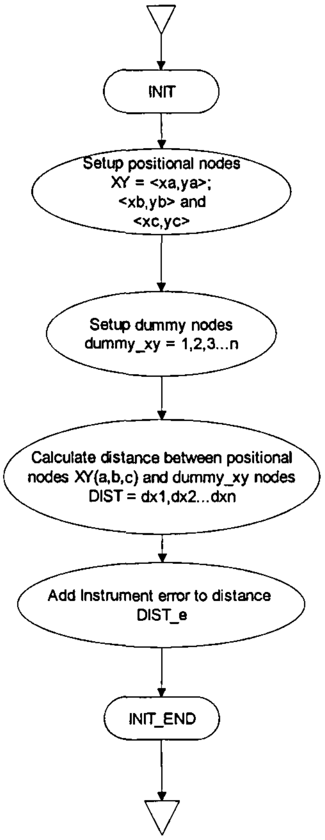
The error in the position is propagated with each consecutive positional solution for an indefinite number of unknown node positions. This process is terminated when the error becomes larger that a predefined threshold for instance when this error exceeds the expected distance between the nodes. The expectation is that the errors would increase exponentially. In addition the algorithm may also become unstable when the numbers used in the calculation exceed computational limits. The sensitivity at each of the solved node positions is also calculated using the methods described in section 3.2.3. The flow diagram in Figure 3-6 shows the process.



NOTES:

1) Initialise prepares a node structure for analysis. For setup detail see INIT

2) Dummy nodes are used to construct a network with a specific geometry. The distance between nodes (known or already solved) is calculated and contaminated with a random error (I.e. accuracy depending on the instrument grade). These node is then solved using this information



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[3] MATLAB™ function

Figure 3-6: Algorithm development for sensitivity of more than one node

3.4 Analytical approach

To understand wireless network navigation systems the major or significant error sources needs to be identified and studied to determine its cause and effects. These factors that influence navigational errors are

- The geometry of the nodes
- The node density
- The distance between nodes
- The measurement accuracy of the sensors
- Computational errors (i.e. round of errors)
- Algorithm stability or robustness and
- What the assumptions are from a practical or implementation point of view.

All these factors contribute towards the navigational solution that includes the navigational error. This study focuses on error propagation modelling and only those aspects that contributes to error propagation is investigated. Node geometry is an important aspect when solving node positions while measurement accuracy contributes to error growth as consecutive node errors are summed towards a final navigational solution.

An analytical model is proposed to predict error propagation as a function of the number of nodes used in the navigational solution. The objective is to develop an appreciation for the different sensitivities using a simplistic model. Rewriting equation 3-3 and expanding it with a Taylor approximation:

$$\begin{aligned} d_i &= \left[(U_x - x_i + \Delta x)^2 + (U_y - y_i + \Delta y)^2\right]^{1/2} \\ &= \left[(X_i + \Delta x)^2 + (Y_i + \Delta y)^2\right]^{1/2} \end{aligned} \quad \text{with} \quad \begin{aligned} X_i &= U_x - x_i \\ Y_i &= U_y - y_i \end{aligned} \qquad 3\text{—}13$$

With some manipulation (i.e. rearranging after a multiplication and disregarding of the higher order terms that are much smaller than 1,) equation 3-13 is of the form:

$$d_i = k(1+F_i)^{1/2}\,; \quad k = \left(X_i^2 + Y_i^2\right)^{1/2}$$

where k is a constant scale factor; F_i is a function in X_i and Y_i; and $\frac{\Delta x + \Delta y}{X_i^2 + Y_i^2} << 1$.

Using the first term in the Taylor expansion and ignoring all other terms an approximation for d_i is obtained:

$$d_i \approx k\left\{1 + \frac{1}{2}\left[\frac{2X_i}{X_i^2 + Y_i^2}\Delta x + \frac{2Y_i}{X_i^2 + Y_i^2}\Delta y\right] - \frac{1}{2\times 4}[\ldots]\right\} \qquad 3\text{—}14$$

Of interest is the coe.fficients for the different perturbations (i.e. Δx and Δy) hereafter referred to as the sensitivity coefficients. By using this approximation in a recursive way different forms of these sensitivity coefficients are obtained as summarised in Table 4. Applications for these coefficients are demonstrated in Chapter 4.

Table 4: Derived sensitivity coefficients by using equation 3-14 recursively

x-axis	y-axis
$S_x = 2^{(n-1)} \cdot \frac{x}{x^2 + y^2}$	$S_y = 2^{(n-1)} \cdot \frac{y}{x^2 + y^2}$
$S_{xy} = 2^{(2n-3)} \cdot \frac{xy}{\left(x^2 + y^2\right)^2}$	
$S_x^{\ 2} = 2^{(2n-4)} \cdot \frac{x^2}{\left(x^2 + y^2\right)^2}$	$S_y^{\ 2} = 2^{(2n-4)} \cdot \frac{y^2}{\left(x^2 + y^2\right)^2}$

Chapter 4

4 CASE STUDIES

Network navigation is demonstrated using the simulation models described in Chapter 3. The single node solution was first implemented to create the self-locating function. Subsequently several of the single node solutions were configured in groups to construct a navigational network. By making recursive use of a single node solution as a modular building block a navigational network of any size can be created or be designed to fit a desired geometrical structure. This section describes the experimental work in order to obtain empirical data sets for evaluation and analysis purposes. The following experiments were executed using Monte Carlo simulations to generate statistical data.

- Error sensitivity experiments are conducted to study the effect of the variation of a single parameter for each test run.
- To test and evaluate the behaviour of a multiple of node propagations a network structure was created and tested.
- Analytical model experiments were executed to gain insight and to improve understanding using an approximation of the closed form model.

This section defines the test objectives and describes the test set-up. The basic set-up for these experiments is to solve for a node position, using the closed form solution as defined in the observation equations. The sensitivity coefficients are resolved at each of the node positions being solved and obtained by perturbation of the input variables. The analytical model is a simplified model for consecutive error propagations to determine its usefulness in predicting node behaviour. The objective is to improve the understanding of the major factors that influence positional accuracy with several nodes functioning collectively.

4.1 Single node

The design of a single node with self-localisation capabilities is described. Three nodes at known locations and three distance measurements is used in the close form solution defined in Chapter 3.

4.1.1 Objectives

The objective is to test and evaluate single node response by changing the initialisation node positions with a variation in the accuracy of the estimated distance.

4.1.2 Setup

The number of runs for the Monte Carlo simulations done was selected after experimenting by progressively increasing the simulation steps (i.e. 50, 100, 200 and 500). The output of the experiment was verified by confirming that the recorded data has a Gaussian distribution. The number of simulation runs was chosen to be 200 found to be an acceptable value meeting these criteria.

The experiment is constructed by allocating positions for the initialisation nodes with the geometry depicted by Figure 4-1. Node positions are moved by a small margin (called test cases) and the sensitivity response is recorded for each of the x9 sensitivity parameters. These positions are indicated as (a, b, c) and (a′, b′, c′) in Figure 4-1 with test cases comprising of different combinations. These so called initialisation nodes were purposely chosen to give a good solution while the perturbations around these "good positions" was not allowed as to exceed more than 0.5 of the unit distance between the nodes.

The process followed is to use the Monte Carlo simulation as a brute force method to shows trends regarding network behaviour as a function of a change in the node position. The network structure is purposely distorted and then simulated to determine the influence by using the multiple Monte Carlo runs. Each subsequent change in distance, due to moving a node position, is compensated for by updating the distance vectors. This distance vectors is then distorted by adding a random error to simulate the distance measurement error. The accuracy of the measurement is defined using a percentage value expressed as the quality of the measurement. The location of each newly added node is then solved in terms of its $<x_i, y_i>$ coordinates using the closed form solution.

Two (x2) unknown nodes are used in this experiment. In order to demonstrate and test the concept of error propagation the first node position is solved where after the second node is solved, using the estimated position of this first node. It is also possible to add more nodes as illustrated in Figure 4-1 (i.e. node 3) but for the purpose of this test only the single node propagation is studied. The experiments in Section 4.3 further exploit structural aspects that are enforced, when more nodes are added.

Several tests runs are done with different scaling factors; i.e. 10, 50, 100 and 1000 for the range or distance estimates. The scaling factor is used as a divider to decrease the random number that is added to contaminate the distance measurement.

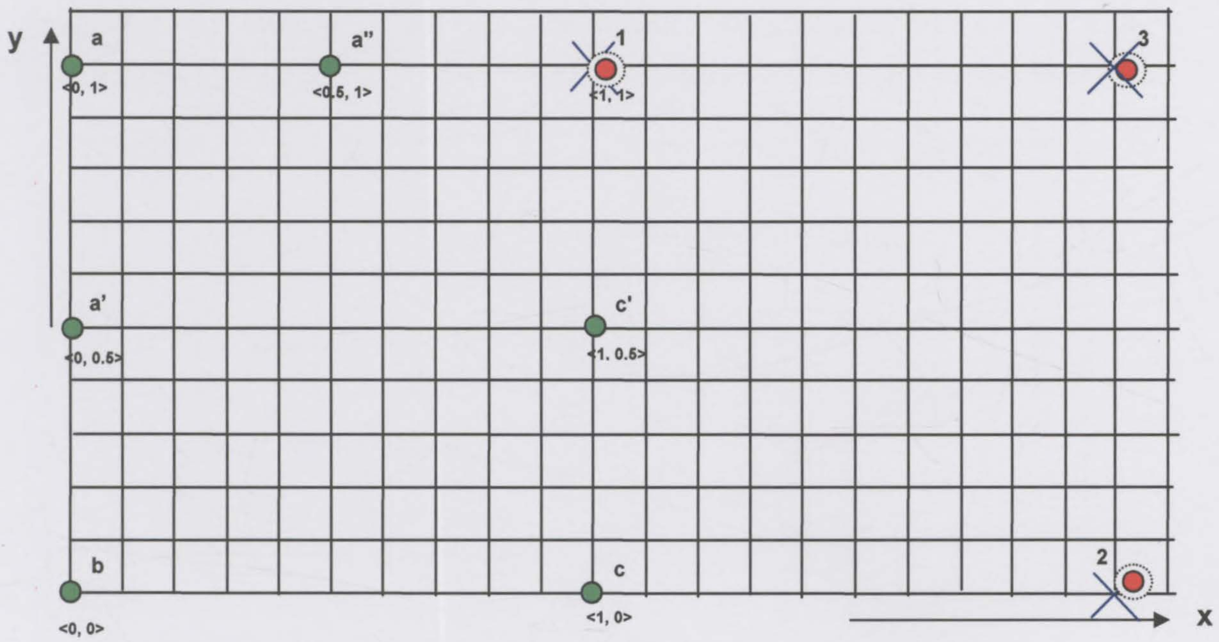
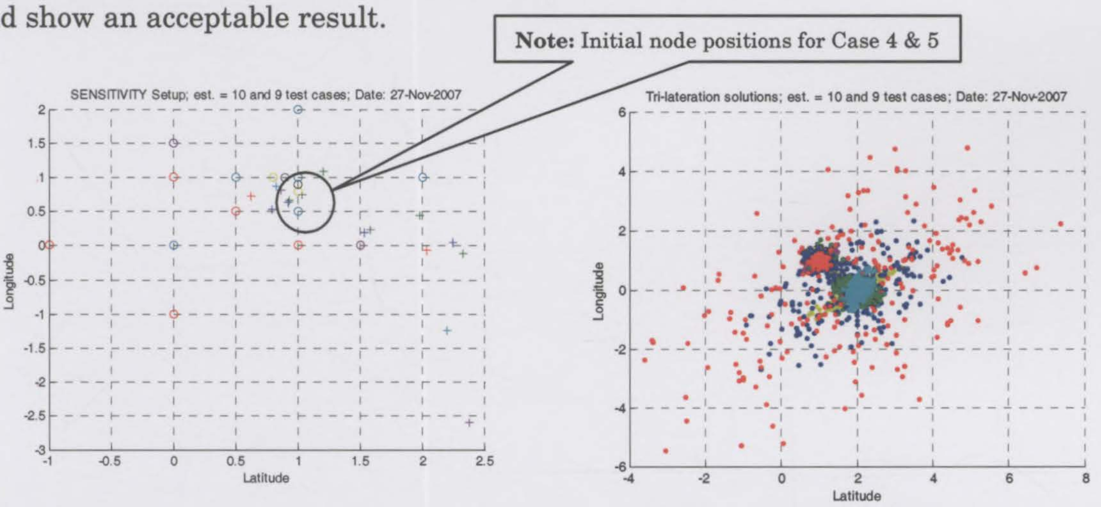


Figure 4-1: Test cases for the Sensitivity analysis during a single node propagation.

4.1.3 Results

Test results were generated using a MATLAB™ program; ***onenode_v4.m***, for this purpose with typical test program outputs presented in Figure 4-2. These plots show the solution (after taking the mean value for all the solutions) for a good and bad example. The positional solution (i.e. graphs a) and b)) with a scale factor of 10 (i.e. "scale down factor" for a randomly generated error) is not acceptable because the node positions are merging. The example in graphs c) and d) is done for a scale factor of 100 and show an acceptable result.



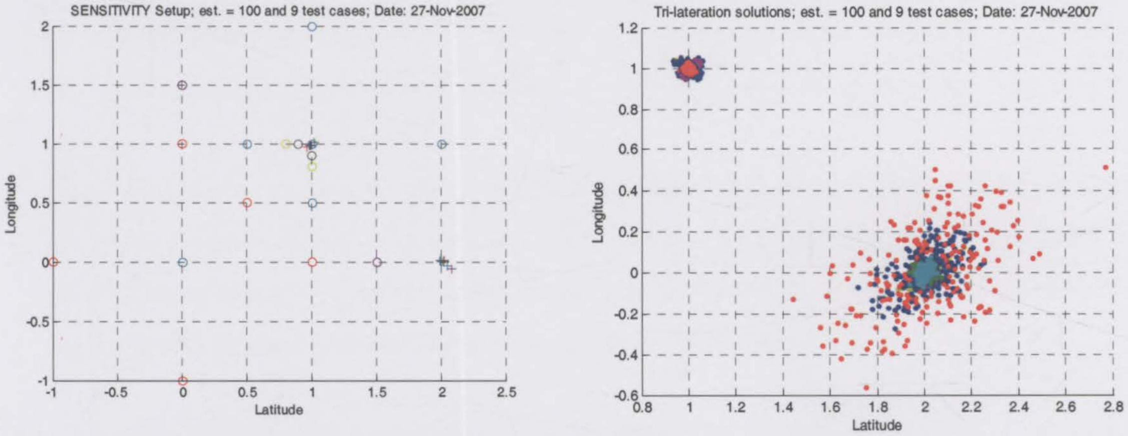
Note: Initial node positions for Case 4 & 5

SENSITIVITY Setup; est. = 10 and 9 test cases; Date: 27-Nov-2007

Tri-lateration solutions; est. = 10 and 9 test cases; Date: 27-Nov-2007

[a] Initialisation node setup for x9 test cases with unacceptable results.

[b] Single node propagtion Statistics (at <x,y> = <2,0>) with an unacceptable position estimation.



SENSITIVITY Setup; est. = 100 and 9 test cases; Date: 27-Nov-2007

Tri-lateration solutions; est. = 100 and 9 test cases; Date: 27-Nov-2007

[c] Initialisation nodes setup (x9 test cases) with an acceptable positional solution.

[d] Statistics for a single node propagation with acceptable position estimation.

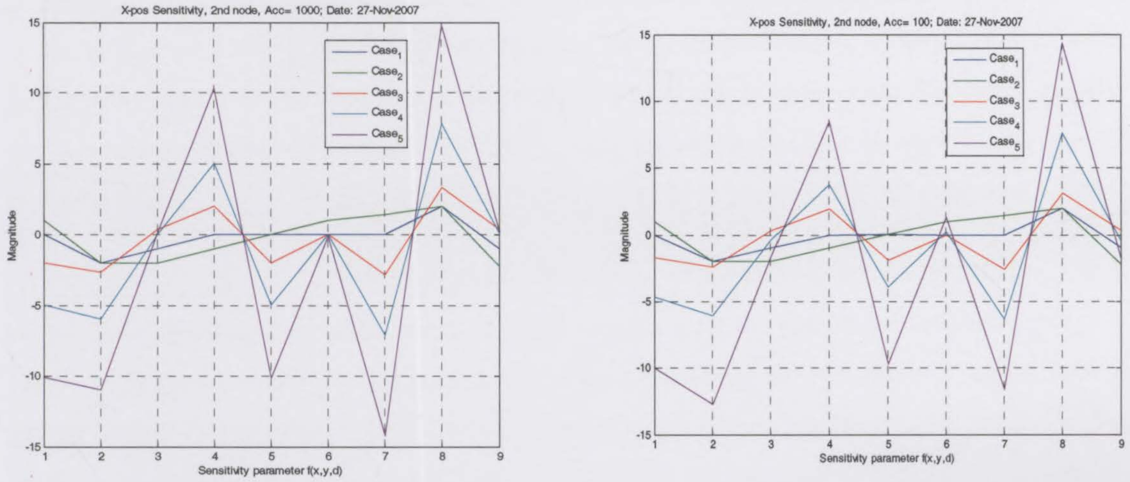
Figure 4-2: Typical test results for a single node propagated solution, showing a good and bad solution for the estimated node position at *(x, y)* = *<2, 0>*.

Table 5 is a summary of test results obtained from using different scaling factors for distance estimation. The results for both node positions (x_1, y_1) and (x_2, y_2) are presented for four different error scale factors. A more detailed table is presented in the Appendix.

Table 5: Summary of test results for a single node propagation

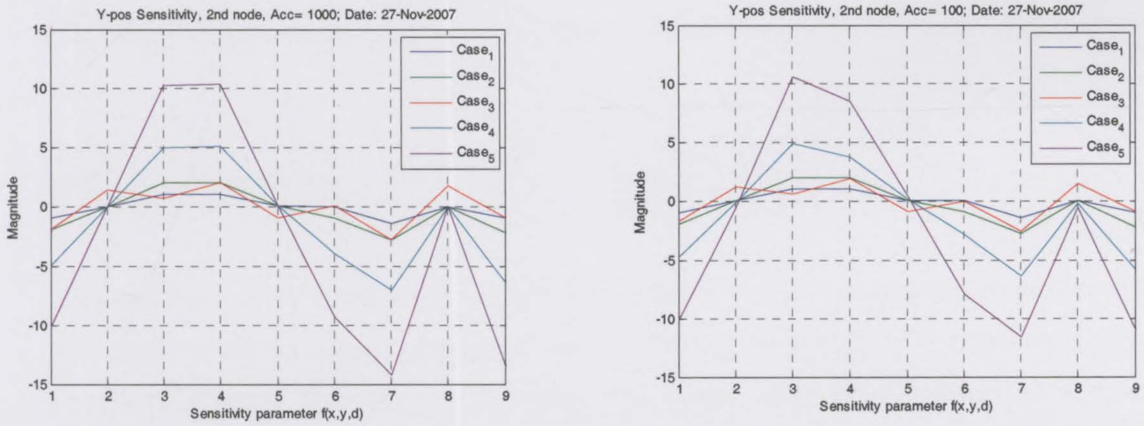
Distance estimation		Average	Standard deviation	Error
1/10 scale; $(x,y) = <1,1>$	x_1 y_1	0.9345 0.7926	0.1785 0.1818	0.0655 0.2074
1/50 scale; $(x,y) = <1,1>$	x_1 y_1	1.0016 1.0081	0.0216 0.0144	-0.0016 -0.0081
1/100 scale; $(x,y) = <1,1>$	x_1 y_1	0.9925 0.9903	0.0149 0.0126	0.0075 0.0097
1/1000 scale; $(x,y) = <1,1>$	x_1 y_1	0.9991 0.9994	0.0009 0.0007	0.0009 0.0006
1/10 scale; $(x,y) = <2,0>$	x_2 y_2	2.0286 -0.2960	0.2840 0.9433	-0.0286 0.2960
1/50 scale ; $(x,y) = <2,0>$	x_2 y_2	2.0878 0.1031	0.1752 0.1579	-0.0878 -0.1031
1/100 scale; $(x,y) = <2,0>$	x_2 y_2	2.0157 -0.0031	0.0268 0.0212	-0.0157 0.0031
1/1000 scale; $(x,y) = <2,0>$	x_2 y_2	1.9911 -0.0023	0.0129 0.0029	0.0089 0.0023

The sensitivity responses are presented in Figure 4-3 using Cobweb diagrams. The x9 sensitivity parameters are presented for 5 cases using separate graphs for the x and y-axis. The x9 sensitivity parameters comprises of the three pairs (2x3) initialisation node position coordinates and the three (x3) distance estimations.



[a] Cobweb for x-position; x5 test cases and x9 sensitivity parameters, Error = 1/1000 scale

[b] Cobweb for x-position for x5 test cases and x9 sensitivity parameters, Error = 1/100 scale



[c] Cobweb for y-position; x5 test cases and x9 sensitivity parameters, Error = 1/1000 scale

[d] Cobweb for y-position; x5 test cases and x9 sensitivity parameters, Error = 1/100 scale

Figure 4-3: Cobweb diagrams showing sensitivity parameter responses for x5 test cases for two different distance estimations (i.e. error scale factors equals 100 and 1000).

4.1.4 Observations

The following observations are made with reference to the test results presented in Table 5. The error growth as a function of measurement accuracy and the geometrical layout of the initialisation nodes are of interest. Errors decrease sharply with a decrease in measurement accuracy using the results for node position 2 presented in Table 5. Initial observations are that the estimated node position is more sensitive with regard to the geometry of the initialisation nodes. This aspect is further evaluated by the next experiment.

The Cobweb diagrams show very similar results and appear to be independent of the error scale factor used. It becomes evident by comparing the graphs in Figure 4-3. For the [a] graph (error scale factor = 1/1000) and the [b] graph (error scale factor =1/100) the cases 1, 2 and 3 show similar sensitivity response for the x9 parameters. Using these same graphs and cases 4 and 5 the sensitivity responses are much greater if the condition is that the geometrical poisoning of the initialisation nodes is bad. It is thus in support of the previous statement regarding the greater influence of geometrical positioning of the initialisation nodes on the propagated error.

4.1.5 Conclusions

The objective of this test has been achieved. The effect on the positional accuracy of a propagated node has been evaluated and explained in terms of the geometry of the initialisation nodes and accuracy in range estimations. The conditional statement holds true given that the initialisation nodes are not ill conditioned and do provide an acceptable solution. With reference to the sensitivity diagrams (Figure 4-3 above) this becomes evident in Case 4 and Case 5 showing larger sensitivity values. Closer scrutiny of the chosen initial positions for these two cases (See bulleted note in Figure 4-2 [a]) that explains these artefacts.

The error sensitivity when estimating the position of a single node can be optimised by selecting a solution with good positioned initialisation nodes. If this condition is not met the magnitude of the sensitivity parameters tends to be large in comparison with the ideal or optimal case.

4.2 Error analysis

The analytical approach is useful because the close form solution hides many of the complexities and does not necessary provoke a better understanding of the problem. The theory for an approximation of the error propagation model is developed in Chapter 3 and demonstrated in this section.

4.2.1 Objectives

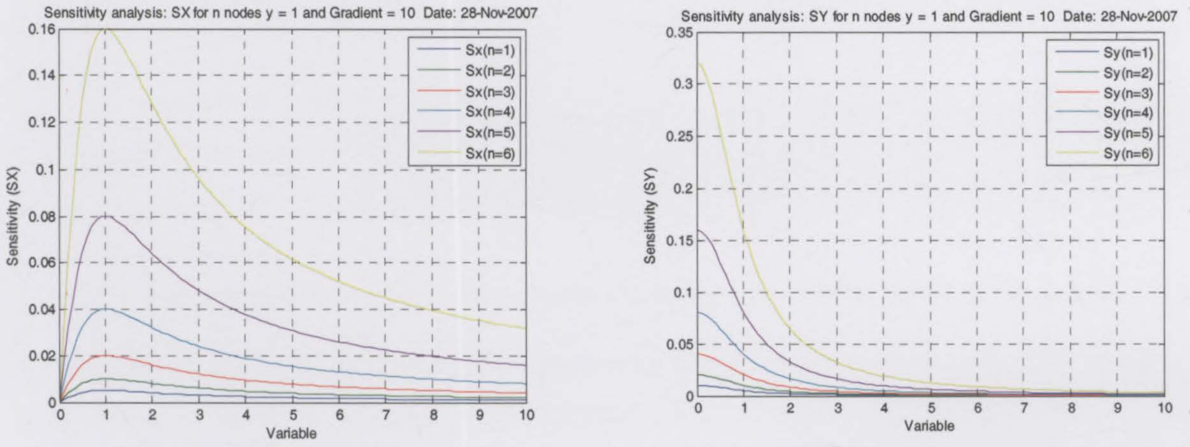
The trends for equations presented in Table 4 (Chapter 3) are evaluated. The objective is to develop an appreciation for sensitivity parameters by investigating the responses of the listed parameters.

4.2.2 Setup

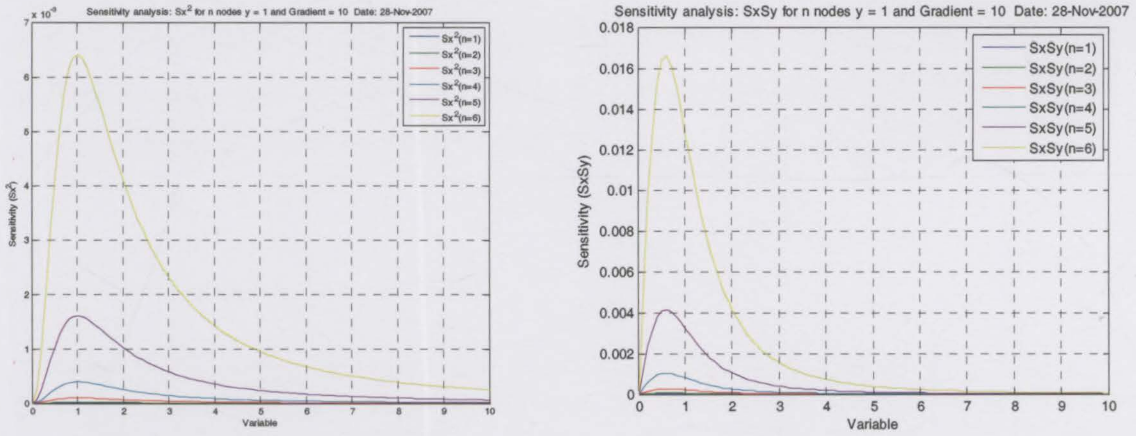
The program ***sens_anal_2.m*** was used to generate and plot the response for these equations. Only the x axis was evaluated because the test evaluate the behaviour of the deduced sensitivity parameters and the y-axis would produce similar results. For this test the y was set equal to “1” while the x value was evaluated over the range $1 \cdots 10$. The results are plotted as graphs to be evaluated. The evaluation was done for 6 nodes with an assumed value for the distance measurement accuracy, $\Delta x = \Delta y = 0.01$.

4.2.3 Results

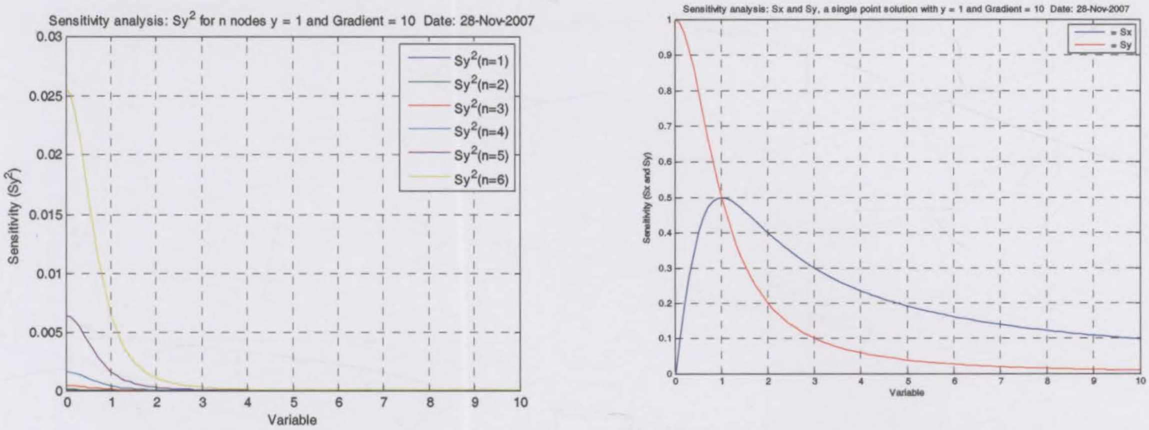
Results presented in Figure 4-4 are for 6 nodes and for the sensitivity coefficients in [a] S_x; [b] S_y; [c] S_{xx} and [d] S_{xy} respectively.



[a] X-Sensitivity (S_x) [b] Y-Sensitivity (S_y)



[c] X-Sensitivity; power of 2 (S_{xx}) [d] Combined X*Y Sensitivities (S_{xy})



[e] Y-Sensitivity; power of 2 (S_{yy}) [f] X- and Y-Sensitivities compared (S_x & S_y)

Figure 4-4: Analytical model output graphs for error sensitivity analysis

4.2.4 Observations

The sensitivity coefficients increase with an increasing number of nodes. This relationship is more sensitive in the x-axis for a small node number and a ratio for $x/y \approx 1$. For $x/y < 1$ the sensitivity increases with an increase in x while a ratio for $x/y > 1$ has the opposite effect. The y-axis show similar effects. This indicates that the geometry of the node positions is the governing factor. It is expected that the behaviour of a skewed network of nodes would be optimal as this presents the best compromise between the x and y coordinates. It is noted that the number of nodes are basically a scaling factor of the form $2^{(n-1)}$, $2^{(2n-4)}$ or $2^{(2n-3)}$ (See Table 4, Chapter 3). This can be offset by the quality of the distance measurement i.e. $\Delta x = \Delta y = 0.01$ as for this simulation. By inspection an appreciation for the accuracy requirements for distances measuring between nodes can be developed.

4.2.5 Conclusions

The analytical approach is a useful tool to understand the major factors that contributes to increase the sensitivity margins. Using this information it is expected that an optimal navigational network would have a skewed or diagonal structure. This type of structure maintains the ratio between the x and y coordinates.

4.3 Interconnected node analysis

The single node behaviour was demonstrated in section 4.1. These experiments expand the single node solution by constructing arbitrary chosen geometrical structures. The single node solution is used as modular building blocks for creating different structures.

4.3.1 Objectives

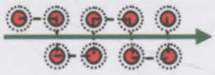
The objective is to evaluate the behaviour of a set of interconnected nodes. This experiment is done to evaluate how errors propagate through different structures of configured nodes. Previous experiments predicted that error growth is sensitive for the geometrical layout of the initialisation nodes and it is expected that this behaviour would also effect the positioning of nodes for a larger setup of interconnecting nodes.

4.3.2 Setup

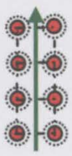
Several nodes are stringed together to create structures as depicted below and labelled using descriptive names. The initialisation nodes is chosen accordingly but are not necessary the same for all the structures. A program ***netnav_v2.m*** was used to generate the data.

Elongated:

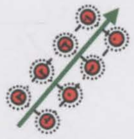
Inverted Elongated:



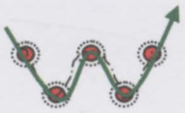
Towered:



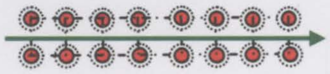
Diagonal (Skewed):



S-Curved:



Large network:



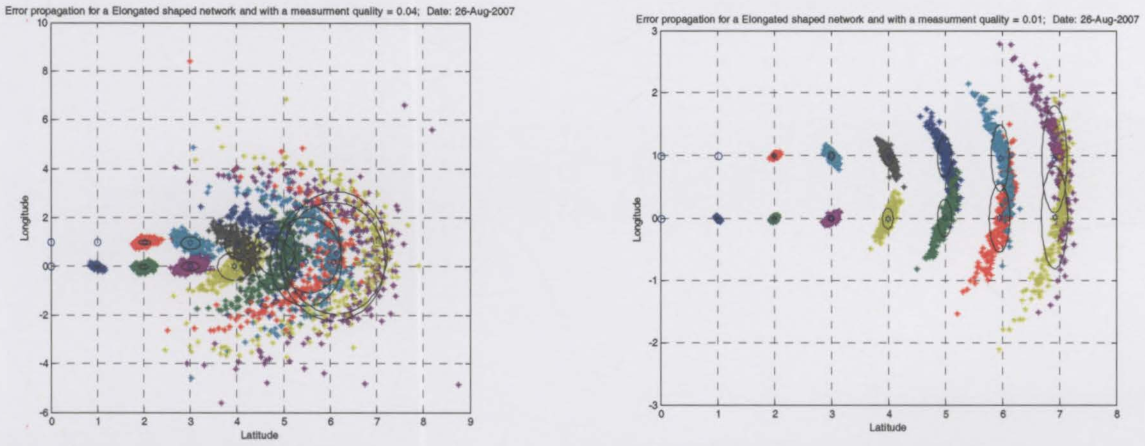
The single node propagation algorithm (section 4.1) is recursively used to solve each individual node position through out the network structure. At each node point solution the sensitivity parameters are calculated. In addition the dilution of precision (DOP) value was also calculated using the covariance matrix. A number (=200) of consecutive Monte Carlo simulations were used to generate statistical data sets for evaluation purposes. The consistency of these data sets was checked for errors and verified to be normally distributed.

The accuracy of a distance measurement is used as a variable parameter to generate data sets for each of the different structures. Table 6 presents a summary of these results.

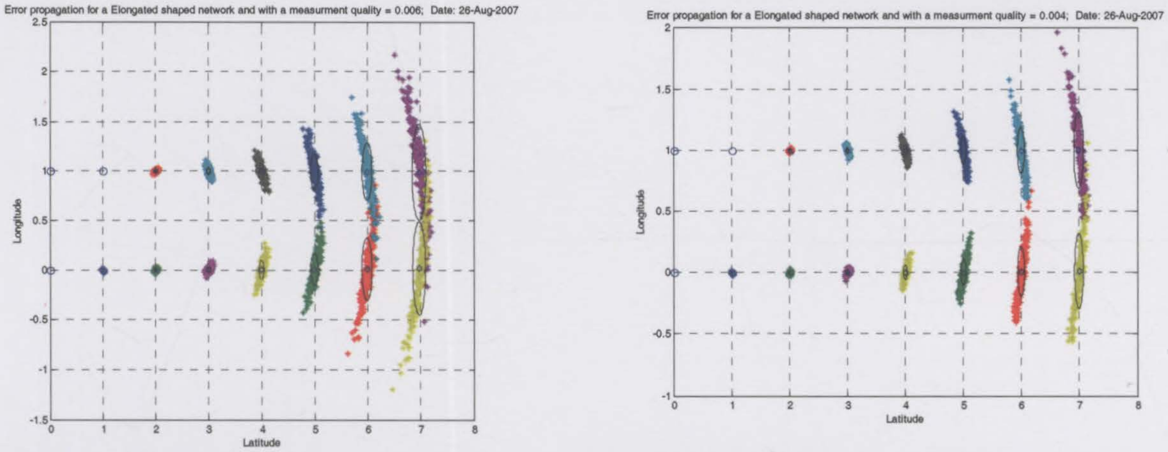
4.3.3 Results

Test results for arbitrary chosen structures are is presented as graphical outputs in Figure's 4.5 and 4.6. Figure 4.5 depicts an Elongated structure with varying degrees of the distance accuracies. Figure 4.6 is a sample set of data outputs that compare different type structures using the same value for distance accuracy.

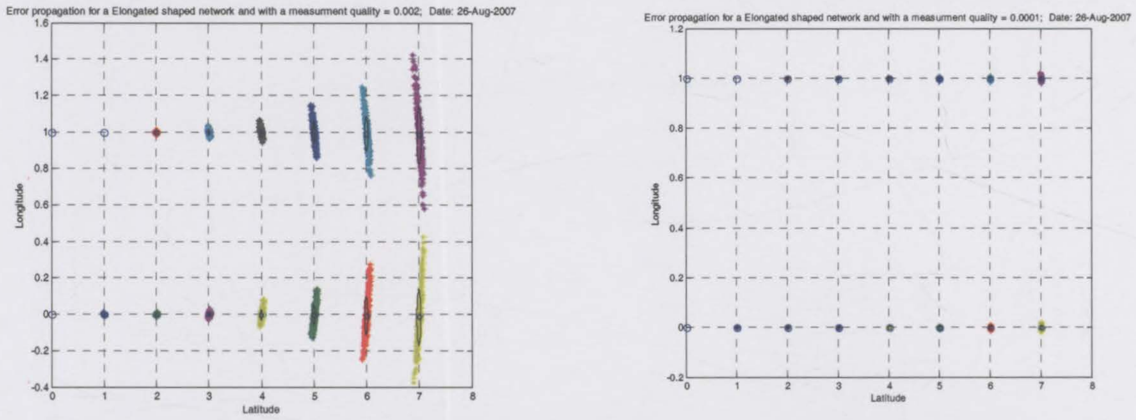
The data reduction process entailed calculating the mean and standard deviation for all data sets for each estimated node position (i.e. calculated on the Monte Carlo data set of 200 data points) and for all the different structures. These results are summarised in Table 6 and sample data are presented as graphs in Figures 4.7 and 4.8.



[a] Elongated structure: 4% distance error [b] Elongated structure: 1% distance error

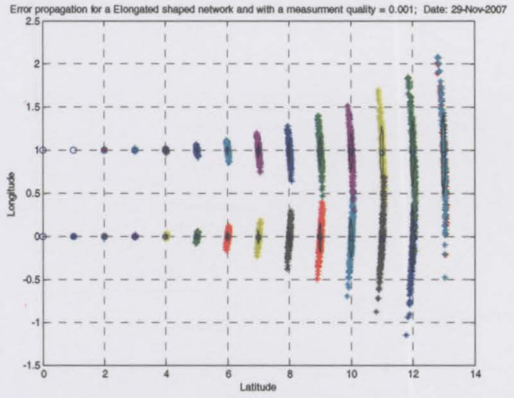


[c] Elongated structure: 0.6% distance error [d] Elongated structure: 0.4% distance error

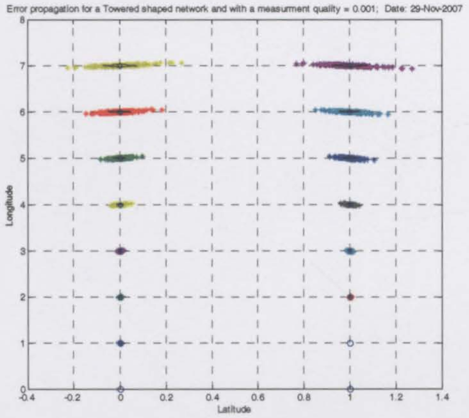


[e] Elongated structure: 0.2% distance error [f] Elongated structure: 0.01% distance error

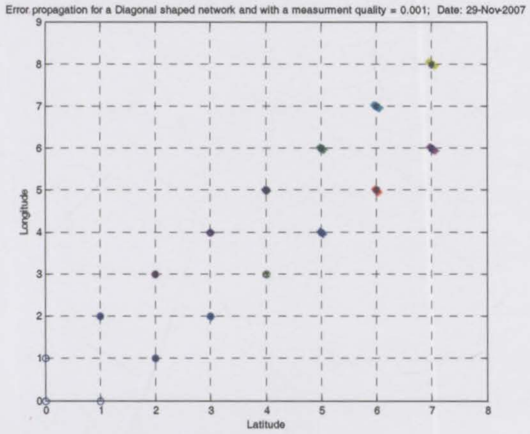
Figure 4-5: Elongated structure with varying degrees of distance measurement accuracies; [a]=4%, [b]=1%, [c]=0.6%, [d]=0.4%, [e]=0.2% and [f]=0.01%



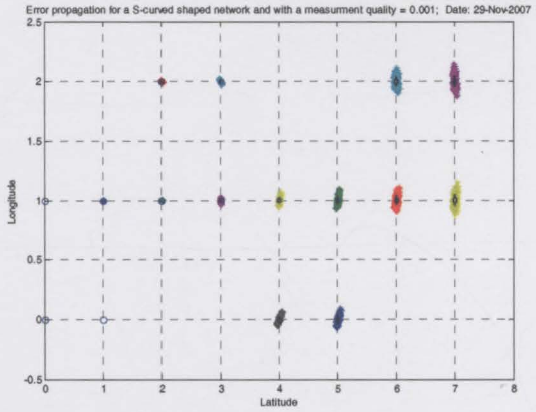
[a] Elongated structure: 25 nodes



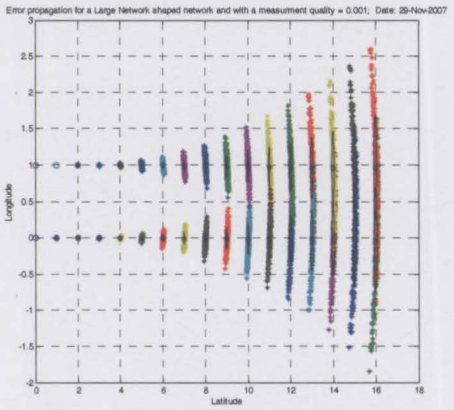
[b] Towered structure: 13 nodes



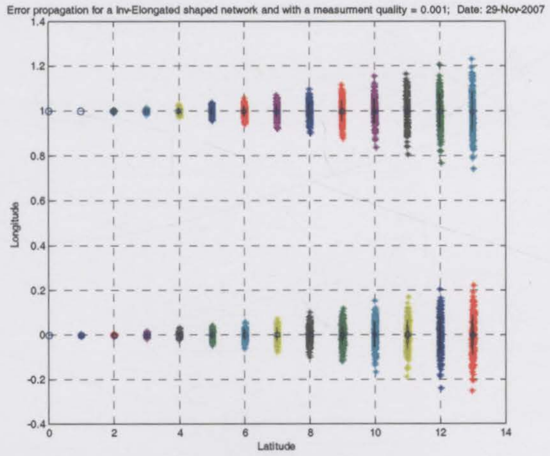
[c] Diagonal structure: 13 nodes



[d] S-Curved structure: 13 nodes



[e] Larger structure: 31 nodes

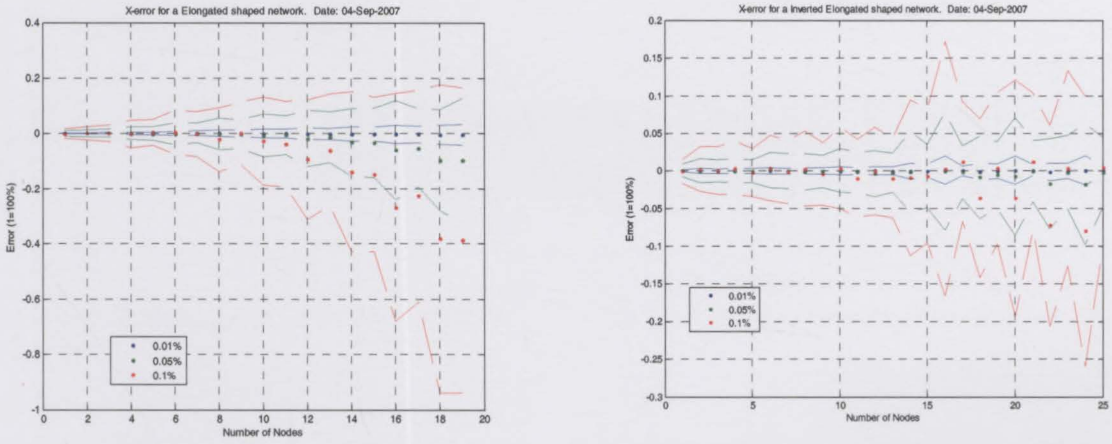


[f] Inv-Elongated structure: 25 nodes

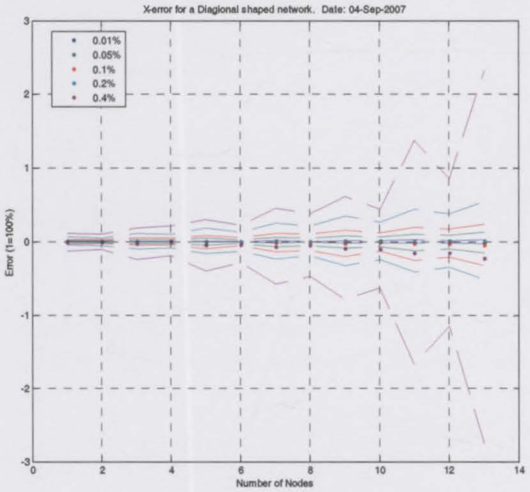
Figure 4-6: Different structure types compared for an accuracy = 0.1%

Table 6: A summary of the results for interconnected nodes and varying accuracies after the data reduction process.

Geometry	Accuracy [%]	x_e	x_{std}	Node #	y_e	y_{std}	Node #
Elongated	0.001	-0.00682	0.034936	19	0.008956	0.22539	19
	0.005	-0.1058	0.220403	19	0.03939	0.819686	17
	0.01	-0.31474	0.507237	19	0.030172	0.706833	13
	0.02	-0.50033	0.724992	15	0.019946	0.876826	11
	0.04	-0.38534	0.724992	11	-0.09315	0.509796	7
	0.05	-0.25414	0.567147	9	-0.06606	0.686346	7
	0.06	-0.2247	0.834595	9	-0.15926	0.767121	7
	0.08	0.03822	0.646976	4	0.023831	0.609193	5
	0.10	-0.02867	0.265078	2	-0.07953	0.280795	2
Towered	0.001	-0.00196	0.073067	13	-0.00099	0.018361	13
	0.005	-0.02523	0.372985	13	-0.02044	0.093669	13
	0.01	0.020065	0.705299	13	-0.06373	0.190142	13
	0.02	-0.13077	0.932489	11	-0.26254	0.471428	13
	0.04	0.107985	0.998519	9	-0.38969	0.675605	11
	0.05	-0.09249	0.682147	7	-0.1928	0.539811	9
	0.06	-0.15499	0.90999	7	-0.29147	0.676547	9
	0.08	0.077704	0.449568	5	0.063331	0.433819	5
	0.10	-0.02052	0.254543	3	-0.00085	0.781769	4
Diagonal	0.001	-0.00349	0.027624	13	0.00187	0.021115	13
	0.005	-0.00536	0.150952	13	-0.00048	0.11281	13
	0.01	-0.02802	0.274179	13	0.013485	0.211124	13
	0.02	0.018221	0.537469	13	-0.03036	0.420017	13
	0.04	0.01642	0.401674	8	-0.05307	0.442154	8
	0.05	0.052146	0.713038	10	-0.18757	0.845519	11
	0.06	-0.0414	0.747416	7	-0.01498	0.567448	7
	0.08	0.074845	0.779005	5	-0.00841	0.500604	5
	0.10	0.024989	0.609564	3	-0.04392	0.651438	5
S-Curve	0.001	0.000347	0.020833	13	0.004141	0.04504	13
	0.005	0.003798	0.09447	13	-0.00574	0.24657	13
	0.01	-0.03329	0.193257	13	0.002497	0.435885	13
	0.02	-0.0773	0.438062	13	0.050983	0.880158	13
	0.04	-0.16712	0.523756	9	0.148367	0.812344	7
	0.05	-0.33853	0.643766	9	0.091025	0.934285	7
	0.06	-0.38107	0.967215	7	0.006084	0.597662	5
	0.08	-0.03571	0.62791	4	0.022171	0.334663	3
	0.10	-0.14845	0.728074	4	0.048633	0.484172	3
Large Network	0.001	-0.00377	0.031458	19	-0.00212	0.21084	19
	0.005	-0.10237	0.195388	19	0.034556	0.784981	17
	0.01	-0.39815	0.590529	19	0.064096	0.72694	13
	0.02	-0.55571	0.759176	15	0.09127	0.567998	9
	0.04	-0.37702	0.700471	11	0.013109	0.518677	7
	0.05	-0.19541	0.567851	9	-0.1132	0.669136	7
	0.06	-0.32115	0.857268	8	0.098012	0.856332	6
	0.08	0.077203	0.366326	5	0.125127	0.397625	5
	0.10	-0.02897	0.990041	4	-0.00231	0.266431	3
Inv-Elongated	0.001	0.001075	0.008867	19	-0.00307	0.049579	19
	0.005	0.006709	0.043696	19	-0.02011	0.250224	19
	0.01	0.0143	0.097151	19	-0.13334	0.492064	19
	0.02	-0.02936	0.331253	16	-0.17465	0.855516	16
	0.04	-0.05304	0.860002	11	-0.06466	0.621504	8
	0.05	-0.04141	0.915581	7	-0.05318	0.574268	7
	0.06	-0.01353	0.252845	4	-0.04957	0.344076	4
	0.08	-0.00773	0.587329	4	-0.07252	0.753108	4
	0.10	0.056775	0.442855	2	-0.09439	0.86994	4



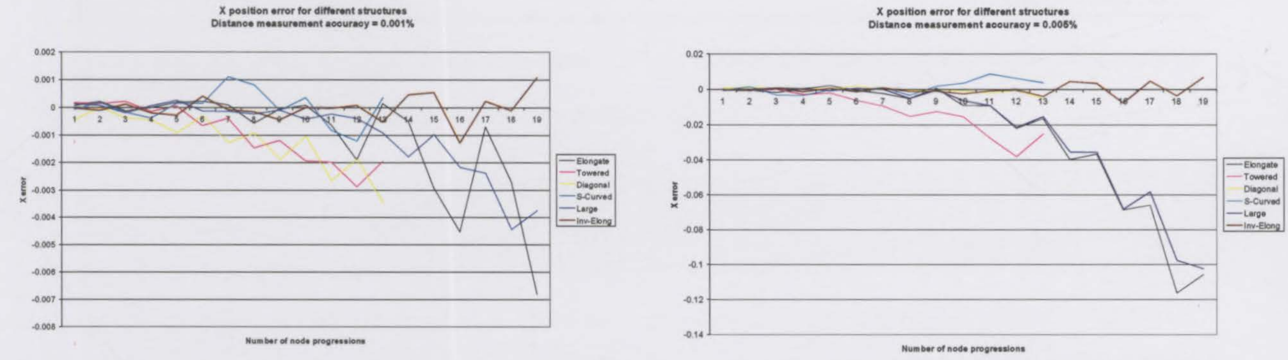
[a] Elongated: Error = $(\bar{x} \pm \sigma)$ [b] Inv-Elongated: Error = $(\bar{x} \pm \sigma)$



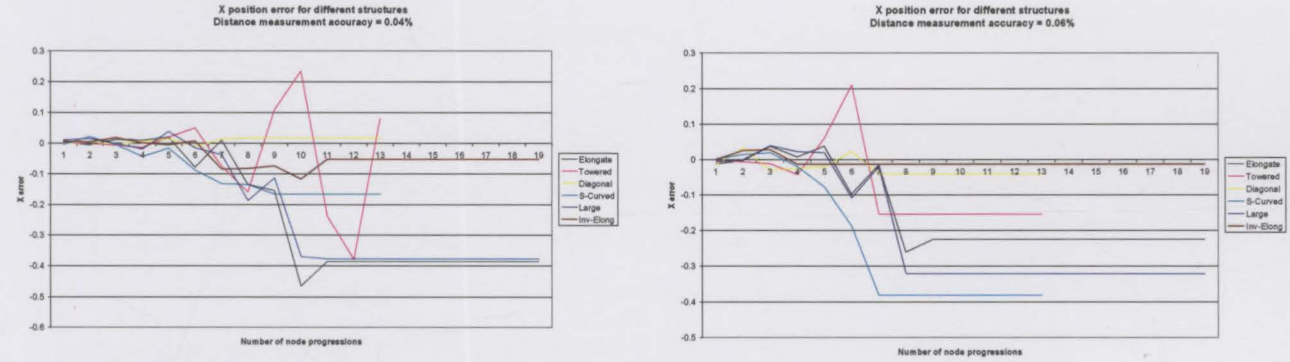
[c] Diagonal: Error = $(\bar{x} \pm \sigma)$

Figure 4-7: X_{err} as a function of the number of nodes for different structures and varying distance measurement accuracies. (Data sample set)

The data presented in Figure 4-8 is for the x-axis only. The mean error value is obtained by calculating the average of the simulated solution (i.e. 200 Monte Carlo points) and subtracted from the actual true position for a particular node. The results is summarised in Table 6 using a threshold equal to "1". The threshold was defined as a value that does not exceed "one" when taking both the error and the standard deviation into consideration.



[a] X-error; Measurement accuracy = 0.001%   [b] X-error; Measurement accuracy = 0.005%



[c] X-error; Measurement accuracy = 0.04%   [d] X-error; Measurement accuracy = 0.06%

Figure 4-8: Comparing X_{err} for different node structure performances but similar distance measurement accuracies (Data sample set).

4.3.4 Observations

The results in Figure 4-6 show that the behaviour of the nodes can be managed with increasing performance by improving the distance measurement accuracy. This can be done using more accurate sensors or by taking more measurements. These two aspects have a major impact on how the navigational network is configured. More measurements increase bandwidth demands, eventually leading to more power consumption. Accurate sensors become a cost factor. In the simulated example for an Elongated structure the network starts to stabilise with a relative distance measurement accuracy of 0.6% assuming that the complete network is to be functional.

Although these percentages are defined to have a relative meaning the simulation results indicate that a high degree of precision measurements are required. From a practical point of view this does raise some concern because it is a driver for selecting the type of processor and word size with an impact on memory utilisation.

The structure type does play a significant role as been deducted from the sample plots in Figure 4-6. Using the same degree of accuracy for distance measurements allow comparison between the chosen structures. It is clear that the diagonal structure outperforms all other sample sets. This supports the observation made when the analytical model was studied (See section 3.2.4). No attempt was made to analyse the sensitivity parameters due to its complexity other than the analytic model approach discussed in the previous section.

Figures 4-7 and 4-8 present similar data in two different formats to illustrate behavioural aspects. Figure 4-7 [a] and [b] compare the Elongated and the Inverted-Elongated structures. It is observed that the initialisation nodes do play an important role in node behaviour because the error growth rate for the latter structure is much slower for all other conditions being the same. Using DOP to monitor and control the integrity of the solution can thus have a significant impact on how positional errors propagate. Figure 4-7 [c] show the Diagonal structure to be well behaved being symmetric and with a significant increase in performance. Figure 4-8 is the error growth in the x-axis showing that the Diagonal structured case outperforms all other cases with the Elongated and Large structures the worst performers. The similar performances for the latter cases are expected because both have the same structure with only a different number of nodes for the "Large structure".

4.3.5 Conclusions

It is obviously that many strategies and/or processing techniques can be used to improve error growth rate. The major factors that contribute are the positioning of the initialisation nodes and the accuracy of the distance measurement sensor. A proposed solution for node positioning is to use DOP for optimisation purposes. The secondary effect regarding the accuracy of the distance measurement causing a delay in the error growth rate should be dealt with once the error due to initialisation node position has been compensated for.

Chapter 5

5 APPLICATION FOR NAVIGATION

The primary objective of this study is to solve a navigation problem. This is addressed using a set of interconnected nodes. An algorithm was developed that enables a single node to locate itself and used recursively to build a structure of interconnected nodes. The feasibility of using a set of these networking nodes as a platform for navigation is investigated. The construction of navigational paths is explained and the criteria for identifying good or bad paths are discussed.

5.1 Navigational path modelling

The navigation path model study the effect of different path constructions on the final destination point in an Ad-hoc navigation network (AHNN).

5.1.1 Defining paths

A scheme is defined to evaluate different aspects that can influence the final accuracy of a navigational solution through a maze of interconnected nodes. This scheme comprises of several fixed waypoints or nodes, identifiable by a unique number and defined by its position coordinates; $<x_i, y_i>$, i = 1, 2, 3… with "i" defined as the node number. This problem is simplified using 2-D space but can easily be extended for multi-dimensional space by adding a third axis i.e. 3-D space = $<x_i, y_i, z_i>$.

Nodes can be randomly dispersed or placed at pre-allocated or fixed locations. This experiment uses the method of pre-allocating nodes. The behaviour and performance of different paths are studied using these fixed allocations to calculating the error. Typical examples are pre-planned missions with known waypoints or a set of randomly distributed nodes that presents an ad-hoc sensor network. Both these examples do require the self locatable node (SLN) capability.

The experiment is constructed using a simulated environment that consists of a number of paths based on these fixed allocations for nodes. In practice this experiment comprises of dynamically mapped locations for which uses the SLN algorithm is used to determine the cumulative error of using several of these nodes as waypoints. Each node position is calculated based on the error propagation model defined in Chapter 3.

5.1.2 Definitions

Path: A path is a set of legs selected to navigate from the staring point (A) to an end point (B). Per definition the path uses the Leg numbers in sequence to navigate through the maze.

Node: A node is a network connection with the ability to determine its own location. Once a node location is known it functions as either a waypoint for a navigation solution or an anchor for other nodes that need to determine their position.

Waypoint: A Waypoint is a fixed position defined within a relative coordinate frame. For the purpose of this study these waypoints are defined as the known positions (without error). In practice these are typically GPS coordinates, survey beacons, map positions or resolved positions (using an ad-hoc sensor or meshed networks)

Leg: A connection between two waypoints (or nodes) with a staring point and an end point. Note that these are the measurements based on the triangulation algorithm used for solving the different waypoints.

5.1.3 Setup

The grid defines an area of arbitrary shape and size. Node positions are marked form the various paths which can be constructed using nodes as waypoints. The paths are investigated in terms of overall path-lengths, the number of nodes and the magnitude of the error at the final destination node.

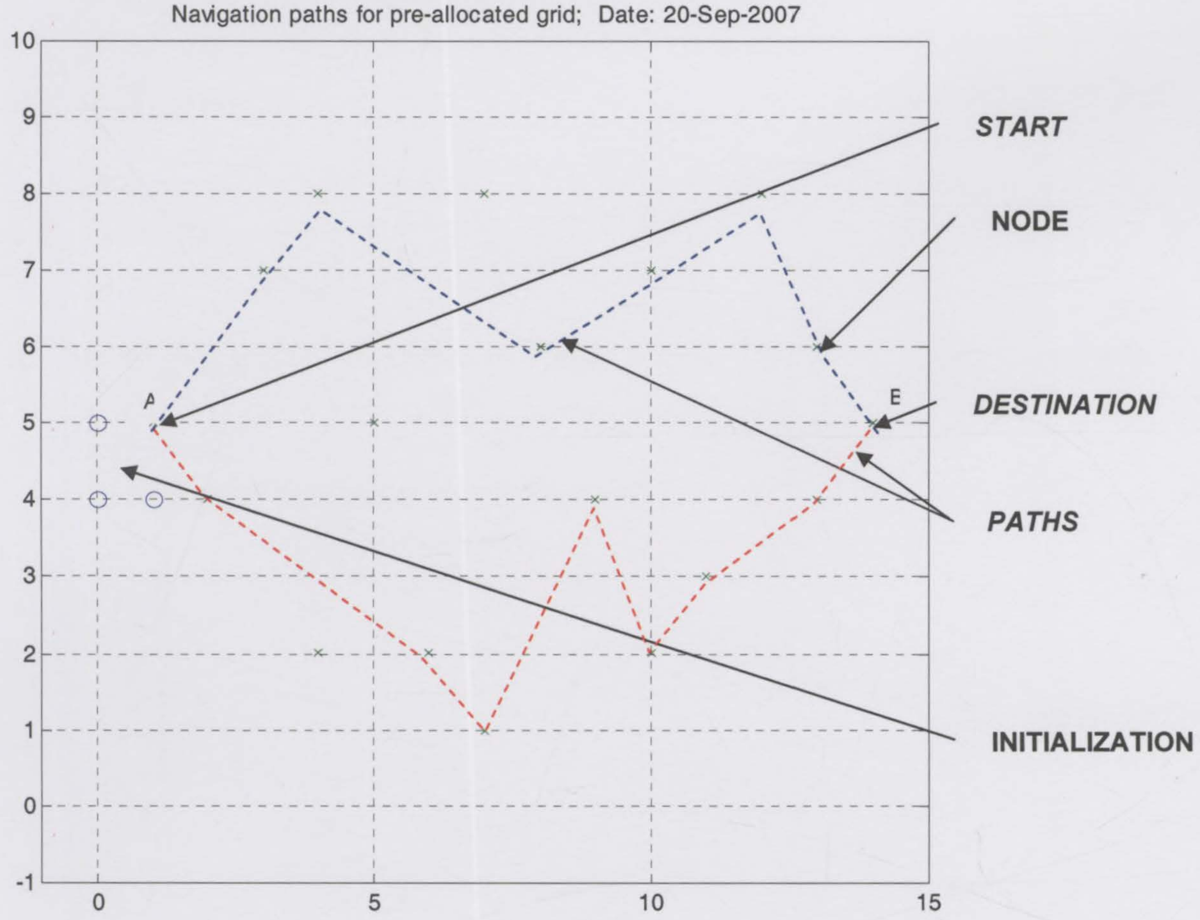


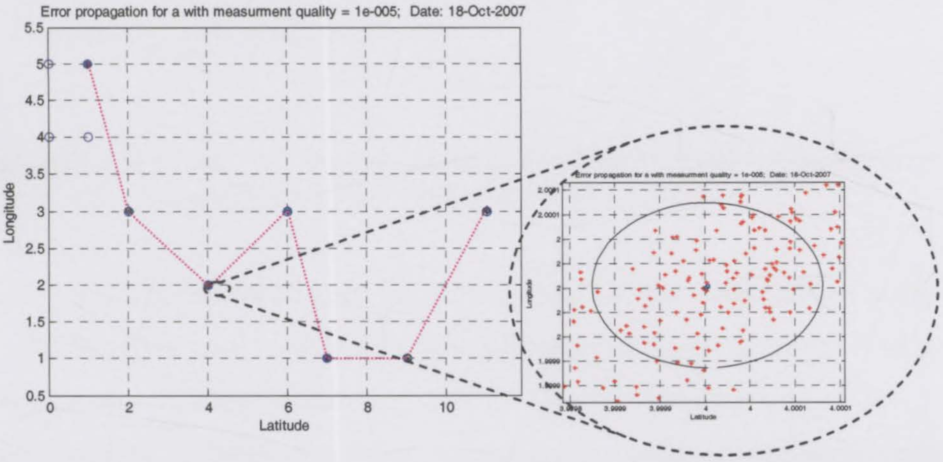
Figure 5-1: Navigation path construction

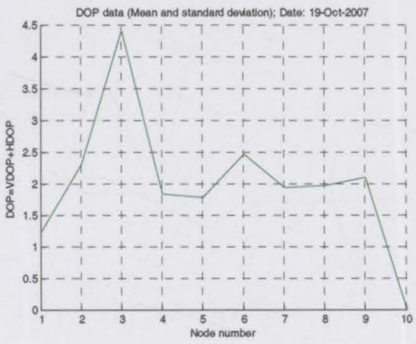
Arbitrary chosen paths are simulated and presented using graphs as depicted in Figure 5-1 above. Any form or shape can be constructed using the concept that a navigational path is defined with a collection of waypoints. The SLN algorithm Each waypoint is plotted using its mean position, <*x, y*> coordinates and the associated standard deviation (1□-value). This is calculated from a Monte Carlo simulation with 200 random data points. For this experiment the accuracy of the random distance measurements was set to a high value in order to evaluate how the geometry of the selected nodes does effect the final destination. To illustrate the geometric effects a parameter referred to as the delusion of precision (DOP) was calculated for each of these position updates. The position updates is determined by means of the error propagation algorithm (EPA) defined in Chapter 3.

The distance measurement error was set to a high percision value for the purpose of this demonstartion enforcing the experimental results to be more dependent on the geomtery of the nodes.

5.1.4 Results

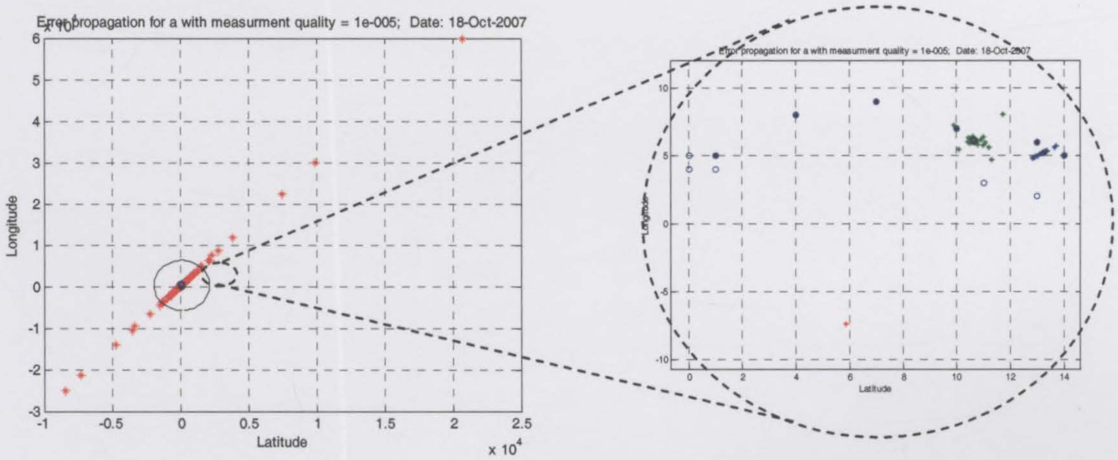
The results are presented as graphs in Figure 5-2 and Figure 5-3. Table 7 is a summary of all the different paths used in this demonstration.

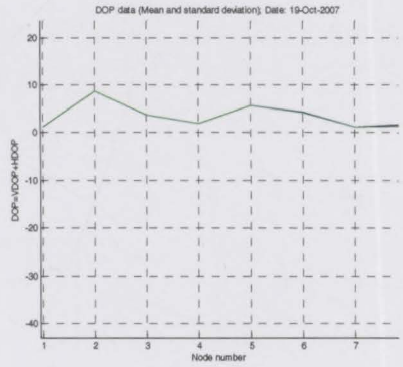




NOTES: Path #1 shows excellent behaviour because the destination error is not affected by path geometry. The final result is obtained irrespective of the higher DOP value for position 3 (~4.42) being higher than an average DOP = 2 for the complete path. This higher DOP value is explained as the anchor nodes used to calculate node 3 positions are ill conditioned, being almost aligned.

Figure 5-2: Path #1 output results showing the path plan and DOP performance metrics.





NOTES: Path #7 shows a path that became unstable at nodes 9 and 10 with corresponding DOP values 9 ~ 431 and 10 ~ 850. These last two nodes results in the unacceptable path length result of 132 units.

Figure 5-3: Path #7 output results showing a bad path plan with corresponding DOP performance metrics.

Table 7 presents the different path lengths using the final designated waypoint as the end. The path lengths used in this demonstration differ using between 8-10 nodes as the planned waypoints. After inspecting the results of the experiment the larger error values were removed i.e. typically those caused by the solution becoming unstable. The final error at that terminated node is recorded in the table with the corresponding node number in brackets

Table 7: Summary of the navigation path errors with performance metrics

Path #	Path-length	X-error	Y-error	DOP		Ratio inc [+%]
				mean	maximum	
1	19.1727	-0.0004 ± 0.0009 (9)	0.5569 ± 2.4027 (9)	2.0042	4.4159	47.48
2	82.0703	-0.0003 ± 0.001 (7)	0.4281 ± 2.2253 (7)	3.9335	20.9009	531.31
3	22.5597	0.0032 ± 0.0836 (10)	-0.0035 ± 0.1682 (10)	2.1625	3.2304	73.54
4	25.5472	0.0000 ± 0.0001 (7)	-0.0001 ± 0.0001 (7)	2.5122	6.2450	96.52
5	23.9510	-0.0077 ± 0.0219 (10)	-0.0152 ± 0.0258 (10)	2.6308	4.4097	84.24
6	25.9113	0.5714 ± 0.7868 (7)	-0.0007 ± 0.0011 (7)	2.6806	8.6602	99.32
7	132.0979	0.0004 ± 0.0007 (6)	0.0004 ± 0.0013 (6)	130.9686	850.2105	916.14
8	585.7696	0.056 ± 0.1373 (6)	-1.7263 ± 2.6297 (6)	7.0086	11.2824	4405.92
9	40.7876	1.3185 ± 3.8903 (8)	-1.4815 ± 3.2068 (8)	7.8021	14.4458	213.75
10	36.9243	0.0000 ± 0.0001 (6)	0.0001 ± 0.0002 (6)	3.4043	7.5683	184.03
11	36.8458	0.2815 ± 2.1367 (8)	1.3611 ± 2.3271 (8)	3.3714	10.8923	183.43
12	31.7810	-0.0017 ± 0.0028 (6)	0.0051 ± 0.0083 (6)	2.8705	7.5681	144.47
13	26.6929	0.0000 ± 0.0001 (10)	0.0001 ± 0.0001 (10)	1.9451	4.4159	105.33
14	24.9006	-0.0001 ± 0.0002 (9)	-0.0003 ± 0.0003 (9)	1.8759	3.1317	91.54
15	21.5802	0.0002 ± 0.0007 (9)	-0.0003 ± 0.0011 (9)	2.0689	4.4159	66.00
16	22.9485	0.7746 ± 1.4347 (8)	-1.5493 ± 2.8693 (8)	2.6333	5.4897	76.53
17	26.8814	-0.2738 ± 1.9555 (9)	2.1658 ± 2.9105 (9)	2.3509	5.6458	106.78

5.1.5 Observations

The selected paths are but a subset of all possible paths. Some of the paths were eliminated (using a method of inspection) because it produced unstable solutions. The shortest possible path length is 13 units. The ratio of over-estimating the paths were calculated and presented in Table 7 as the percentage increase in path length.

5.1.6 Conclusions

Above results demonstrates a typical navigation application. Paths with bad solutions were eliminated using manual inspection but the DOP value can be used as a figure of merit to optimise the process thus allowing for autonomous navigation. From a practical point of view nodes can be dispersed in any random way. The typical communication distances between nodes in an AHNN are 30–100m apart, say on average 50m. This gives some means to scale the navigation network using 10 nodes to cover an area of $500m^2$.

Chapter 6

6 CONCLUSION and FUTURE WORK

6.1 Conclusions

The autonomous navigation problem has been solved using a wireless Ad-hoc Network (AHN) as backbone technology for the navigation solution. A recursive algorithm was developed that enables interconnected nodes to perform self-locating functions. Similar algorithms that falls in the category of wireless node localisation methods such as GPS-less, Anchor free or Self Positioning Algorithms (SPA) are being developed. Although many researchers address the problem of solving node location no reference was sourced that addresses the navigation problem as an application for these types of networks.

The study used simulations to demonstrate the behaviour of a single node solution with experimental results showing that the result is much a function of the geometry of the nodes used in the solution. The distance measurement accuracy was found to be less critical and for the purpose of these experiments was controlled by using extremely accurate values to minimise their affect.

The analytical model in section 3.4 uses a Taylor approximation to explain how sensitive the positional error is with repetitive applications of the algorithm. The important observation was the prediction that an optimal navigation network is one with a skewed structure – due to the form of the nodes. This was proven in a subsequent experiment that evaluated the structured response of several interconnected nodes.

The experiment for clustering nodes in some arbitrary chosen structure shows interesting behaviour but is significant to highlight the fact that the geometry is the major factor here. Any bad position for a node impacts all other node positions down the solution chain because the error is accumulatively carried through to be used in the solving the next node position. For those cases when the geometry of the initialisation nodes produced an acceptable solution (i.e. small positional error) the distance measurement accuracy between nodes was evaluated and found to be a logarithmic function of the number of nodes and the selected accuracy for the distance measurement.

The navigation solution is demonstrated using a few selected paths in Chapter 5. The feasibility of using this algorithm for navigation in areas deprived of traditional means of positioning oneself is illustrated. Using this method the typical path length is longer by a percentage margin that vary form +47% (best case scenario) up to +4406% (worst case scenario) using the shortest path as reference. This is not that unrealistic as for any navigation application the waypoints are never aligned in a straight line as obstacles needs to be avoided and/or mission planning may require different routing to serve some or other objectives.

This work developed tools using MATLAB™ that are useful for further experimental work. The initial literature study indicated that open source programs are available capable to simulate wireless Ad-hoc and/or Meshed networks the navigational concept was identified as a novelty that demanded a new angle to solve the problem. Obviously these tools can be used but do require some adaptation as their main focus is on network protocol developments. These simulation tools do not address the particular aspect of error growth using the propose method of interconnecting nodes. This work is thus unique in this sense as no other similar work could be sourced. Much of the research work done to solve the distance measuring problem and node localisation were very useful and crucial for the proposed navigation concept to work properly.

This work has many application fields that goes beyond navigation per se as it can be used to enhanced network connectivity, improve traffic control, for emergency services, for military use as part of a digital battle field, in solving the NLOS Communication problem or for adaptive surveillance and for underwater navigation tasks.

6.2 Future work

6.2.1 Robust algorithms

A more robust process is required for autonomous navigation with regard to the sensitivity of node position due to the identified factors that influence positional accuracy. This study did consider sensitivity analysis of the proposed model for verification purposes only, but it did not consider methods and techniques to optimise the behaviour of the proposed algorithm. Typically further research work is needed to eliminate ill conditioned solutions prior to computing a new node position. This is required prior to a rigorous application of the algorithm in a recursive way with the objective to save unnecessary computational time, and memory usage in an attempt to solve ill conditioned nodes.

6.2.2 Alternative solutions

Consider alternative solutions that can work in conjunction with the network navigation concept. Typical examples thereof are to exploit Artificial Intelligence like the rule based methods (i.e. fuzzy logic or Neural Networks) to assist in path planning and node optimisation. The latest trends are in Bayesian networks and Markov chains are also worth further investigation as part of this optimisation effort.

6.2.3 Path enhancements

The Ad-hoc network is an active network that continuously gathers statistical data. This process needs to be automated using statistical analysis methods such as LSA for optimisation and verification of positional data. This automation would also benefit land surveyors because the used process is very similar to what they do but adding autonomy using intelligent nodes.

6.2.4 Node redundancy

Further study is required to investigate the accuracy of node position determination as a function of increasing the number of nodes used in the tri-lateration or triangulation solution. This study solved the problem using the minimum requirements for a 2-D solution (i.e. 3 nodes) but an unlimited number of nodes can be clustered to enhance the accuracy of the node position using statistical methods for all combinations of the visible nodes. Typically this study should address aspects such as the advantages in terms of trading the required number of computations for increased node position accuracy. This feature can be seen as a dynamic way to save power during crucial stages, for instance to purposely allow for a degradation in navigation accuracy for the complete network in order to extend its durable life, or to save costs by using a lower performance processors, or to determine a course initial position first and thereafter to selectively optimise the solution, or to find a better solution using only the most viable node geometry in the calculations. Some of these issues have been discussed for instance using the residue equation first or what is referred to as the DOP approach.

6.2.5 Practical demonstrations

Work should continue to further optimise the navigational solution by implementing it on mobile or handheld platforms. Some example kits are presented in Chapter 2 (section 2.8) and can be used for prototyping and testing of the feasibility of implementing the developed algorithm. This solution may be further extended to include already available systems such as the augmented navigational solutions that already use GPS as the absolute positioning sensor but with a seamless transgression using the navigational network instead when GPS becomes unavailable.

6.2.6 Simulation tools

Open source networking programs such as OPNet++ and/or GloMoSim are available and worth further scrutiny. Further work to get acquainted using these open source modelling tools is recommendable. If funds is not an issue tools such as OPNet or Navtk can be purchased for speeding up the development process. This simulations needs to be followed with physical hardware prototype models. To avoid delays in developing this hardware it is recommended to purchase some demo kits such as those mentioned in Chapter 2 (section 2.8).

GLOSSARY

Accuracy	The absolute nearness of a measured quantity to its true value. The true value of a quantity can never be determined thus accuracy is always unknown. GPS: The degree of conformance between the estimated or measured position, velocity, and/or time of a GPS receiver determination and its true position, time and/or velocity using an accepted standard. Radio-navigation accuracy is usually presented as a statistical measure of error and can be characterized as follows: Predictable Accuracy: The accuracy of a radio-navigation system's position solution with respect to the geodetic, or the most accurately known position information. Both the navigation system position solution and the reference information must be based upon or converted to the same datum. Repeatable Accuracy: The accuracy with which a user of a radio-navigation system can return to a position. The position is a previously measured position with known coordinates using the same navigation system. Relative Accuracy: The accuracy with which a user can determine position relative to that of another user at a different position but at the same time using the same coordinate reference system. The application may include a real time data link between both users.
Inertial Navigation System (INS)	The INS consists of a inertial measuring/reference unit and a navigation computer
Inertial Measuring Unit or Inertial Reference Unit (IMU/IRU)	A cluster of sensors consisting of accelerometers and gyroscopes rigidly mounted on a base (platform)
Accelerometer	Sensor that measure the rate at which an object change speed. Unit of measurement is m/s^2. This is an inertial measurement using the earth as the inertial body of reference.
Gyroscope	A sensor that measure rotation rate. Different types of Gyroscopes are manufactured; Rate Gyroscope (measures rotation rate), Displacement gyroscope or Whole-angle gyroscope (measures rotation angle)
Geoids	Geoids are an approximation of mean sea level optometric height using the earth ellipsoid model as reference. The definitions of the Geoids differ from location to location depending on the height deviations in the spherical harmonics used to do the fit. The WGS 84 geiod heights vary about ±100 m from the reference ellipsoid. Grewal {2001, 162} [25]
Earth Centred Earth Fixed (ECEF)	Coordinate definition that uses the centre of gravity of the earth.
Transformation	A transformation is typically a translation or rotations. As these are based on a set of measurements the outcome differs for each state i.e. errors are propagated.
Conversion	Exact mathematical expression to convert form one form to another
Latitude	North-South line
Longitude	East-West line
Cartesian	Right-hand rule, orthogonal reference frame
World Geodetic System (WGS)	Currently defined as WGS84 as an international standard
Calibration	A process that compares instrument outputs with known reference information and determining coefficients that forces the output of these instruments to agree with the reference information over a range of output values. [CHA79]

Precision	The degree of consistency between measurements that are based on the size of discrepancies within a data set. Precision is affected by the stability of the environment during the time of measurement (i.e. temperature changes) and the quality of the instrument used to make the measurement and the skills of the observer in using both the equipment and with the measurement procedures
Radians (rad)	The circumference of a circle in Euclidian space equals 2π (equals 360 Deg) radians
International Traffic in Arms Regulations (ITAR)	Regulations set by the USA government to control the export and import of defence-related articles and services.
System on a Chip (SoC)	High density functional integrated chips that combines both analogue (RF, discrete electronics) and digital (Embedded systems, Gate Logic) as a single chip solution.

APPENDIX

6.3 Appendix A – Vectors

6.3.1 Vector analysis and analytic geometry

The scalar and the vector are both quantities that are used to define physical phenomena. The Scalar is a real number ($\Re$) used to express quantities such as temperature, volume and speed. Vectors are used to define quantities such as force, velocity, acceleration and angular rates all with attributes for both direction and magnitude. Vectors are graphically presented as a line with an arrow that indicates direction and the line-length to present its magnitude, using a defined unit of measure (i.e. meter [m], feet [ft], Newton [N]).

The notation used for presenting scalars is A. Vectors is presented using bold face alphanumeric characters i.e. **a**, **A**, **B**, or ω. The magnitude of the vector is denoted A or $|A|$. A direction is denoted by an angle (α, β, γ) measured clockwise staring from the reference axis (x, y, z) and ending on the corresponding vector line. Angles between vectors are denoted using symbols from the Greek alphabet (ϕ, φ, θ).

Vector theory is well defined and used extensively to describe and/or solve positioning and navigational problems. Vector algebra is used to model and simulate the statistically and the dynamic behaviour of navigation and/or localisation systems. The objective is to research error propagation and its affect on navigational behaviour for a proposed Ad-hoc Wireless Network (AWN) solution. This proposed model is simplified using two-dimensional (2-D) vector descriptions to define either a position or a navigational path. Once properly understood this problem can easily be expanded into three dimensions (3-D) using appropriated vector notations.

6.3.1.1 Vector Fundamental definitions

For geometric descriptions it is useful to express position vectors in terms of a reference coordinate system as defined in Figure 5-1 below. Vectors have many advantages as the operators can add and multiply vectors.

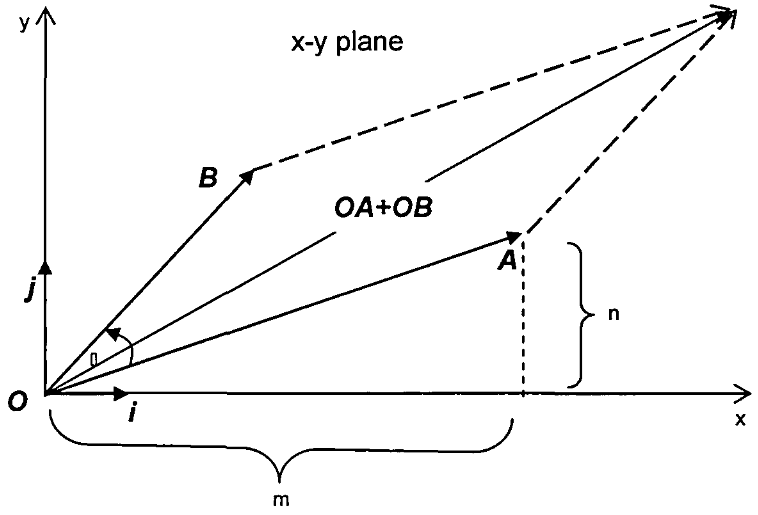


Figure 6-1: Position vector and coordinate frame definitions

i and ***j*** are unit vectors in the ***x, y*** axis respectively.

A and ***B*** are two vectors defined by their position coordinates in the x, y plane for which;

$\boldsymbol{A} = \mathrm{m}\boldsymbol{i} + \eta\boldsymbol{j}$ and

$\boldsymbol{B} = \mathrm{p}\boldsymbol{i} + \mathrm{q}\boldsymbol{j}$ with {m,n,p,q} $\varepsilon\ \Re$ and ***i, j*** unit vectors with magnitudes equal to 1 unit and directions collinear with the x and y axis respectively.

Matrix algebra is used for the modelling and simulating of the navigation system. MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation [45]. The MATLAB script can easily be converted into C code using MATLAB built-in functions for later implementation as embedded code that is executable on a variety of platforms that support C-compliers. The matrix algebra has the following definitions.

A vector in 2-D space is defined as $\boldsymbol{A}$ = [m n] and $\boldsymbol{B}$ = [p q][4].

$A = \begin{bmatrix} p \\ q \end{bmatrix}$ is a column vector (default for MATLAB) and **B** = [m n] is a row vector.

6.3.2 Vector Algebra

The fundamental laws and algebra for vector manipulation are described. The MATLAB definitions and notation applies when presenting a vector as either a row or a column vector. MATLAB defines the column vector as the default.

The fundamental laws are as follows:

- Vectors are equal if both magnitude and direction attributes are equal
- A vector is scaled when multiplied with a scalar value. If the value of the scalar is negative the direction of the original Vector is in an opposite direction. A zero value for the scalar results in a null vector (i.e. both magnitude or direction is zero)
- The vector sum is defined as a newly constructed vector; ***BA*** = ***OA***+***OB*** or ***AB*** = ***OA***-***OB***. This definition is equivalent to the parallelogram law for vector addition. This law can be expanded to sum any number of vectors
- The unit vector is defined as a vector with unit length. The value of the unit vector is obtained by normalization of a defined vector i.e. **a** = A/|A| for |A|>0.

6.3.3 Algebra laws for Vectors

If *A*, ***B*** and *C* are vectors and m, n are scalars then;

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[4] This allows for rigorous mathematical manipulation using MATLAB or C (for implementation) as programming languages. The models for this study are developed in MATLAB due to its powerful matrix algebra processing capabilities.

- Commutative law for addition: $A+B=B+A$
- Associative law for addition: $A+(B+C)=(B+A)+C$
- Associative law for multiplication: $m(nA)=mn(A)=n(mA)$
- Distributive law: $(m+n)A=mA+nA$ and $m(A+B)=mA+mB$
- Multiplication: $C=A*B$ or $C=AB$; (Note: the inner product of these vectors are equal)
- Division: $C={}^{A}\!/_{B}$; (Note: C =A\B has a significant different meaning in MATLAB)
- **DOT or Scalar product:** $A \bullet B = AB\cos(\theta)$; □= angle between vector *OA* and *OB*
- **CROSS or Vector product:** $A \times B = AB\sin(\theta)$ **u**; **u** a perpendicular vector on a plane constructed by *A* and *B*
- **Magnitude or Length:** $A=\sqrt{x^2+y^2}$

The advantage of using vectors to define the geometry of the navigation network is numerous. It can easily be expanded into multidimensional space for instance a three dimensional space (3-D) is defined by adding the third axis with the resulting *D = [a b c]* and a complete description D = a***i*** + b***j*** + c***k***, ***i***, ***j*** and ***k*** unit vectors in a *x*, *y*, *z* coordinate frame. Grewal [26] is recommended for further reading.

6.4 Appendix B - Detailed results

Details of some of the experimental results are presented:

Table 8: Sample of statistical data for a single node propagation (i.e. Node 2 coordinates are (*x*, *y*)=<2, 0>)

Node1 :x1	c1	c2	c3	c4	c5	c6	c7	c8	c9
10	0.7937	0.9279	0.6288	0.8263	0.8657	1.2052	1.0361	0.9212	1.2052
20	1.0037	0.9832	0.9775	0.9844	0.9750	1.0081	0.9852	1.0031	1.0081
40	0.9768	0.9878	1.0456	1.0112	1.0112	0.9888	1.0492	1.0546	0.9888
50	1.0300	1.0200	1.0100	1.0200	1.0200	0.9850	0.9730	0.9710	0.9850
100	0.9884	0.9886	0.9667	0.9838	0.9842	1.0165	0.9949	0.9935	1.0165
200	0.9993	0.9977	1.0051	1.0017	1.0017	0.9982	1.0035	1.0064	0.9982
400	0.9960	0.9980	1.0000	0.9990	0.9990	1.0000	1.0100	1.0100	1.0000
600	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
800	0.9993	0.9991	0.9999	0.9998	0.9998	1.0002	1.0007	1.0012	1.0002
1000	1.0005	1.0001	0.9981	0.9994	0.9994	1.0006	0.9985	0.9984	1.0006

Node1 :y1	c1	c2	c3	c4	c5	c6	c7	c8	c9
10	0.5343	0.6565	0.7183	0.8648	0.8048	1.0872	0.7476	0.6327	1.0872
20	1.0508	1.0284	0.9728	0.9783	0.9692	1.0145	0.9994	1.0174	1.0145
40	1.0048	1.0164	1.0663	1.0416	1.0450	0.9610	0.9879	0.9933	0.9610
50	1.0100	1.0100	0.9950	0.9890	0.9890	1.0100	1.0300	1.0300	1.0100
100	0.9876	0.9878	0.9702	0.9883	0.9884	1.0117	0.9841	0.9827	1.0117
200	1.0080	1.0064	1.0062	1.0032	1.0032	0.9967	1.0002	1.0031	0.9967
400	0.9960	0.9990	1.0100	1.0000	1.0000	0.9960	0.9970	0.9960	0.9960
600	1.0000	1.0000	1.0000	1.0000	1.0000	0.9990	1.0000	1.0000	0.9990
800	1.0009	1.0007	1.0004	1.0004	1.0003	0.9996	0.9994	0.9999	0.9996
1000	0.9998	0.9994	0.9976	0.9987	0.9987	1.0013	1.0001	0.9999	1.0013

Node2 :x2	c1	c2	c3	c4	c5	c6	c7	c8	c9
10	2.2448	2.3238	2.0329	2.2002	2.3764	1.9778	1.5845	1.5396	1.9778
20	2.1154	2.1369	2.0495	2.1170	2.1983	2.0032	1.9077	1.9000	2.0032
40	2.0276	1.9913	2.1100	2.2593	2.5053	1.9581	2.0106	2.0213	1.9581
50	2.0100	1.9600	2.1000	2.2600	2.5100	1.9500	2.0200	2.0300	1.9500
100	2.0166	2.0153	2.0177	2.0413	2.0769	1.9960	1.9905	1.9907	1.9960
200	2.0006	1.9998	2.0023	2.0052	2.0100	1.9993	2.0006	2.0009	1.9993
400	2.0000	2.0000	2.0000	1.9900	1.9900	2.0000	2.0000	2.0000	2.0000
600	2.0000	2.0000	2.0000	2.0100	2.0100	2.0000	2.0000	2.0000	2.0000
800	2.0049	2.0039	2.0068	2.0169	2.0323	1.9977	1.9965	1.9967	1.9977
1000	1.9943	1.9961	1.9908	1.9780	1.9579	2.0029	2.0028	2.0023	2.0029

Node2 :y2	c1	c2	c3	c4	c5	c6	c7	c8	c9
10	0.0481	-0.1107	-0.0739	-1.2359	-2.6018	0.4391	0.2385	0.1936	0.4391
20	0.0145	-0.0383	-0.0366	-0.3840	-0.7808	0.0957	0.0738	0.0662	0.0957
40	0.0737	0.0706	0.0831	0.1712	0.3475	-0.0418	0.0266	0.0373	-0.0418
50	0.0789	0.0833	0.0976	0.2400	0.4830	-0.0516	0.0183	0.0300	-0.0516
100	0.0095	0.0030	0.0045	-0.0267	-0.0543	0.0066	0.0115	0.0117	0.0066
200	0.0014	0.0014	0.0016	0.0041	0.0085	-0.0013	0.0004	0.0006	-0.0013
400	-0.0013	-0.0017	-0.0017	-0.0081	-0.0178	0.0040	0.0002	-0.0004	0.0040
600	0.0011	0.0002	0.0003	-0.0032	-0.0057	-0.0003	0.0014	0.0016	-0.0003
800	0.0044	0.0024	0.0032	-0.0050	-0.0108	0.0020	0.0041	0.0042	0.0020
1000	-0.0057	-0.0037	-0.0047	0.0014	0.0030	-0.0007	-0.0045	-0.0049	-0.0007

6.5 Appendix C – Notes

6.5.1 Criteria for Ad-Hoc Networks

Optimal Power consumption: The survivability of a node is a direct function of its capability to sustain or replenish its source of power. Portable systems are battery powered and thus need to be managed with the objectives of maximising the usability of the node. Several techniques are used to achieve these objectives. Embedded controller designs have built-in functions that provide for on-chip and peripheral function power management. These features comprise of putting unused functions to sleep and/or in a standby mode only to be awakened when needed. This may pose other problems as it requires faster recovery times, as a prerequisite, thus adding complexity and overheads that may overload the processor functions. Recent technology inventions are the clock-less processors that contributes to reduce power consumption with additional benefits for instance being lesser prone to Electromagnetic Interference (EMI). Typically the power consumption during communication cycles is by far the largest contributing factor and requires very effective data exchange protocols. These issues are discussed in several references titled; Energy-efficient, Energy-aware, Wireless Network Energy Consumption and Real-time portable device power optimisation.

Optimal communications: Effective communication between nodes needs to be considered to optimise the many attributes that describe the communication functions. Some examples of these performance parameters are; to minimize power consumption, to provide a secure link, to control and manage effective data exchange, etc. Wireless networks that use radio or to a lesser extent optical links are being deployed to function as a network with a wide range of protocols and standards that attempt to achieve the required objectives. The wireless links are an extension of the well defined and widely used Ethernet, used to provide mobility to their users. The dynamics and complexity of these wireless links motivated the development of these new standards and protocols.

Node density (Network size and distance between nodes): Ad-hoc and Mesh networks are specific instances of Wireless network applications developed for applications that involve mobility of one or both the receiver and transmitting devices. Although system solutions are emerging many problems are still to be solved before infrastructure less global connectivity becomes a reality. This is made possible with the very latest technology achievements like integrated Systems on a Chip (SoC), advantages in embedded processing power and increased battery capacity/weight ratios. These achievements are driven by the very demanding consumer market with an abundance supply of product options for handheld and mobile applications (i.e. Laptops, Cell phones and PDA's). Future trends plan too interconnect portable and handheld devices using ad-hoc or meshed networks by combining the Wi-Fi (IEEE-802.xx) [36] and 3G (ETSE-3GPP) [15] connectivity standards. It is expected that the recommendations by the 4G standard working groups will opt for interoperability issues by merging standards for cell phone and wireless technologies.

It is apparent that the preferred solution for mobile network connectivity should be a distributed control option. It would be difficult, if not impossible to manage network dynamics and to control the network size based on requirements for node density and subsequent distance between nodes from a centralised base station. Several protocols (MAC), network concepts (MANET) and the proposed internet addressing scheme (IPv6) are being investigated and/or developed to address problem areas such as network handover methods, hidden nodes, unlimited growth of the network, the tracking of users and reliable connectivity....

Reliability: The reliability of network connections in a non-static environment is numerous. The typical Figures of Merit (FoM), being Quality of Services (QoS), Data latency, Bandwidth, Connectivity, Error rate etc., have an impact on reliable data transfer. Obviously all the reliability requirements depend on the application itself, and are driven by the cost effective tradeoffs of a specific solution. For example, the delivery of a short message does not have any specific latency requirements (data can be delivered within reasonable time) as opposed to voice communications that require real-time data delivery. Short messages may even tolerate some margin of error as the receiver (person) only needs to understand the message for ordinary day-to-day information exchanges between two parties to successfully occur. A total different scenario is defined if this same messaging service is utilized for an E911 emergency call. To meet the objectives for this emergency service the reliability, availability and latency requirements for delivering the navigation and related data message is much higher. Although it depends on the application this study assumes that the figures merit (i.e. reliability, latency, availability, etc.) falls somewhere in between the examples mentioned above.

Redundancy: A high value for redundancy of the network nodes is expected for network navigation applications to function properly. The proposed algorithm requires that nodes are widely distributed or scattered over the area of interest. For the proposed algorithm to function effectively a minimum of 4 nodes need to be visible at all times. Although the accuracy of node positioning can be improved when more nodes are used in the calculation this study did not expand on this aspect. The proposed Network navigation concept explores these multiple nodes, seen as clusters, to optimise the positional accuracy of each of the nodes. Depending on the type of system and the environment these nodes can be static or dynamic. Wireless networks in urban environments are fairly common and mostly static. Rural areas may require that nets are purposefully deployed when the need arises for navigation leading to a concept referred to as scatter nets.

Robustness: Robustness includes several aspects of network design. Broadly defined this imply to what extent the accuracy of a specific node can be kept within predefined boundaries. This is to be achieved irrespective of changing conditions. An assessment of all the factors and the corresponding sensitivity when these factors change needs to be properly modelled. Both the influence on node accuracy and the behavioural aspects need to be understood.

Deploy-ability: Issues related to the deployment of proposed solutions needs to consider both the environment and users. Commercial applications demand high bandwidth and connectivity in densely populated areas. Military and emergency services do not always have the luxury of a supporting infrastructure and need to be able to deploy or setup such a system with ease. The lower costs of using the public and scientific frequency bands leads to overexploitation and eventually more interference as more and more users are making use of these so called “free bands”.

Technology: Selecting a specific type of technology to implement a concept design or to realize the application in hardware or software, one needs to consider the maturity of that specific technology.

Application and mission: The intended application or mission of the proposed solution puts constraints on the design. Any system needs to consider practicality and performance within these constraints.

7 REFERENCES

1 Akyildiz Ian F. and Wang Xudong; *A Survey on Wireless Mesh Networks*; IEEE Radio communications, September 2005, p525-530

2 ditto

3 Akyildiz, Ian F.; Su, Weilian; Sankarasubramaniam, Yogesh; CayirciA, Erdal; *Survey on Sensor Networks*; IEEE Communications magazine; Aug 2002

4 Anonymous; *How the Birds and the bees (and the Ants and moths and the turtles) Find Their Way*; ION Newsletter; 17(1), Spring 2007, p1

5 Beutel, Jan; *Geolocation in a PicoRadio Environment*; Diploma Thesis Department of Electrical Engineering ETH Zürich, UC Berkeley, 2000

6 ditto

7 Blazevic, Lj.; Giordano S. and Le Boudec J. Y.; *Self-Organizing Wide-Area routing;* SCI 2000/ISAS 2000;Orlando; July 2000.

8 Capkun Srdjan, Hamdi Maher, and Hubaux Jean-Pierre; *GPS-free positioning in mobile ad hoc networks*;

9 Chen, Wenli; Jain, Nitin and Singh, Suresh; *ANMP: Ad Hoc Network Management Protocol*; IEEE Journal on Selected Areas in Communications; 17(8); August 1999

10 ditto

11 ditto

12 Collett, Thomas S. and Graham, Paul; *Animal Navigation: Path integration, Visual Landmarks and Cognitive Maps*; Current Biology; 14; June 22, 2004; p475.

13 Diddams, S.A.; Bergquist, J.C.; Jefferts, S.R. and Oates, C.W.; Standards of Time and Frequency at the Outset of the 21st Century; Science 19 November 2004: Vol. 306. no. 5700, 1318–1324

14 Diggelen van, F. and Abraham, C.; *Coarse-Time AGPS; Computing TOW From Pseudorange Measurements, and the Effect on HDOP*; Global Locate, Inc.; GNSS2007

15 ETSI 3GPP standards, www.etsi.org, or www.3gpp.org

16 Farrell Jay A. and Barth Matthew; *The Global Positioning System & Inertial Navigation*; MacGraw Hill, NY, 1998, p14

17 ditto, p171

18 ditto, p21-25

19 Ford Tom, Hamilton Jason, Bobye Mike and Day Dr. Laurence; *GPS / MEMS inertial integration methodology and results*; Novatel; 2004.

20 Gieck; K. and GieckR.; *A collection of technical formulae*; Gieck-Verlag, WG, 7th ed.; 1990, g55

21 Gould, James L.; *Animal Navigation: Northern Exposure*; Current Biology; 15(17); September 6; 2005; p653.

22 *GPS III Faucet Opened*; GPS world; magazine; Jan 2007, p18

23 GPS world; GNSS Accuracy, Lies, Damn Lies, and Statistics; Jan 2007, p26 (www.gpsworld.com)

24 Greenspan Richard L., *Inertial Navigation Technology from 1970-1995*; April 1995; p182

25 Grewal Mohinder S., Weill Lawrence R., Andrews Angus P.; *Global Positioning Systems, Inertial Navigation, and Integration*; John Wiley & Sons, NY, 2001, p162

26 ditto, p296

27 ditto, p328-345

28 ditto, p1

29 ditto, p265

30 ditto, p252

31 Guo J., Wang W. and Chao B.; *A New GNSS Software Receiver Signal Acquisition Method Research Based on Ambiguity Function*; Wuhan University, China; GNSS2007

32 Hasik, J. and Rip, M.; *Military Applications of the Galileo Global Navigation Satellite System* ; Michigan State University; GNSS2007

34 Hodgart, M.S.; Blunt, P.D. and Unwin, M.; *The Optimal Dual Estimate Solution for Robust Tracking of Binary Offset Carrier (BOC) Modulation* ; University of Surrey; U.K.; GNSS2007

35 Hou Ting-Chao and Li Victor O.K.; *Transmission Range Control in Multihop Packet Radio Networks*; IEEE transactions on communications; COM-34(1), January 1986,p38-44

36 IEEE 802 LAN/WAN Standards Committee; www.ieee802.org or http://standards.ieee.org/getieee802/

37 Jordt Gustav Julio ; *Evaluation of energy costs and error performance of range-aware anchor-free localization algorithms for wireless sensor networks*, Thesis, AFIT, March 2006

38 Ko Y.B. and Vaidya N.H., *Location aided routing (LAR) in mobile ad-hoc networks*, MOBICOM, 1998.

39 Kocaman Sultan; *GPS and INS integration with Kalman filtering for direct georeferencing of airborne imagery*; Institute of Geodesy and Photogrammetry; ETH Zurich; 2003

40 Langendon Koen and Reijers Niels; *Distributed localization in sensor networks: a quantitative comparison*; Computer Networks 43; Elsevier 2003; p499-518

41 ditto, p504

42 ditto, p499-518

43 Lee Myung J., Zheng Jianliang, Ko Young-Bae, Man Shrestha Deepesh; *Emerging Standards For Wireless Mesh Technology*; IEEE Wireless Communications, April 2006

44 Lin, Chunhung Richard and Liu, Jain-Shing; *QoS Routing in Ad Hoc Wireless Networks*; IEEE Journal on Selected Areas in Communications, Vol.17,No. 8, August 1999

45 MATLAB user manual, 2005

46 Mattos, P.; *Indoor Galileo Receivers - Sensitivity, Pilot Signals, Secondary Codes*; ST Microelectronics R&D Ltd.; U.K.; GNSS2007

47 McHenry Michael, Cheng Yang and Matthies Larry; *Vision-based localization in urban environments*; Unmanned Ground Vehicle Technology VII; SPIE, Bellingham, WA, 2005.

48 Murthy C. Siva Ram and Manoj B.S.; *Ad-Hoc Wireless Networks, Architectures and Protocols*; Prentice Hall; 2004; p155

49 ditto, p191

50 ditto, p755

50 Pagès-Zamora, Alba; Vidal Josep and Brooks, Dana H.; *Closed-form Solution for positioning based on Angle of Arrival measurements*; PIMRC; IEEE; 2002

51 Park, 'Kyung Su, Cho Dong Ho, Cho Cheol Hye, and Lee Hun; *Performance Analysis of the Network Management Protocol in the CDMA PCS Network*; IEEE Network, 2001

52 Wolf, Paul R. and Ghilani, Charles D.; "Adjustment Computations, Statistics and Least Squares in Surveying and GIS", p.357

53 Perkins C.E. and Royer E.M.; *Ad-hoc On-Demand Distance Vector Routing*; 1998

54 ditto

55 Read, Roger; Graham, Ron; *Manual of Aerial Survey: Primary Data Acquisition*, p.24.

56 Seah Winston K.G., Zheng Hwee-Xian Tan and Ang Liu Marcelo H., Jr.; *Multiple-UUV approach for enhancing connectivity in underwater Ad-hoc Sensor Networks*, University of Singapore; 2005

57 Tsai Tzu-Jane, Tseng Hsueh-Wen and Pang Ai-Chun; *A New MAC Protocol for Wi-Fi Mesh Networks*; 1550-445X/06; IEEE AINA'06 proceedings; 2006

58 W. John Smit; "Animal Cognition in Nature, Cognitive Implications of an Information-sharing Model of Animal Communication", p227, Academia Press; 1998.

59 ditto, p231 and p241

60 Wiltschko Wolfgang and Wiltschko Roswitha; *Varying Views of Animal and Human Cognition, The Navigation of Birds and its Development* ; Academic Press;1998; p155

61 Wolf; Paul R.; and Ghilani, Charles D.; "Adjustment Computations, Statistics and Least Squares in Surveying and GIS", p2-7

62 ditto, p8

63 ditto, p250

64 Wong, C.M.; Messier, G.G.; and Klukas, R.; *Evaluating Measurement-Based AOA Indoor Location using WLAN Infrastructure*; GNSS2007

65 www.automow.com

66 www.automow.com

67 www.darpa.mil/grandecahallenge

68 www.darpa.mil/grandecahallenge

69 www.dust-inc.com/products

70 www.gpsworld.com

71 www.tinynode.com/index.php?id=99

72 www.wikipedia.org

73 www.xbow.com

74 www.zigbee.org/en/about/members.asp, 21 Nov. 07