1 Introduction

Location is becoming an important and integral part of our everyday lives, spurred on by the widespread, almost ubiquitous, availability of GPS (Global Positioning by Satellite) technology in everyday consumer devices such as car navigation systems, mobile phones and cameras, and the increasing adoption of inertial sensors, particularly accelerometers and magnetometers in everyday products. In order to set the context, this book first looks at coordinate systems and what is meant by position or location and how to describe this information [Chapter 2].

Because of the importance of GPS, the next topic covered is global navigation satellite systems (GNSS) [Chapter 3]. The ability to determine the precise location of a device anywhere in the world is in turn leading to the emergence of many different Location-Based Services promoted by leading global companies such as Google with Google Maps and Latitude, Nokia, Microsoft, AOL and community initiatives such as OpenStreetMap.

However, despite the hype surrounding GPS it is not the only positioning technology available and indeed there are many applications for which it doesn't offer the required capability or performance. This book is intended to give a clear understanding of the different options available for locating and positioning systems with an emphasis on their real-world capabilities and applications. The next chapter [Chapter 4] covers the most important methods for determining position using radio signals, then Chapter 5 covers inertial navigation techniques and Chapter 6 looks at other methods of locating and positioning things. Chapter 7 deals with accuracy and performance and what they mean, as well as some of the fundamental techniques relating to location and position. Of course things never go entirely as planned, so Chapter 8 considers errors and failures and how to deal with them.

Having looked at the different technologies, architectures, systems and solutions available the book rounds off this essential foundation with a discussion of selected applications [Chapter 9], followed by a quick look at emerging opportunities and future challenges [Chapter 10].

1.1 A brief historical perspective

This book is intended to provide the essential things you need to know about locating and positioning technology and applications today. This chapter includes an overview of the different methods, techniques and technologies used for determining location, but it is not intended as a treatise of the history of navigation. There are several good books that describe the history of navigation and, despite being primarily a broad text about Global Positioning Systems, Samama [1] gives an excellent historical overview that could be a good place to start for many readers interested in the historical aspects of modern positioning technology.

1.2 What is meant by location or positioning?

The terms Location and Position are sometimes used interchangeably. For example we refer to the Global Positioning System (GPS), but we talk about Location-Based Services (LBS). The locations used in the latter are very often GPS positions.

However, location and position require more than just an X,Y,Z point in space or a latitude and longitude: time, velocity, orientation and other parameters describing the point may also be relevant. In this book we will sometimes use the terms Location and Position interchangeably; this simply reflects that they are to a large degree synonyms. Being pedantic we interpret Location as usually referring to a geographic position, often best described as a latitude, longitude and optionally height. On the other hand a position is more generic and may describe relative position and orientation of objects, not necessarily using the global coordinate system of latitude and longitude, and usually including time and often direction information.

The basic measure of a position or location is its place in space, typically described using Cartesian coordinates (X,Y,Z), or latitude, longitude and altitude. A detailed look at coordinate systems is presented in Chapter 2.

Since positions are transient, the basic position information is usually associated with a time at which it is valid.

However, positioning an object is often only complete if we also know its orientation – for example the direction one is facing.

Therefore to fully describe the position of an object in 3D one ideally needs at least seven parameters: three position, three orientation and time.

It is also often advantageous to include some of the derivatives of the basic positional measures, in particular velocity. Velocity can be described as a Cartesian vector or alternatively as a speed and direction. In either case three parameters are needed to fully describe velocity in 3D. Sometimes the derivatives of orientation being rate of rotation can be useful and similarly the second derivatives of position – acceleration. These are particularly useful when looking at inertial navigation techniques and for dynamic modelling of an object's motion. More detailed descriptions of inertial techniques will be covered in Chapter 5.

1.3 Describing a position

There are many different ways of describing the position of an object, depending on how the information is to be used.

In a navigation context the location of an object is usually described using latitude, longitude and height based on a suitable coordinate system. This method was invented by mariners for navigation at sea in order to know where they were located in a global context. It is the format generally used by GPS receivers today – they usually provide an output in latitude, longitude and height which defines a unique location relative to the planet as whole, although this is not the coordinate system used for carrying out the GPS position calculations. Chapter 2 provides an in-depth description of global coordinate systems and some of the intricacies involved in using them.

For our day-to-day activities a latitude and longitude is often not very helpful. As humans we usually use position information in a contextual manner. For example:

- I am at work
- I'm in the car

- I'm driving down the A1 and expect to arrive in about 20 minutes
- I'm sitting on the sofa watching television
- I'm with my mother
- The shipment is in our warehouse
- I'm wearing my glasses
- He's in 3rd place, 4 seconds behind John who's leading the race

The interesting thing about all of these examples is that the positional interest is in the relationship between two or more people and/or objects. With reference to Figure 1.1 one could measure the precise latitude, longitude and height of the sofa, the television set and me separately and from this compute the relationships to infer that I was sitting watching television. However, it is a very clumsy (or sophisticated) way of solving the problem, especially as you also need to know that I'm sitting, awake and facing the TV!

The other thing to notice is that in many of the examples above the position information is imprecise and it is the context within which the information is interpreted that matters.

1.4 Location as a context for applications

Whilst sea navigation and some scientific uses of location do require latitude and longitude, many of our day-to-day requirements for position information don't, and as we have seen the value to applications is the context in which the position information is interpreted.

Figure 1.1 Position is about the context

For example if an application requires to know that I am in my car – for example to modify the behaviour and services offered by my mobile phone – it could measure the position of the car and me, compare them and act accordingly. For this the positioning technology would need to work wherever the car goes, including tunnels, multi-storey car parks etc., and it would have to be sufficiently accurate; a non-trivial task. Alternatively a simple proximity detector that works over a few feet and detects when I am sitting in the car could do the same thing more reliably and cheaper.

A system for monitoring the wellbeing and activity level of someone recuperating from an accident is largely unconcerned about exactly where they are, but it is important to keep track of how far and how quickly they've walked, how long they spent sitting down, lying down or standing along with other clinical measurements.

Most of our daily activities involve some aspect of location and position and those applications that make the best use of this information to inform the context and behaviour of the application are likely to be the ones that turn out to be the most useful. Putting it another way – the use of location and position information is a very good way of improving the relevance of the information presented to us by the devices and technology we use in our daily lives.

1.5 Techniques for determining the position of an object

There are many different ways of determining location, so to set the scene this section provides a short description of the different approaches that may be used. The rest of this book focusses on those methods based on the use of modern technology, but references to information about the other techniques is included to allow the reader to widen the scope of their study should they wish.

1.5.1 Observations of the natural world

Using only observations of the natural world it is possible to find one's way using clues from plants, animals, weather, sea, Sun, Moon, stars and nature in general. These techniques are usually imprecise in comparison to modern technological solutions, and very often they rely on direction vectors rather than absolute positions. For those readers wishing to find out more about natural navigation or wayfinding, *The Natural Navigator* [2] [3], is a good starting point.

In a very simple piece of technology, the magnetic compass, we have one of the oldest and most basic instruments for navigation. It is generally believed that the magnetic compass was discovered in China around 200 BC, with very early references to the possible use of magnetic fields for direction finding as far back as 2643 BC.[1] In 1190 Alexander Nekam wrote of sailors using the compass to aid with navigation. One of the earliest descriptions of the principle of operation and construction of the magnetic compass is set out in a letter written by Peter Perigrinus in 1269. Mottelay [4] provides an interesting historical treatise for those interested in reading more of the historical background.

A compass is an instrument that is able to measure and display the direction of the Earth's magnetic field at the point of observation. It is based on the principle that the Earth is like a large magnet and is surrounded by a magnetic field in which the poles of the magnet are located near to (but not coincident with) the poles of the axis about which it rotates. Therefore the direction indicated by the compass, 'magnetic north', differs from the direction of 'true north'. The difference is known as the 'magnetic declination' being positive when magnetic north is east of true north and negative when west of true north. Since the magnetic poles are not co-located with the polar axis of the Earth, the value of the magnetic declination varies depending on one's geographical location. Furthermore the position of the magnetic poles varies with time and this can introduce changes that may drift by several degrees per century. A global spherical harmonic model of the Earth's magnetic field known as the IGRF (International Geomagnetic Reference Field) is maintained under the auspices of the IAGA (International Association of Geomagnetism and Aeronomy). For more detailed information about the Earth's magnetic field a comprehensive starting point is [5].

[1] Historians do not believe that there is conclusive evidence of the use of magnetism at this time, although accounts indicate the use of tools that might have made use of magnetism.

Since the Earth's magnetic field is relatively weak it is affected by local variations caused by the presence of magnetic materials, including iron and iron alloys, and electromagnetic fields from electrical machines. This can lead to large local variations. For example using a compass inside a car, which is predominantly built from steel, is notoriously unreliable. Nevertheless, the magnetic compass is still a valuable tool for navigators today, especially considering that modern sensors for measuring magnetic fields, magnetometers, are cheap, accurate and require very little power to operate.

It is interesting to note that most of these natural observation techniques lead to an indication of direction rather than a definitive geographical position. Therefore they need to be linked with observations of specific points, typically geographic features, in order to be useful. The relevance and usefulness of direction and orientation when coupled to a geographic position is an essential part of the art of navigating, locating and positioning and we will return to this theme throughout the book.

1.5.2 Celestial observations

Astronavigation is the art and science of navigation using observations of the Sun, Moon, stars, planets and other celestial bodies. It is one of the oldest practices in human history. Typically navigators use observations of the Sun, Moon or one or more of the navigational stars listed in the nautical almanac.

Polaris, often called the North Star, is one of the best known navigation stars. It lies in a due north direction being less than one degree from the celestial north pole. It is only visible in the northern hemisphere. In the southern hemisphere the Southern Cross constellation is a group of stars that with a simple geometric construction, as illustrated in Figure 1.2, can be used to indicate a true south direction to an accuracy of about 5 degrees.

By making careful observations of the angle between a celestial body and the horizon, or other celestial bodies, and a knowledge of time, it is

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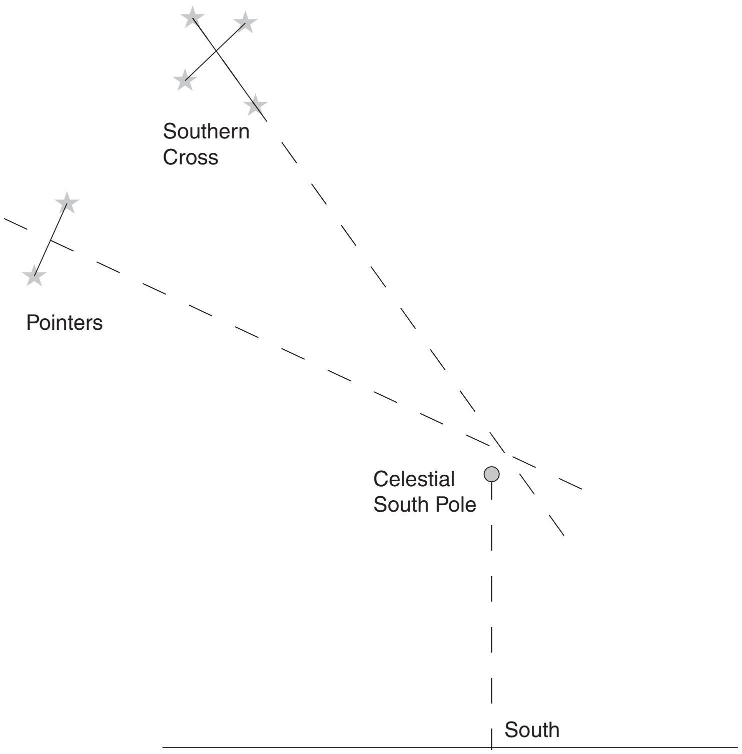

Figure 1.2 Finding South using the Southern Cross and pointers

possible to compute the geographic position of the observer on the surface of the Earth. The sextant has long been the instrument used by sailors to determine their positions at sea. It provides an accurate measurement of the angle between two objects by sighting both simultaneously. An excellent general reference for navigation including a chapter on the sextant is Bowditch [6] [7].

For more in-depth information about celestial navigation, the reader is referred to Karl [8], though there are many books on the subject. No further references will be made to celestial navigation in this book.

The role of time, and having an accurate clock was one of the technological limitations that plagued early navigators. Sobel [9] provides an interesting and absorbing read about John Harrison and his lifetime spent developing precision mechanical clocks in the eighteenth century, and the role they played in ocean navigation. Time is an absolutely crucial element of many navigation techniques, and the use and role of time will also be a recurring theme throughout this book.

1.5.3 Using radio signals

There are numerous systems and techniques for using radio signals to aid in the determination of the position of an object. They can be broadly divided in three classifications:

1. Direction finding;
2. Range measurement, generally using Time of Flight, Time of Arrival, Time Difference of Arrival, signal strength or other characteristics of the radio signal;
3. Velocity measurement, generally based on the principles of Doppler shift.

The earliest systems used direction finding by rotating the antenna to find the strongest signal and hence the direction. These techniques are still used in simple tracking systems such as many used in conservation for wild animal tracking.

Later the principle of a transmitted signal received at two different locations, or two different synchronised transmitters received at one location was used to determine the difference between the times of arrival of the two signals and this led to the category of hyperbolic systems, which given two pairs of signals are able to determine a unique position (two-dimensional) for the transmitter or receiver. One of the earliest such systems was DECCA. A more recent example of such a system is LORAN, which operated until 2010.

The same techniques, with some adaptation, can make use of public signals, such as those from mobile cellular network base stations, or signals transmitted by TV and radio broadcast transmitters.

GPS is another system that uses radio signals, this time transmitted by a constellation of satellites orbiting the Earth. A GPS receiver measures the times of arrival of signals from multiple satellites in order to determine the position of the receiver. It may also measure and make use of signal Dopplers to determine velocity.

Whilst most modern systems rely on an infrastructure of either transmitters or receivers at known locations in order to track the position of a mobile object, there is significant effort going into the development of new architectures for collaborative positioning in which measurements between mobile devices can be used to determine their relative positions without recourse to fixed infrastructure.

A large part of this book will be devoted to more detailed description and analysis of modern locating and positioning systems using radio signals. For information about the history of radio locating systems, or for information about historical systems, the reader is referred to some of the excellent reference works on the subject.

1.5.4 Inertial techniques

According to Newton's first law of motion: '*Every body remains in a state of rest or uniform motion (constant velocity) unless it is acted upon by an external unbalanced force. This means that in the absence of a non-zero net force, the centre of mass of a body either remains at rest, or moves at a constant speed in a straight line*.' Inertia is the property of a body that links force with mass and change of velocity and is the physical basis for inertial navigation.

An inertial coordinate frame is one in which Newton's laws of motion hold true: they are neither rotating nor accelerating. This is usually not the same as a navigation coordinate system which may be fixed to the surface of the Earth – which is rotating and translating. Chapter 2 introduces coordinate systems and explains how they can be related to one another.

Inertial navigation is the principle of using sensors to measure changes in the equilibrium state of Newton's laws of motion and using the measurements to compute the new position (including velocity, acceleration and attitude) of the body within a coordinate system at a later date. The main sensors used for inertial navigation are: accelerometers and rate gyroscopes.