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"Teaching the Global Positioning System Principles and Applications"

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Abstract

We live in one dimension of time and three dimensions of space as defined by the rotating and revolving spaceship which is our earth. Only recently have humans had accurate, affordable and portable instruments to measure time. During the last decade we suddenly have such an instrument to measure where we are in three dimensions of space.

The satellite and atomic clock based Global Positioning System is a technological marvel that has and will continue to change our lives in more ways than realized. There is a large proliferation of uses such as by the military for targeting and navigation, civilian uses in surveying and traffic monitoring and hobbyists for hiking and treasure hunts.

The author has found that there are large numbers of early adapters who are highly excited about the applications and accuracy. However, there are relatively few who appreciate and understand how it works and the marvelous convergence of aerospace, microwave, computer, mathematical and atomic clock technologies that have made the system possible.

Accordingly, the Global Positioning System should be introduced in various ways into engineering education. While the application is now well established in courses such as surveying, the author knows of no courses that have been developed to teach about the principles of operation.

Thus, the author has been introducing the principles behind the operation in various courses ranging from freshman engineering to a graduate course in Engineering Analysis. He has also been offering GPS related lectures during Engineer's Week programs. This paper will present some GPS related instruction that has been used. It also offers some ideas for further curriculum development to make students and engineers more familiar with this new marvel and additional possibilities.

1. Introduction

The Global Positioning System has suddenly become a vital part of our civilization. It was only a decade ago that it became operational. Most people including engineering students were not aware that it existed. Ten years later it is a pervasive and a vital part of our lives.

We can now buy low price clocks and wrist watches that are set by a radio signal from the same atomic clock in Boulder, Colorado that provides the reference for the Global Positioning System. In the near future the standard wrist wore instrument should provide a measurement of our coordinates as well as time.

While most people including engineering students are now familiar with the expanding applications of the GPS, remarkably few have the fundamental understanding of the amazing convergence of space, atomic clock, microwave, process computers and efficient problem solving algorithms technologies and sciences that have made the system possible.

This paper will discuss how some of the GPS related concepts that have been introduced into various courses taught by the author, along with National Engineer's Week lectures over the last few years. Additional descriptions and applications are contained in the "Where on Earth?" article by the author which was the cover story on the July, 2002 issue of Mechanical Engineering (Reference 1).

2. Defining the Navigation Problem

Navigation means getting from where you are to where you want to be. We start our daily travel from home to work by first knowing where we are and from experience we have a mental view of where we are going and the possible routes from here to there.

Alternatively, if you go into a strange shopping mall and want to go to Walden Books you first look for the directory and layout map of the mall. It shows all the stores that are possible destinations and the corridors which are potential routes. However, the crucial information you need before proceeding is that arrow on the map that says "you are here".

There is only one answer to "Where you are". It is a unique point in space and time. Thus, it is a closed ended problem. "Where you are going" is an open ended problem. It might be your intended Walden Books or it might be any other store or destination. The routes are also an open ended problem.

The fundamental problem the GPS solves for by using secondary calculations from a constellation of artificial satellites is the closed ended problem of "where you are". There is only one answer. The additional problem of destinations and routes is open ended. There is no limit to the number and types of destinations and routes. A GPS receiver in the car might interface with an open ended data base of roads, towns, hotels, and restaurants. A GPS for aviation should interface with a data base of airports and the corresponding classes of air space. A GPS on a boat should interface with a data base of shorelines, depth, favorite fishing spots and marinas.

3. The Concept of Space and Time

Everything exists at a unique point in three dimensions of space and one dimension of time. The rotating sphere that is our earth defines our time and space. The rotation and revolution of position of the sun defines time. The spatial coordinate system is latitude which is defined by the equator and polar axis, longitude which has been arbitrarily defined relative to Greenwich Observatory on the outskirts of London and elevation relative to sea level define our three dimensions of space.

Only recently has our species had an accurate and affordable instrument to measure time. Time measuring instruments have progressed from hour glasses and sundials to mechanical clocks with pendulums and gears. The frequency is established by the pendulum. The gears integrate pendulum cycles per second into cumulative pendulum cycles that are displayed as time in seconds, minutes and hours.

Pendulums were replaced by spring loaded oscillating flywheels for compactness and resulted in a time measuring instrument that people could carry on their person. It also made it possible to design an accurate clock for shipboard navigation, which was achieved by two generations of John Harrison's family in England in the 1700s. Latitude in the northern hemisphere can be obtained by the angle to the north or pole star. Longitude requires comparing local time of star positions versus the star positions as a function of time at a reference longitude such as the Greenwich Observatory.

Mechanical vibration was then replaced by the natural electrical frequency in a quartz crystal, which has been cheaper lighter and more accurate than a mechanical oscillation based clock. With the advent of ultra high frequency radio receiver technology in the 1930s the Noble Prize winning physicist Isadore Rabi suggested that atoms are radio wave transmitters and that a receiver could be tuned to measure atomic vibrations.

The resulting atomic clock uses the 9,192,631,770 natural frequency of the cesium atom for a pendulum, with an error of less than a second per million years. The mechanical based measurement of distance has been replaced by 30.66336583 vibrations of the cesium atom. This is the number of vibrations during the time that light travels one meter in a vacuum. The ultrahigh accuracy atomic clock is a vital enabling technology for the GPS.

4. Triangulation vs Ranging Techniques

Triangulation and Ranging are the two techniques that are used to establish a position relative to beacons at known locations. The popular press often describes GPS as triangulating on satellite signals. This is not true. The GPS is based on ranging.

Triangulation is performed by measuring the angle relative to north to two beacons of known position. Your location is determined by drawing lines at this angle through each beacon. The intersection is your location. If the direction north is not known a third beacon is required. A knowledge of time is not required for triangulation.

Ranging is based upon the measurement of distance from beacons of known location. The GPS is based on ranging. The satellites are the beacons. The distance is the product of the speed of light the time after transmission by the satellite that the signal is received. This distance defines a sphere around each beacon. If the receiver has a perfect clock, the receiver position is an intersection point of two circles in two dimensions or the intersection point three spheres in three dimensions.

However, the beacons have virtually perfect atomic clocks, but the receiver has a quartz clock that can have some error. Thus, the receiver requires four beacons to define four equations and four unknowns which are xr, yr, zr ant t error, from the know data of xa, ya, za, and t measured for the "a" beacon. The "a" beacon equation is based on the law of right triangles and is given by equation 1.

$$(xa-xr)^2+ (ya-yr)^2+(za-zr)^2= (c*(t\ measured + t\ error))^2 \qquad (1)$$

Identical equations are developed from measurements relative to the "b", "c" and "d" beacons. The resulting four equations are solved for the four unknowns of the xr, yr, zr and t error of the receiver.

The mathematical challenge is the development of an algorithm that can rapidly converge on the solution. It requires an initial trial solution. This is either input to a new receiver or is based on the last location of the used receiver. The author assigns students to develop a solution for this problem of intersecting spheres in a graduate level Engineering Analysis course.

5. Air Navigation and Traffic Control and Pilotless Aircraft

Radio based radio navigation system have evolved from homing on a single beacon to triangulation with multiple beacons to LORAN which was a ground based ranging system with limited coverage to the satellite based GPS with continuous worldwide coverage. Air traffic control has been radar based starting with passive reflection to active transponders that respond to a radar signal with a signal of identification and altitude.

The GPS has made all prior navigation systems obsolete. It should also make air traffic control radar obsolete. Australia has installed GPS based air traffic control. It will be more difficult but ultimately doable in the United States with the much larger system to convert. The GPS has enabled the radio control of unmanned aircraft are rapidly replacing pilots for many military surveillance and attack applications.

6. Conclusions

Applications of the GPS have gone far beyond the original purpose of allowing soldier to know their positions on a battlefield. It is expected to be a $40 billion industry by 2006 and continue to grow. This indicates a large number of GPS related engineeirng opportunities. Our educational challenge is how best to incorporate GPS into the curriculum that will produce these engineers of the future.

Reference

1. Frank Wicks, "Where on Earth?", ASME Membership Publication, Mechanical Engineering, pp 34-37, July, 2002.

Professor Frank Wicks is a member of the Mechanical Engineering Department at Union College and a GPS using aircraft pilot. He is also a Professional Engineer in New York State. He holds a B.Marine.E from New York Maritime College, a MSEE from Union College and a PhD in Nuclear Engineering and Science from Rensselaer. He has served as an engineering officer on navy and merchant marine ships, an engineer for general Electric and a member of the Nuclear Engineering Department at Rensselaer.