Using Spread-Spectrum Ranging Techniques for Position Tracking in a Virtual Environment

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Abstract

This paper proposes a radio frequency position tracking system for a virtual environment utilizing spread-spectrum (SS) communication technology. The system utilizes two unique characteristics of spread-spectrum technology that are important to position tracking in a virtual environment: code division multiple access (CDMA) and precision ranging. These characteristics allow multiple transmitter-receiver pairs and position accuracies in the millimeter range. Triangulation techniques used by the Global Position System (GPS) are also examined in relation to position tracking in a virtual environment. Finally, the paper ties both of these technologies together and describes an example spread-spectrum position tracking system for virtual environments.

Introduction

Position tracking in a virtual environment (VE) can be performed by a number of methods. Existing systems employ mechanical, magnetic, optical, acoustic or inertial sensors to track the position of the body, arm, and hand movements. Each method has varying degrees of accuracy, resolution, sampling rate, latency, range, workspace, cost, encumbrance, convenience, susceptibility to obscuration, ease of calibration, number of simultaneous measurements, and orientation versus position tracking. A survey of requirements and research needs in the area of position tracking and mapping are given in [NRC95]. Each position tracking method has certain advantages and disadvantages, but one goal is clear: the researcher needs to accurately track the limbs of a person in a virtual environment at reasonable costs.

This paper proposes a position tracking system that is performed by radio frequency (RF) devices. Radio frequency devices have unique characteristics with both advantages and disadvantages. Some advantages important to position tracking are that radio frequencies can penetrate objects, walls and the human body. They are resistant to masking (hiding), easy to construct, and are scaleable to both large and small areas. However there are several undesirable characteristics that radio frequency devices have over other position

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tracking methods. Government regulations restrict or license the use of many frequency bands available to transmitting devices. Transmitting devices have the potential of causing interference with other electronic equipment and receivers. In a closed environment, radio frequency device performance can be severely degraded due to reflections off surfaces, metallic and non-metallic, and is subject to attenuation when passing through objects. Computing devices in close proximity of the radio frequency devices can cause interference with the receivers. These are issues that have to be dealt with in designing a radio frequency position tracking system for a virtual environment (Figure 1).

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1. Transmitting devices are regulated by government agencies.
2. Frequency allocations are limited.
3. RF exposure limits (ANSI/IEEE C95.1-1991).
4. Reflections and absorption by surfaces and objects.
5. Interference by occluding objects.

Figure 1. Potential problems using radio frequencies in a VE

This paper proposes a method of position tracking that uses spread-spectrum (SS) communications technology. Spread-spectrum communications were first used in the 1950's as a reliable means of communications that exhibits unique characteristics not found in conventional means of communications. Some of these characteristics are anti-jamming, high processing gain and low probability of intercept. Spread-spectrum communications exhibit two important characteristics important to obtaining a position in a virtual environment. The first is excellent ranging ability which allows accurate measurement of distance between two points. The second is code division multiplexing (CDM) which allows multiple transmitter-receiver pairs to compatibly share the same frequency at the same time, thus allowing for several position sensors to be used on the body and on multiple individuals.

To address how radio frequencies can be used for position tracking in a VE, the reader needs to have an understanding of radio communications technology. This is because it is closely related to the radio frequency position tracking method that is described in this paper. The description of how radio frequency communications are employed is used as a vehicle to describe to the reader how certain concepts such as Frequency Division Multiple Access (FDMA) and range determination are performed. This is not to train the reader to become a communications engineer, but the discussion uses familiar metaphors that will guide the non-communications engineer to understanding the techniques that are described in the last section that directly relate to position tracking in a virtual environment.

In order to explain the technical details of how spread-spectrum can be used in a virtual environment, this paper presents a brief tutorial on conventional and spread-spectrum com-

munications. Next, the paper describes the Global Positioning System (GPS) and how it uses a constellation of satellites in orbit around the earth to communicate with low cost ground receivers to determine the users position (latitude, longitude, altitude) and time. GPS is significant in this context because the techniques we describe for tracking the human are similar. The last section then combines preceding concepts and describes a novel approach of using spread-spectrum technology for position tracking in a VE.

Conventional Communications

Conventional narrowband radio frequency (RF) communications employ a modulation technique (such as Amplitude Modulation (AM) or Frequency Modulation (FM)) to superimpose the intelligence of a signal, (e.g. music or voice) over a transmitted radio frequency carrier. A receiver is tuned to the carrier frequency, demodulates the signal and produces the message that is being broadcast to the listener (see Figure 2).
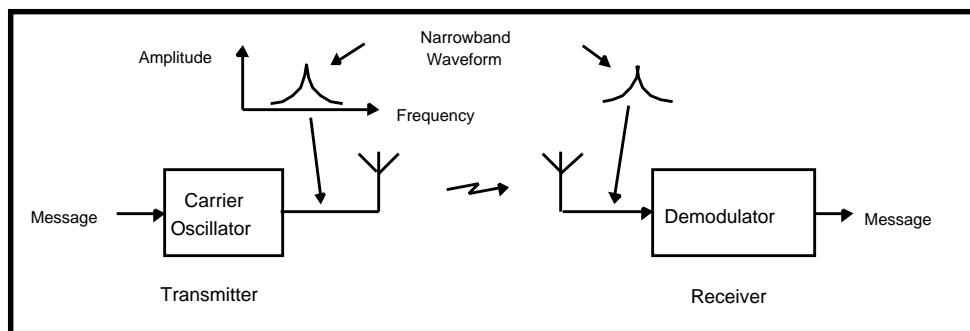

Figure 2. A simplified block diagram of a narrowband communications system.

The width of the carrier frequency and the superimposed information, is known as the bandwidth of the signal. Bandwidth is a function of the rate of information transfer. The more information that is transferred per time requires more bandwidth compared with a signal that has a lower rate of transfer.

The technological challenge facing most communications engineers has been to compress as much information into as narrow a bandwidth as possible. The method described above is called narrowband communications (Figure 3). Narrowband allows for many different transmitting stations to occupy a given band of frequencies. Frequency separation essentially channelizes the band and allows the user to select the desired channel. It also allows more users to share the available frequency space as in fixed-mobile communications such as police and fire bands. One notable goal in broadcast communications is to make the individual carrier frequency as narrow as possible so that many different broadcasts can be transmitted at the same time. This technique is known as Frequency Division Multiple Access (FDMA).
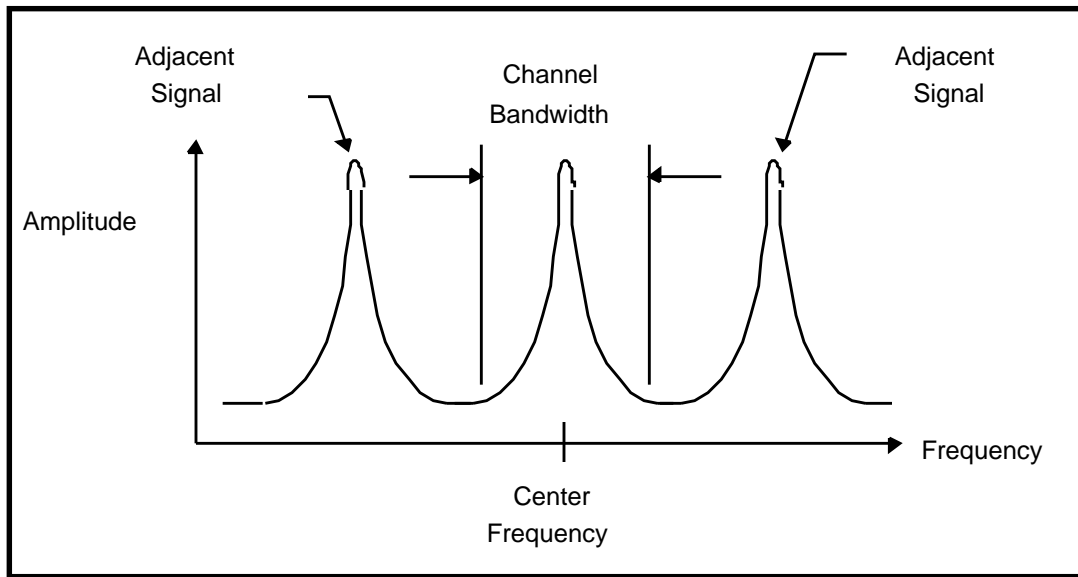
Figure 3. Amplitude verses Frequency of a narrowband signal.

Rules and Regulations Governing Transmitting Devices

The available radio frequency spectrum is a limited resource and use is controlled by government agencies such as the United States Federal Communications Commission (FCC). The need for regulation is clear. It is necessary to allocate frequencies so that services do not conflict (e.g. citizens' band does not interfere with ambulance communications). Frequencies also need to be allocated fairly, dividing the available spectrum among many qualifying services (broadcast, police, fire, ambulance, and citizen band).

Historically there has not been enough radio frequency spectrum to meet demand. With today's rapid advances in technology, wireless applications that utilize radio frequencies are growing faster than the available spectrum. Frequency allocation and availability is therefore another challenge for designers of radio frequency devices in a VE (Figure 1). The design of a position tracking system utilizing radio frequencies must therefore follow FCC rules and regulations. Currently, there is a provision for non-licensed use in Title 47, Section 15 of the Code of Federal Regulations (CFR), also known simply as Part 15 devices. Here a device emitting radio frequencies as specified in the rule under one watt of transmitted power does not require a license. This is a rule favorable for design and use of a radio frequency tracking device. The designer of course needs to become familiar with the rules and regulations governing transmitting devices. The designer also needs to be aware of other countries' regulations concerning transmitting devices if the device is to be eligible for export.

Spread-spectrum Communications

Spread-spectrum communications were a natural result of the Second World War contest for electronic supremacy, a war waged with jamming and antijamming tactics. A typical wartime scenario to jam enemy transmissions was to transmit a high-powered signal on a frequency of interest, thereby rendering the communications channel useless for both the enemy and the jammer. Thus was born a need for reliable communications that possessed antijamming properties. Wartime research was unable to develop a communications system that could "undo" the destructive nature of the jamming radios. What was finally determined was a system that spread the operating frequencies as the most desirable engineering approach to the problem. [SCHO82]

During this period Claude E. Shannon had begun to establish a fundamental theory of communications within a statistical framework [SCHO82]. This gave rise to the science of Information Theory. Shannon's information rate theorem states that the capacity of a channel is proportional to its bandwidth and the signal-to-noise ratio (S/N). This relationship is summarized in the formula:

$$C = W \log (1 + S/N)$$

where C = capacity in bits per second (bps), W = bandwidth in hertz (hz), S = signal power in decibels (db), and N = noise power in decibels. By expanding the bandwidth of the communications signal to several times the required bandwidth, there is ordinarily enough bandwidth to carry the required data rate while countering the effects of noise and jamming. Thus a spread-spectrum signal possesses antijamming properties which remain the goal of ongoing research.

One definition of spread-spectrum communication techniques is in [PICK82]:

> "Spread-spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by a means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery."

The "code" in this definition is a pseudorandom code that is mixed with the data to "spread" the signal. Thus for the spread signal to appear noiselike, the code needs to be random but reproducible. This is an apparent contradiction in terms since a truly random signal is unpredictable. Nevertheless, pseudorandom number generation is statistically random, repeatable and well-understood. In order to recover the spread signal, both the transmitter and the receiver must know the coding sequence and be able to synchronize to one another. Thus the spreading code is a pseudorandom sequence and is called the pseudo noise (PN) code.

A PN code sequence must possess adequate randomness properties (such as high variance and low auto correlation), have long periods and be difficult to reconstruct from short segments [SCHO82]. The randomness property includes equal probability of a one or a zero in a binary coded sequence. Long periods prior to repetition are important since the autocorrelation function determines the spectrum spreading. Long periods also affect the amount of cross interference with other users sharing the same frequency spectrum in Code Division Multiple Access (CDMA) situations. Reconstruction difficulty due to long segments reduces the probability that false locks occur in the synchronization of the receiver to the transmitter. Choice of PN codes has many important consequences in position tracking in a virtual environment (Figure 6).
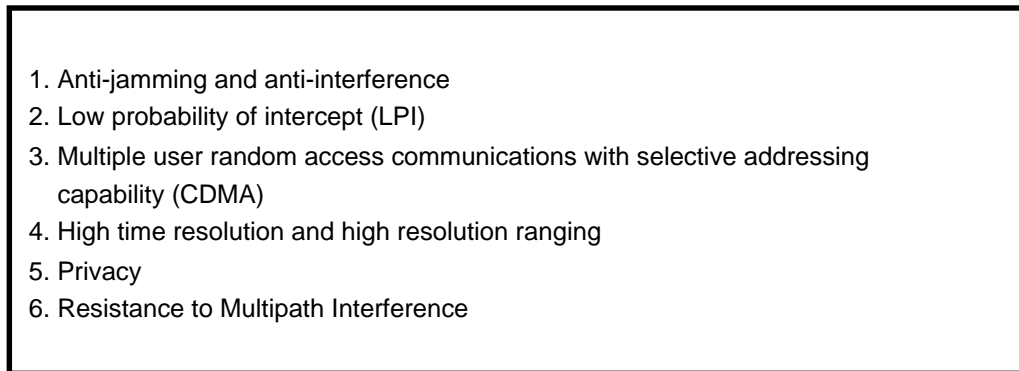
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1. Anti-jamming and anti-interference
2. Low probability of intercept (LPI)
3. Multiple user random access communications with selective addressing
   capability (CDMA)
4. High time resolution and high resolution ranging
5. Privacy
6. Resistance to Multipath Interference

Figure 4. Unique properties of spread-spectrum communications

The unique properties of spread-spectrum communications are summarized in Figure 4. Properties relating to multiple users and high-resolution ranging are of particular interest for position tracking in a virtual environment. Code Division Multiple Access (CDMA) allows multiple transmitter-receiver pairs to operate using the same frequency spectrum when each pair operates with different code sequences. This ability can allow for multiple position tracking devices to be placed on the body of an individual (or even multiple people) immersed in a virtual environment. High-resolution ranging allows for positioning accuracies in millimeters. Both CDMA and precision ranging are desirable characteristics needed for precise position tracking in a virtual environment.

To understand how CDMA and precision ranging might be implemented in this context, a fundamental understanding of spread-spectrum techniques is needed. There are several methods for spreading a signal over a wide frequency band[1]. One method of interest is Direct Sequence Spread-spectrum (DSSS). Figure 5 shows a simplified block diagram of a DSSS communications system. On the left is the transmitter and on the right is the receiver. A narrowband carrier is modulated by a predefined pseudo noise code sequence. The carrier phase of the transmitted signal is abruptly changed in accordance with this code sequence by a mixer circuit. The code sequence is generated by a pseudo noise code gen-

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1. Other methods of spread-spectrum communications are discussed in [SCHO82, SCHO83, PRIC83, PICK82, DIXO84].

erator that has a fixed length. After a given number of bits the code repeats itself exactly. The repetition rate of the code sequence is called the chipping rate, measured in chips per second (cps). For direct sequence, the amount of spreading is dependent upon the ratio of chips per bit of information. At the receiver, the original message information is recovered by synchronously mixing the signal with a locally generated replica of the PN code sequence.
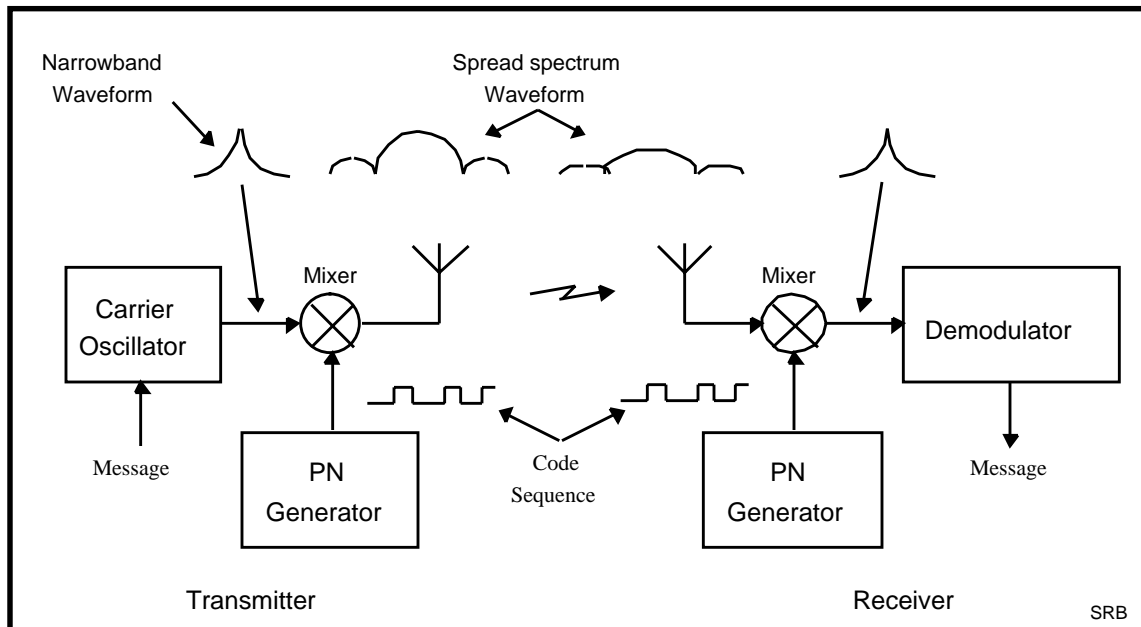

Figure 5. A simplified block diagram of a direct sequence spread-spectrum communications system.

This simplified diagram illustrates how CDMA works. The PN code sequence determines the code division among transmitter-receiver pairs. Only the transmitter-receiver pairs that are operating with the same code sequence are able to communicate with each other. Other transmitter-receiver pairs that are not using the same code will effectively not hear the other pairs since signal-to-noise ratio of the incorrectly decoded signal is extremely low. CDMA allows multiple transceiver-receiver pairs to share the same frequency band more efficiently than TDMA or FDMA methods can.

Although the simplified discussion above illustrates how CDMA works, there are other factors that influence its functionality. The first are the PN code sequences chosen. It is desirable that code sequences have low crosscorrelation properties and be orthogonal, i.e. not share any subsequences. This ensures minimal cross-interference between any pair of users. The second factor is a phenomenon known as the "near-far problem." This phenomenon occurs when a second transmitter is physically closer (and therefore may have a stronger signal) than a transmitter further away. The stronger signal overwhelms the receiver such that it cannot hear the intended transmitter. The near-far problem can be mitigated by

instituting power control on the transmitters. These factors deserve further investigation as potential problems for position tracking in a virtual environment (Figure 6).

1. Choice of spreading codes (cross correlation and orthogonality)
2. Near-far problem
3. Clock (timing) accuracy
4. Speed of code sequence for range accuracy

Figure 6. Further research needed into the use of spread-spectrum technology in a VE

Precision ranging using spread-spectrum techniques requires examination of ranging fundamentals. The speed of a radio signal is 2.99792458 x 108 meters per second. When a signal is transmitted, it takes a finite amount of time to travel from point x to point y. If the receiver knows the exact times the signal was transmitted and received, it can determine the amount of time the radio signal took to travel. Thus delta-time multiplied by the speed of the radio signal equals the range between the two points in meters. Notice the requirement that the receiver must accurately measure the exact times of transmission and reception with adequate temporal resolution.

For a receiver to know the time of transmission, it must either be told by an external means or have timing information embedded in the received signal. This latter method is ordinarily how a spread-spectrum system notifies the receiver of the time of transmission. A PN signal is transmitted with timing information embedded in the message. The receiver now knows exactly when the PN signal was transmitted. One disadvantage is that this method requires both the transmitter and the receiver to have accurate synchronized clocks.

Both the transmitter and the receiver knowing the exact time is a stiff requirement. Accuracy of both clocks is a must. For example, if the timing error is off by 10 nanoseconds, the range error would be three meters. Timing is a fundamental challenge in obtaining millimeter accuracies needed for position tracking in a virtual environment (Figure 6).

Timing is not the only requirement for accurate ranging. Conventional radio communications techniques can only obtain accuracies on the order of meters. Yet spread-spectrum technology again excels in its ability to allow precision ranging on the order of millimeters. This is accomplished by detecting the phase difference in the PN code sequences of the transmitter and receiver (Figure 7 adapted from [DIXO84]). The accuracy of this technique is coupled to the speed of the code sequence: the higher the speed, the finer the resolution. This is another area of exploration for position tracking in a virtual environment (Figure 6).
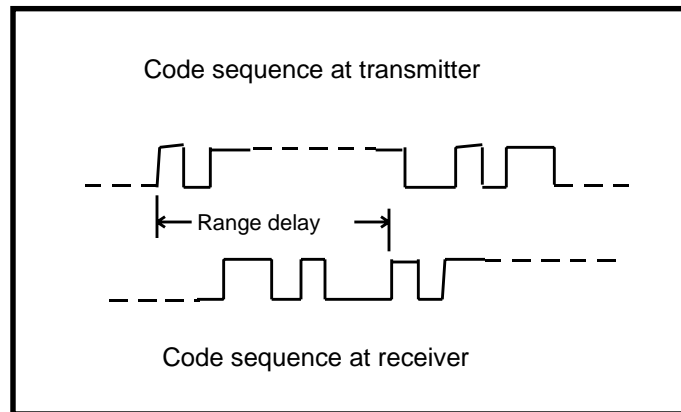
**Figure 7. Code sequence comparison at transmitter and receiver
(adapted from [DIXO84]).**

The next step is how to relate all this spread-spectrum technology to position tracking in a VE. There is a system in use today that provides meter accuracies from a large system of orbiting satellites: the Navstar System, otherwise known as the Global Positioning System (GPS).

Global Positioning System (GPS)

The Global Positioning System (GPS) works on the principle of CDMA spread-spectrum ranging techniques described earlier [MORG95], [DALY95], [GETT93], [MOOR94]. The satellites use a single frequency band and differentiate one satellite from another by individual code sequences. Each GPS satellite transmits a precise code sequence and each receiver has an exact copy. The receiver locks onto the code for signal syncronization and reads the satellite's position information and time of transmission. The receiver computes range to the satellite using timing information and an internal clock. Since the receiver's clock may be imprecise and is not synchronized with the satellite's clock, the range calculation is inaccurate. Thus the range calculation is called a pseudo range.

The GPS receiver calculates its position on earth by triangulating the pseudo ranges of three satellites. Each pseudo range forms a range sphere with the satellite in the center. The intersection of the three range spheres defines a location of the GPS receiver. Nevertheless the intersection of three inaccurate ranges does not produce a precise fix. Therefore there is still the question of the inaccurate time kept by the receiver.

Every GPS satellite keeps accurate time using atomic-standard clocks and all are synchronized to one another via ground station control. When a GPS receiver receives the timing information from the satellite signal, it therefore knows that the information is accurate and the resulting bias from its clock is the same for all observations. To solve for time, the

GPS receiver takes a fourth observation. Time is mathematically determined from four observations, including position. The position calculated is in earth-centered earth-fixed (ECEF) coordinates (Figure 8) and is converted to latitude, longitude, and altitude.
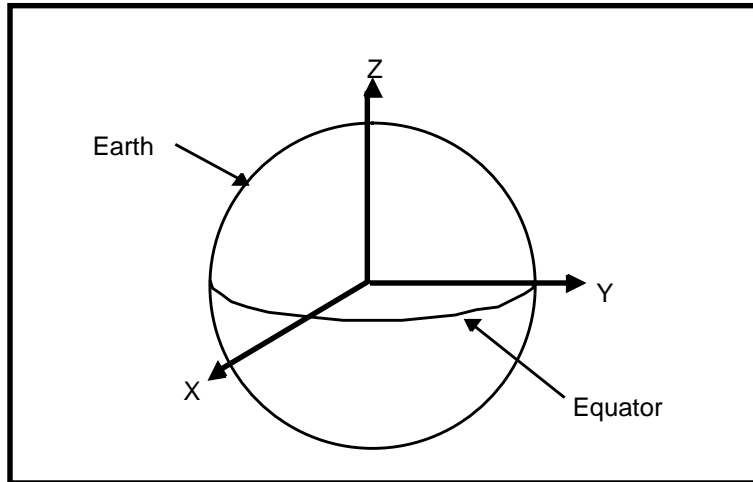

Figure 8. Earth-centered earth-fixed (ECEF) coordinates.

Position Tracking in a Virtual Environment

Basic knowledge of spread-spectrum ranging and the Global Position System's method of triangulation can now be applied to position tracking in the virtual environment. As mentioned earlier, spread-spectrum has two distinct advantages over conventional communications methods: accurate ranging commensurate with code sequence speed, and code division multiple access (CDMA). These advantages bring to the virtual environment the ability to track position to millimeter accuracies while allowing multiple transmitters to use the same frequency band at the same time. A notional example spread-spectrum position tracking system using four stationary transmitters and multiple receivers is shown in Figure 10.
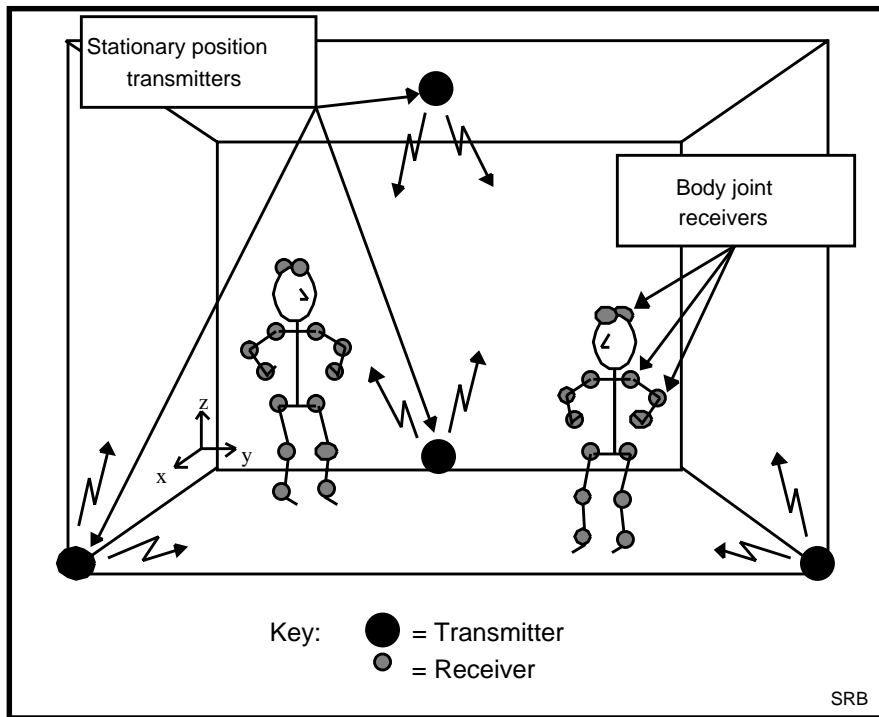
Figure 9. Notional spread-spectrum position tracking system for a VE.

Four transmitters are placed in the virtual environment because of the need to simultaneously solve four unknowns: x, y, z, and time. This arrangement also minimizes the internal complexity of receivers. An optimal geometry exists when one transmitter is centered directly overhead and three others are evenly spaced around the base of the room [MORG95]. All four transmitters transmit using the same spread-spectrum frequency band, but each transmitter has its own unique code sequences so mutual interference is avoided.

Receivers might be positioned on the major body joints of each person for a total of fourteen receivers per person. This placement provides sufficient resolution to provide tracking of the body and its extremities. Each receiver receives the transmitted signal from all four stationary transmitters and calculates position (x, y, and z) with respect to the room origin. Choice of origin location is arbitrary.

Each individual receiver independently calculates its position (x, y, and z) in the virtual environment and reports position to a position tracking computer. This is done by collecting position data from all fourteen body joint receivers, multiplexing them into one signal, and transmitting the composite telemetry stream to the position tracking computer. This arrangement introduces one new transmitter-receiver pair per person. The transmitter-receiver pair has a different code sequence from the other transmitters in the room. Because of spread-spectrum's code division ability, multiple people can be immersed into the virtual

environment without obscuration (Figure 10). It is likely that such body tracking systems might coexist in a single VE without mutual interference.
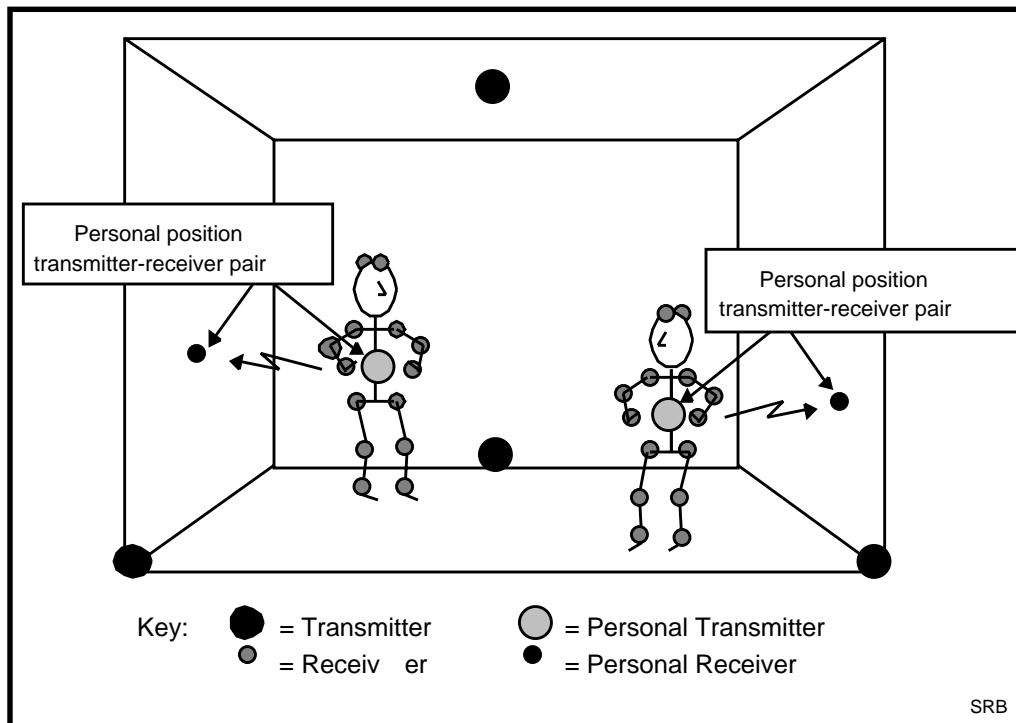

Figure 10. Position information for each person is transmitted to position tracking computer using different code sequences.

The spread-spectrum position tracking system breaks down into three major components: 1) stationary position transmitters - four per room, 2) body joint receivers - fourteen per person, and 3) personal position transmitter-receiver pairs - one per person. The architecture of the system is easily scaleable. If the virtual environment extends to multiple rooms then four stationary position transmitters need to be installed per room. If a new person is introduced into the virtual environment, they don an apparatus of fourteen body joint receivers and one personal position transmitter with a unique code sequence. We call this combination of devcies a personal tracking system (PTS).

The spread-spectrum position tracking system can be scaled to any area size. The physical size of the virtual environment can be as small as a room or as large as a football field. The accuracy of the system is dependent upon the frequency, coding and signal processing implementation rather than the size of the area.

The stationary position transmitters are of simple construction. The only critical design issue is timing. All four transmitters must transmit their precise code sequence at the same time. This time is relative only to the four transmitters and it is not necessary that the time be synchronized with the exact time of day.

The construction of the receivers is a little more involved than the transmitters. Each receiver must receive on four channels, one for each of the coded sequences from each of the stationary transmitters. The receiver must calculate its position using the triangulation method similar to the Global Positioning System. This requires that each receiver has a processor and a clock. Once the position of the receiver is known, it is sent to a central processor which collects the position data from all of the body position receivers and combines it into a composite signal that is transmitted to the position tracking computer.

Off-the-shelf components for the spread-spectrum position tracking system can be used from the manufacture of GPS receivers, digital cellular telephones, and wireless LANs. Since spread-spectrum communications is becoming more widespread through the proliferation of wireless devices, the components that make up these systems are consumer items and inexpensive. These components are in the form of application specific integrated circuits (ASIC), i.e. integrated circuit chips that are built for a specific purpose. These chips can be combined to construct the spread-spectrum position tracking system described in this paper.

Recommendations for Future Work

A proposed spread-spectrum tracking system can be built using commercial off the shelf (COTS) components in three phases. The first phase would establish millimeter track position accuracy. The second phase would evaluate candidate GPS engines and GPS ASIC chips sets for use as a position tracking receiver. And the third phase would integrate the entire system into a room for testing and evaluation.

For the first phase, to test millimeter track position accuracy, a simple transmitter-receiver pair is required. Two Loral EB200G Spread Spectrum Modems can be used[2]. These modems are complete digital communication systems, fully programmable, and can be plugged into a PC-AT ISA slot or can operate stand-alone. One unit shall be used as a transmitter and the other as a receiver. Approximate cost per unit is $2500.00. Testing of these units would involve evaluating and solving the problems summarized in Figure 6. Later, these units can be used as the four transmitters needed for position tracking as illustrated in Figure 10.

The second phase, evaluate candidate GPS engines and GPS ASIC chips sets for use as a position tracking receiver, requires a search for off-the-shelf devices that can be easily modified. One such device is a GPS Engine, an original equipment manufactured (OEM) device available from several companies. The engine implements the basic functions for a GPS receiver. It has a connection for an antenna and an output for a computer. The output is location information formatted in a text string. These devices are available in small quantities for approximately $150.00 each. Although these engines are manufactured to re-

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2. Loral Communication Systems Division, 640 North 2200 West M/S F1F12, Salt Lake City, UT 84416, Phone: 801-594-3737, 594-4127/fax.

ceive on GPS frequencies, modification of the receive section can be easily made and the manufacturer of the device could manufacture a small number of the altered devices for a slightly higher fee.

A continuation of phase two would be a search for ASIC chip sets that implement GPS functions. One candidate is the GEC Plessey GP2010 and GP2020 GPS ASIC chip set. These chips implement the basic GPS functions. These would require more engineering than modifying a GPS engine, however, they could provide a customized solution to position tracking in a virtual environment that cannot be achieved by modifying a GPS engine because of its primary design purpose.

The third phase, integrating the entire system into a room for testing and evaluation, would be a culmination of the first two phases. At this point, many of the problems and issues surrounding the implementation would be addressed and system integration can proceed. It is anticipated that the first body suits would be bulky due to the size of the components required. However, as testing and evaluation of components progresses, manufactures could be convinced to modify their existing products to position tracking in a virtual environment at a substantially reduced cost from developing such devices from the ground up.

Summary

This paper began with a discussion of communication basics. A conventional narrow-band system was first described and then the fundamentals of a spread-spectrum communications system was outlined. We learned that spread-spectrum technology has many unique characteristics that are not found in conventional communications - anti-jamming, anti-interference, low probability of intercept (LPI), selective addressing capability (CDMA), and high resolution ranging. The latter two, CDMA and high resolution ranging, are of the most interest to us in position tracking in a virtual environment. The spread-spectrum position tracking system can utilize CDMA for multiple transmitter-receiver pairs. Thus, many receivers are placed on the major joints of the body and several people can be immersed into the virtual environment. High resolution ranging allows accuracies in the millimeter range.

The triangulation technique of the Global Position System is applied to position tracking in a virtual environment. This technique allows for inexpensive receivers that do not have an accurate clock to perform ranging and processing to perform triangulation. This is an important requirement as the spread-spectrum position tracking system will utilize fourteen receivers per person and only four transmitters per room.

The spread-spectrum position tracking system is scaleable. The size of the virtual environment can be as small as a room or as large as a football field. Accuracy of the system is dependent upon implementation, not on the size of the area.

Finally, spread-spectrum technology is pervasive in the electronics industry. Application specific integrated circuits (ASIC) are available on the market today and are inexpensive building blocks for the spread-spectrum position tracking system. Thus the system can be built inexpensively utilizing existing off the shelf components. An inexpensive and accurate position tracking system can be designed and built using spread-spectrum's unique characteristics and its widespread use in the electronics industry.

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