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Where's Waldo? Low-Cost RF Indoor Tracking Systems

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Abstract

Customized mass-manufacturing refers to the ability to mass-manufacture products in such a way that each particular product can be customized by the user to best meet their needs without affecting the flow of production and the rate of production. If a product is manufactured in one continuous process, such as in cell manufacturing, then it is relatively easy to keep track of simply by counting it. Many manufacturing environments, however, may use batch manufacturing systems or hybrid systems making it much more difficult to keep track of any particular product that may need special operations performed on it. It may not be possible to keep track of a particular product within a batch manufacturing process unless it is specifically tagged in some manner. To be of use in a customized mass-manufacturing system, each product must therefore be uniquely identifiable in some manner. A logical way of achieving this is through the use of an Indoor Position System, (IPS), to track and position each product in the indoor environment. This paper briefly examines existing indoor tracking technologies and then describe a test ubiquitous tracking network system built with low cost RF nodes.

Keywords: Indoor tracking, Flexible manufacturing, Ubiquitous Indoor Positioning System

1 Introduction

Imagine purchasing a car that you want to customize to better fit your needs. You might, for example, want a specific colour, special wheels, a particular fuel injection system, and so on. Rather than waiting until after the car is received to begin customizing it, which represents much wastage in removing existing parts and replacing them with new ones, it would be ideal if you were able to customize the car as it was being mass-manufactured as part of a batch of other cars.

Customized mass-manufacturing refers to the ability to mass-manufacture products in such a way that each particular product can be customized by the user to best meet their needs without affecting the flow of production and the rate of production [1].

If a product is manufactured in one continuous process, such as in cell manufacturing, then it is relatively easy to keep track of by counting it. Many manufacturing environments, however, may use batch manufacturing systems, or hybrid systems such as a combination of batch manufacturing and cell manufacturing, making it much more difficult to keep track of any particular product that may need special operations performed on it. A manufacturing operation, such as chrome plating, may be done as a batch process after which all products in the batch are placed in storage until they are ready for the next process. It may not be possible to keep track of a particular product within that batch. To be of use in a customized mass-manufacturing system, each product must therefore be uniquely identifiable in some manner [2]. A logical way of achieving this is through the use of an Indoor Position System, (IPS), to track and position each product in the indoor environment.

There are many technologies used for IPS systems, and the most common are usually based on the technologies such as Infrared, Radio-frequency, DC Electromagnetic, Ultrasound, etc. [3].

This paper describes a ubiquitous indoor positioning system based on low-cost radio frequency (RF) nodes that can be used in a customized mass-manufacturing or flexible manufacturing environment.

2 Current Tracking Technologies

Tracking technologies are those that allow the control computer to know where any particular product is within a production environment and what processes it needs to have performed on it. Some of the commonly available technologies that are suitable for tracking networks include:

Infrared: Due to their ubiquitous deployment infrared (IR) transceivers are inexpensive, compact, and low power. IR propagation is fast but effective bandwidth is limited by interference from ambient light and from other IR devices in the environment. IR signals reflect off most interior surfaces but diffracts around few. Typical range is up to 5 meters. They are also restricted by line-of-sight limitations.

Radio frequency: RF signals diffract around and pass through common building materials. RF signals compare favourably to IR in propagation speed, bandwidth, and cost. Since the RF spectrum is heavily regulated, typical systems operate at 900MHz or 2.45GHz and comply with Part 15 FCC regulations so as not to require licensing. Transmission range of 10m-30m indoors is common.

RFID (Radio Frequency Identification) is a commonly available system which uses either low-cost passive Radio tags, or higher cost active tags. An RFID system comprises a reader, its associated antenna and the transponders (Tags/ RFID Cards) that carry the data. The reader transmits a low-power radio signal, through its antenna, that the tag receives via its own antenna to power an integrated circuit. Using the energy it gets from the signal when it enters the radio field, the tag will briefly converse with the reader for verification and the exchange of data. Once that data is received by the reader it can be sent to a controlling computer for processing and management.

DC Electromagnetic: DC electromagnetic fields have been used in high-precision positioning systems. While the signal propagation speed is high range is limited to 1m-3m. These signals are very sensitive to environmental interference from a variety of sources including the earth’s magnetic field, CRTs, and even metal in the area. Systems based on these signals need precise calibration in a controlled environment.

Ultrasound: Ultrasound signals are becoming more common in positioning systems the relatively show propagation speed of sound (343m/s) allows for precise measurement at low clock rates, making ultrasound based-systems relatively simple and inexpensive. The signal frequency is limited by human hearing on the low end and by short range on the high end. A keen human can hear 20KHz sounds. Typical systems use a 40KHz signal. Conveniently, standard sound cards have a 48KHz sampling rate, sufficient for 1cm resolution distance measurements. Environmental factors have substantial but not prohibitive effects on ultrasound propagation, particularly speed. Humidity can slow ultrasound by up to 0.3%. More drastically, a temperature rise from 0 ºC to 30 ºC alters the speed of sound by 3%. Finally, ultrasound reflects off most indoor surfaces. Empirical studies show that 40KHz ultrasound signals reverberate at detectable levels for about 20ms.

AT&T has developed a system called the bat ultrasonic system. The bat system involves the use of an ultra-sonic tracking technology developed at AT&T Laboratories in Cambridge. A small device carried by the users emits ultrasonic beeps, thus allowing a network grid of ultrasonic receivers to track which node the user is nearest [4].

Global Positioning System (GPS): GPS has been in consumer use in the last five years with the availability of affordable navigation tools. These devices usually include GPS receivers to locate the user and a map database to give context such as streets and surroundings. Sometimes the device can also compute the best route from a source to a source to a destination, or store these planned trips for later retrieval. GPS features positioning accuracy of roughly 10m. For it to function, the receiver must be in line of sight of four satellites above, or be able to receive a supplementary correction signals from a ground station. Due to these limitations, GPS is not a useful tool for indoor or underground navigation.

3 Positioning Methods

To bootstrap a location system, some non-empty sets of locations are assigned symbolic labels a priori. Thereafter, the location of any other point is computed with respect to these reference points. This process is called tracking. Positioning occurs in two steps. First sensor measurements are obtained, and then the measurements are combined to deduce the location of the unknown points. Generally, measurement involves the transmission and reception of signals between elements of the system.

3.1 Measuring Distance

The metric most often used to assign labels to objects is the distance of the object from some other objects whose symbolic labels are already known (either by previous measurement and calculation, or a priori). Distance is estimated by sensing the characteristics of signals from elements of the location system.

Two approaches are commonly used to estimate distance using emitted signals. The first approach measures the attenuation of signal strength at a receiver. Attenuation-based methods attempt to calculate the signal loss due to propagation. Theoretical and empirical models are used to translate the difference between the transmitted signal strength and the received signal strength into a range estimate.

The second approach measures the time of flight (ToF) of a signal. If the signal propagation speed is known (or calculated), signal ToF trivially translates to distance. The key difficulty is to measure, transmit and receive times on the same time scale. The precision with which times need to be synchronized is proportional to the speed of the signal and the desired precision of the distance measurement.

3.2 Measuring angles

Angle of arrival (AoA) of a signal against some arbitrary baseline can also be measured using either signal strength or time difference of arrival. Signal-strength-based systems compare the received signal strength across a spectrum of angles and select the angle of maximum strength as the receive angle. Time-based methods use arrangements of receivers to measure the time difference of arrival (TDoA) and, thus the difference in distance from each receiver to the transmitter. When combined with the known arrangements of the receiver array, the differential distance information is sufficient to solve for the angle of arrival.

3.3 Combining Measurement

Location systems combine basic measurements such as distance, angle, or temperature to compute to assign locations. Four methods are common:

3.3.1 Multilateration

Multilateration is the computation of location using measured distances from reference points. The two dimensional location of a point can be computed from the distances of that point to three non-collinear, reference points. In three dimensions, four non-coplanar constraining points are required. Additional measurements can be used to solve for additional unknowns. Ranges to additional reference points can also be used to reduce error by finding a best fit in an over-constrained system.

3.3.2 Angulation

Angulation is the computation of location using measured angles from reference points. It is simply the angle-based analog of multilateration. Together, the two methods are called triangulation.

3.3.3 Proximity

An alternative to explicit computation of location is to approximate the position of an element by assigning it the same label as that of a proximate reference point. The “closest” (by some metric) reference point to the unknown point is selected as the location of the unknown point. Common metrics include statistical functions of distance and physical contact.

3.3.4 Scene analysis

Scene analysis is a catch-all phrase used to group a diverse set of holistic or complex methods. These methods recognize features of the environment that may not be so easily categorized as distance or angle. Example features include edge or motion detection in video images and received radio signal characteristics such as multi-path or signal strength patterns.

4 Theoretical Tracking Models

4.1 Triangulation Model

The triangulation model is based on a very popular radio propagation model that describes the relationship between signal strength and distance. This model indicates that the received signal power decreases logarithmically with distance. The relationship exists for both outdoor and indoor conditions. It can be represented by the expression:

$$P(d) = P(d0) - 10r\log(d/d0)$$

Where P(d) is the signal strength at a distance d and P(d0) is the signal strength at some reference distance. The factor r represents the path loss exponent and is affected by the external factors like multi-path fading, absorption, air temperature etc.
With this model, the position can be determined using a standard triangulation algorithm. If signal levels from three different base nodes are known, the location of the mobile device can be approximated as the unique intersection point of the three circles. Assuming that the mobile device and the access points are all located on the same geometric plane, the triangulation algorithm specifies that a minimum of three base nodes are required in order to calculate a unique intersection point of the three circle.

4.2 Proximate Reference Model

The proximity reference model approximates the position of a person or object by determining the closest reference point as the position for the unknown point. There are often multiple neighbours that are at roughly the same distance from the point of interest (the object position). Each neighbour is oriented in a different direction. So averaging the coordinates of the neighbours may yield an estimate that is closer to the object’s true location.

5 RF Ubiquitous Networks

A ubiquitous network is one that is present everywhere throughout an area and has the ability to detect where users or items are within the network and, based on that information, meet their needs. A simple example of the use of a ubiquitous network could be that of working on a computer and then moving to a different part of the building to another computer and having the document automatically follow you to that computer allowing you to seamlessly continue your work.

The overall concept for a RF ubiquitous network is as follows: Small RF transceiver modules were attached to the ceiling of the environment to form a grid of linked modules. The modules are spaced 2m apart and each module is set to have a range of 2.4 metres. The grid is connected to a computer via a low cost RS485 network and runs software to deal with the information received via the network. This software includes the ability to track the product over a map of the environment, and displays the product-specific data contained in the tag.

A RF Enabled Tag is loaded with the product-specific data, and it has a range of 2.4m. As the tag is within a distance of 2000mm of the floor, it is always in range of at least one receiver module but never in range of more than 4 receiver modules. It then becomes simple geometry to determine the location of the user relative to either one, two, three or four modules.

As any RF grid module picks up a signal from a tag device, it sends back the information contained in the device, as well as it's own node number to the central computer which then knows which node the information is coming from (and therefore the products position) as well as the products pertinent information. To keep data transmission to a minimum, the complete product-specific data file is only sent on the first node contact, after which time it is stored in the central computer database. Thereafter, only a header identifying the product needs to be sent at a regular interval. From the location information and the product data, the central computer is able to reconfigure the various devices in the vicinity of the product to best suit the operations to be carried out. This burst transmission system also has the advantage of minimizing the risk of co-channel interference [5].

6 System Construction

A network of several Radio Frequency receiver nodes were attached to the ceiling of the environment to form a grid of linked modules. These nodes were spaced 2 meters apart and each module was set to have a range of 2.4 meters.

The radio frequency receiver module (rfRXD0420) received the radio signals and passed the valid signals to the PIC18F242. The PIC18F242 sampled these signals and picked up the useful data from that.

The receiver node, which received the information from the radio frequency transmitter, then transferred its address and received valid information to a central control PC via an RS485 network.

An RS485-to-RS232 converter was placed between PC and the RS485 network because computer's serial port was using the RS232 protocol. The PC was running software to deal with the information received from the network and to control the devices controlled by the system. In the case of the sample system described in this paper, after analyzing the information received, the PC then sent the command to the lighting control box to switch on the appropriate coloured light to represent a particular manufacturing process.

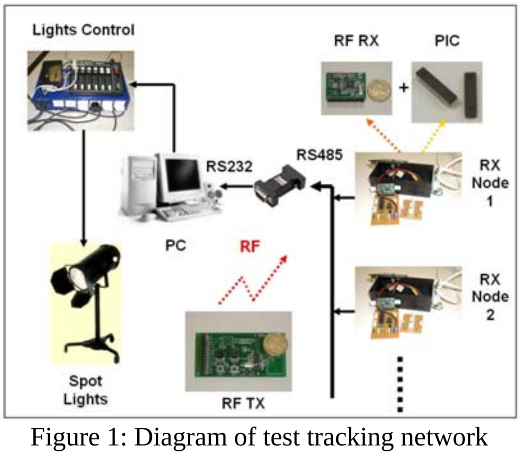

Figure 1: Diagram of test tracking network

6.1 Construction of the RF Tag

An rfPIC12F675 transmitter module was used to be the electronic transmission device. The rfPIC12F675 transmitter module contained:

- 2 push-button switches connected to GP3 and GP4
- 2 potentiometers connected to GP0 and GP1
- RF enable (RFenin) connected to GP5
- Data ASK (DATAask) connected to GP2
- Optional 8-pin socked (U2) for In-Circuit Emulation (ICE) or inserting an 8-pin DIP package version of the PIC12F675

The push-button switch GP3 was used as the main power switch. The push-button switch GP4 was removed and the Low Frequency Communication Circuit was linked to pin GP4. This Low Frequency Communication Circuit (LFCC) acted as an electronic switch with a very short range (typically, 20cm). If no low frequency signal was received by the rfPIC12F675 module, the module sent only the product ID every second. If the rfPIC12F675 module received a low frequency command within the LFCC range, the pin GP4 was pulled-up and the module started to send all the information contained in the tag (Product ID, Operations to be performed, etc.).

Those potentiometers connected to GP0 and GP1 were not used. A power reduction resistor was added on, and the length of the antenna was shortened to decrease the transmission range to approximate 2.5 meters. This was in important step as, if the range of the transmitter were too large, it would communicate with too many receiver nodes, making it more difficult to pinpoint a precise location.

The data transmitted from the rf12F675 module used its own code transmission format, in which there were four distinct parts to every code word transmission as follows: Preamble, Header, Data and Guard Time.

The preamble started the transmission and consisted of repeating low and high phases each of length Te representing the elemental time period. The header consisted of a low phase which had a length of 10*Te. Next came the data bits. The data bits were Pulse Width Modulated (PWM). A logic one was equivalent to a high of length Te, followed by a low of length 2*Te. A logic zero was equivalent to a high of length 2*Te, followed by a low of length Te. The final part of the code word transmission was the guard time which was the spacing before another code word was transmitted.

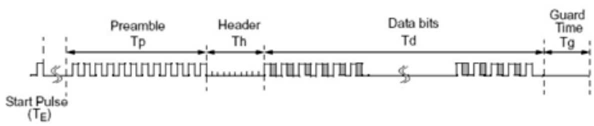

Figure 2: Transmitter Pulse Train

The encoding method used for the transmission was a 1/3 2/3 PWM format with Te (basic pulse element).

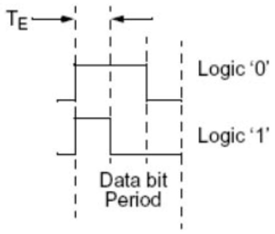

Figure 3: Encoding Method

The device used the following data format: the preamble was 10101010 (8-bits sequence), followed by a 0000 (4-bits) header. The data section contained the product ID, Description, and four different operations to be carried out. Each of these operations was represented by a blue or red light depending on the configuration of each robot. The last section was the Guard Time which consisted of 8 bits 0.

6.2 Low frequency Communication Cct

The power supply was a standard linear regulated main frequency unit with one difference: the mains earth was brought through to the circuit ground. This was necessary to provide the radio output with an earth reference, so it could function effectively as a transmitter [6].

The rest of the circuit consisted of two nearly identical halves, each producing one of the outputs. The first of the three op-amps was the oscillator, calibrated to the desired frequency. The output to the filter was taken not from the square wave output but from the timing capacitor, which had a continuous RC charge/discharge curve. This had fewer high frequency components than a square wave, which resulted in a cleaner output signal. As this output was easily loaded, a second op-amp was included as a 1:1 buffer. The signal was finally fed to a second order low-pass filter with a cut-off frequency identical to that of the oscillator. This removed the majority of the high-frequency components, resulting in an acceptable sine wave at the output.

6.3 Receiver Node

The receiver Node, shown in figure 4, consisted of two main elements: a radio frequency receiver module (rfRXD0420) and a PIC18F242. The receiver module received the radio frequency signals and passed them to the PIC18F242 for processing. The PIC18F242 picked up the useful information and sent them to the PC via the RS485 network.

The assembly code for PIC18F242 performed the following tasks: Recognize incoming signal, pick up the data section of the incoming information package, process the data and send its receiver node address and useful receiving data to the PC via its USART port, Repeat

Figure 4: Tracking System Receiver Node

A MAX485 Chip provided the half duplex RS-485 function with two data lines (A and B), a common ground line, and an extra control line. This control line was used to check whether the bus lines were free or not.

The receiver node also had the in-circuit programming function for the PIC18F242. This function was used to easily re-program or upgrade the PIC18F242 code as the system was developed.

7 Demonstration System

The system described in this paper used a ubiquitous network made up of RF nodes. The RF nodes placed throughout the environment formed a ubiquitous network which allowed for mass-customized production in which consumer products can be mass-manufactured while, at the same time, each product can be customized to a specific user. This allowed for direct integration between the end-consumer and the machines assembling products.

An example of such integration would be that of a fully automated computer assembly cell in which the customer could order his preferred computer configuration over the Internet.

The process would begin by the customers logging in over the Internet and ordering a customized product such as a computer system, for example. As the order leaves the order entry system, its order specific data is downloaded to the RF module on the AGV (Autonomous Guided Vehicle) which then begins its journey through the factory. At each automated workstation a robot sets itself up to, for example, insert 512Mb of Ram, until all the work is complete.

At any stage the control computer system can tell the customer exactly where in the system his machine is, and can estimate when the customers' job will be finished. The product is accordingly assembled and dispatched to the customer.
The system setup, as shown in Figure 5, described in this paper was a simplified system which involved a vehicle with an RF tag moving through an environment along a predefined path. The vehicle employed a simple line following circuit to guide it along a predefined path through the environment.

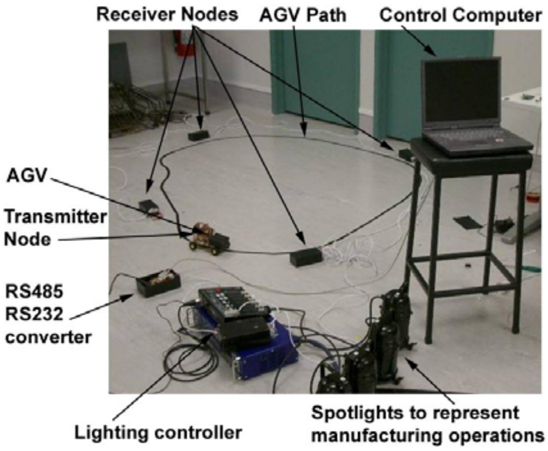

Figure 5: Tracking System Setup

At specific points along the path, pairs of spotlights were positioned to represent particular manufacturing processes. Each pair of spotlights included a blue and a red light to represent the reconfiguration of a particular assembly process. The blue light might, for example, represent a robot inserting a 512Mb RAM module into a motherboard, while the red light would represent the same robot inserting a 256Mb module.

The unique RF tag number from the AGV transmitter was logged on the controlling computer. The controlling computer was programmed with a combination of either red or blue steps to represent the various operations that needed to be performed for that particular transmitter number.

As it followed the path, the RF tag on the AGV was detected by the RF receiver nodes, and both the unique ID number of the transmitter and the unique ID of the receiver node that it was nearest to were sent to the controlling computer via the RS485 network. The controlling computer therefore knew the ID number of the transmitter module as well as the location of the AGV from its proximity to the node the data was received from. Based on this information the controlling computer was able to switch on the appropriate coloured light to represent the manufacturing process that was to be performed. As the AGV passed each node along the path, either a red or blue light was switched on depending on what operation was to be performed.

8 Conclusion

Customized mass-manufacturing refers to the ability to mass-manufacture products in such a way that each particular product can be customized by the user to best meet their needs without affecting the flow of production or the rate of production.

In order to achieve this, the control computer must have the ability to know the precise location of any particular product at any given time as well as what customized operations need to be performed on each product.

This project successfully demonstrated the feasibility of a low-cost customized mass-manufacturing system using an RF node based tracking system.

The system consisted of a transmitter node, placed on an AGV, which transmitted product ID and required operations data at repeated intervals. Receiver nodes placed along the AGV path picked up this information as the AGV moved to within their receiving range, and transmitted this information to the control computer along an RS485 network. Based on this information, the computer was made aware of the precise location of the AGV and was then able to reconfigure the machines to perform the operation required by the product. In the case of the demonstration system, each machine was represented by two different coloured lights to simulate different manufacturing operations.

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