An ultrasonic self-localized Automated
Guided Vehicle System

by

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The Hong Kong University of Science and Technology
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the Degree of Master of Philosophy
in Industrial Engineering and Engineering Management

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This is to certify that I have examined the above MPhil thesis
and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by
the thesis examination committee have been made.

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Abstract

Automated Guided Vehicle (AGV) system is one of the most common used automated material handling systems that have been adopted in warehousing and manufacturing application. Due to the flexibility and the automation ability it can provide, AGV system is now becoming more and more important in recent years.

AGV system was developed for more than fifty years but the penetration is not satisfactory because of the high cost and navigation problem. So this thesis will mainly focus on the development of a better alternative of AGV navigation system.

Estimating physical location of a mobile object in an indoor manufacturing environment is an essential element in developing an automated robotic application likes the AGV system. Today, many location systems have been developed to determine location information based on different mechanisms. Among those mechanisms, determining location using ultrasonic time-of-flight lateration can provide sub-metric accuracy with relatively low implement cost, which makes the systems more suitable in real life application.

In this study, we have successfully developed the pioneer work for a novel AGV system which has lower cost and better performance than the existing AGV system. A prototype of the system is implemented and the performance of the system is evaluated by comparing with other existing positioning systems.
Chapter 1

Introduction

1.1 Mass Customization Background

Traditionally, manufacturing can be divided into two ends – mass production and craft production. By taking the advantage of Economies of Scale, mass production can produce high volume of standardized products at low cost by sacrificing the variety in production. In contrast, craft production can produce more unique and customized products which meet individual needs at high cost and low efficiency. The concept of Mass Customization was first depicted by Davis [1]. With rapidly changing customer needs and market conditions, mass customization aims at the ability to provide uniquely designed products and services to every customer through high process agility, flexibility and integration [2]. In order to achieve mass customization, new manufacturing systems and information technologies are developed to deliver large variety at lower cost. Under this situation, the flexible manufacturing system is particularly important to handle these orders as it provides the ability to handle small volume and high product proliferation orders.
1.2 **Flexible Manufacturing System**

The traditional flexible manufacturing system (FMS) is based on numerically controlled machines in addition to other value-added, automatic and material handling facilities. A degree of flexibility within FMS serves to satisfy demands for a relatively diverse range of products with a small to medium batch size production [3]. The Material handling process plays an important role in determining the performance and the operation cost of an FMS. Normally, about 20% to 50% of the total operating cost is spent on the material handling process [4]. A material handling system serves as a supportive function to the value-added activities, and connects and transverses the whole value chain in the manufacturing system. One of the most common flexible material handling systems is the automated guided vehicle system (AGVs). The deployment of the AGVs aims at increasing productivity, flexibility and the control of materials.

1.3 **Automated Guided Vehicle System**

Automated Guided Vehicle System is a computer controlled industrial transportation system. The basic components of AGVs include Automated Vehicles, Guiding/Navigation System and Control System. An AGVs can perform various material handling duties like movement of products in warehouses and transportation
of subparts between different value-adding stations in a production line. An AGV
system is usually interfaced with other automated manufacturing systems to achieve
the full benefits of integrated automation. [5]

1.4 Thesis Organization

The remainder of this thesis presents the development and evaluation of the proposed
ultrasonic positioning system. Chapter 2 presents the existing vehicle navigation
system and other location systems. In chapter 3, the working principle of the
proposed ultrasonic positioning system is presented. The feasibility of using the
proposed system in vehicle navigation is also discussed. A prototype based on the
proposed system is implemented and presented in chapter 4. The performance of the
proposed system is evaluated. In chapter 5, the problem of dynamic positioning is
introduced and solved using Kalman filter technique. In chapter 6, scalability issues
on both the number of devices tracked and sensing areas are discussed. Chapter 7
describes a new automated vehicle design called Light Load AGV. Finally, chapter 8
summarizes and concludes the thesis.
Chapter 2

Vehicle Guiding System

The localization capability of an automated guided vehicle is the key component for providing advanced path control strategies in the industrial environment. In order to obtain enough location information about the vehicle, various vehicle guiding systems have been developed and widely used in the industry. Current AGV navigation systems can be roughly categorized into two main kinds, Fixed Path Guidance System and Free Ranging System. In both cases the basic requirement of the system is to provide enough guidance or spatial information such that the AGV can follow a pre-defined path.

2.1 Fixed Path Guidance System

For fixed path guidance, neither the control system nor the vehicle knows the current location of the vehicle. The sensors on the vehicle only sense the presence of the fixed path. A built-in closed-loop control system guides the vehicle to travel along the path until a stopper is detected. As its name implies, the path is fixed.

Reconstruction of the layout involves shutting down the whole AGV system and the paths have to be changed manually. Careful planning is a pre-requisite for constructing the path. Although reconstruction of the path is possible, we seldom do
that as the efficiency of the whole manufacturing system will be negatively affected.

2.1.1 **Inductive (Wire) Guidance**

Inductive guidance is based on Faraday's Law of electricity and magnetism. Any change in the magnetic environment of a coil of wire will induce a voltage in the coil, and vice versa. A guiding antenna consists of two coils positioned on both sides of the guide wire. Current is applied to the guide wire to produce a magnetic field and hence a voltage will be induced in the coils. When the AGV is centered on the guide wire, the voltage in the coils will be balanced. If the AGV is shifted to one side, the voltage will be increased in one coil and reduced in the opposite coil. This voltage difference can be used to generate the steering signal to control the steering motor. The working principle is shown in figure 2.1.

![Fig 2.1 Working principle of inductive guidance](image)

In the floor path installation, a floor cutting machine will be used to cut a thin slot on the floor, in which the wire is placed. This installation process is costly and time
consuming. Wire guidance is only suitable for applications for which flexibility is not a critical factor and the vehicle path layout will not be changed frequently.

2.1.2 Surface Mounted Strip Guidance

Instead of using the current-carrying wire, the surface mounted strip guidance is used for determining the vehicle path layout. A magnetic or a photo reflective tape will be stuck on the floor to form the path. A magnetic sensor/ infra-red transducer is installed under the vehicle which can detect the presence of the surface mounted. Feedback signal from the sensor will be transferred to the vehicle controller to make the vehicle steer in the direction of the guide path.

In comparison to wire guidance, the complexity for the path installation is lower for surface mounted strip guidance.

2.2 Free-Ranging System

In a Free-Ranging System, wire-guidance does not exist and there is no fixed path layout. In order to navigate in the environment, which does not benefit from the fixed path, the AGV system must have an existing map of the environment and the knowledge about the spatial information of the AGV. The vehicle position can be obtained either by dead reckoning technique or landmark navigation. When a change
to the original guide path layout is needed, there is no need for floor alterations or production interruption. The flexibility of the manufacturing system and the ability to handle a wide variety of products can both benefit from using the free-ranging AGV system. The drawback of most commercial free-ranging navigation systems is the high cost. Also, the initial setup and calibration are time consuming and expensive.

2.2.1 Laser Guidance

Reflective landmarks with predefined positions are placed in the corners of the environment. The AGV carries a laser transmitter and receiver mounted on a rotating turret with an optical encoder. The laser transmitter keeps emitting a laser beam while the turret is rotating. When the laser beam is reflected back to the laser receiver by the landmark, the angular reading will be obtained by the optical encoder. By obtaining the relative angular displacements between the vehicle and the landmarks, triangulation can be performed to calculate the absolute position of the vehicle. This method gives a high accuracy in free-range navigation at the expense of the high cost. Laser guidance also suffers with the problem that the laser transmitter and receiver have to have an exact line of sight with the reflective landmarks. Also, the environment has to be carefully designed to avoid reflective objects.
2.2.2 Inertial Guidance

This method presents the concept of dead-reckoning navigation. Gyroscopes and optical encoders are installed in the AGV to measure both the bearing and angular displacement of the internal wheels. By giving an initial position, the position of the vehicle can be calculated by using the angular and linear displacement of the vehicle [6]. The main disadvantage of dead-reckoning navigation is that the localization error cannot be bounded but is a growing function of time [7]. Normally external calibration devices like magnets embedded in the floor are needed. The Free Ranging On Grid (FROG) technology combines the inertia and magnet calibration methods [8]. As the AGV has to pass through the calibration targets, the path layout is constrained. As a result, the flexibility of this AGV system is less than other free-ranging guidance system. Also, the installation and position calibration of the embedded magnets is costly.

2.3 Other Positioning Systems

In section 2.1 and section 2.2, different vehicle navigating systems have been described. As a matter of fact, there are existing positioning systems that are designed for other applications, such as user location sensing for content-aware computer application. In this section, various location systems are described.
2.3.1 Global Positioning System

The Global Positioning System (GPS) was developed as a ranging system from known positions of satellites in space to unknown positions on land, at sea, in air and space [9]. The current NAVSTAR GPS satellite constellation system consists of a 24-stellies system. For every instant, this system provides the minimum of four satellites in good geometric position 24 hours a day, anywhere on the earth. RF signals with predefined time stamp is broadcasted by each visible satellite in turns. Once a GPS receiver receives the GPS signal, it compares the GPS system time stamp with the current time and the distance between the satellite and the receiver can be calculated using the velocity of EM wave. A GPS client determines its position expressed by latitude, longitude and elevation by trilateration using the distances measured to satellites.

The accuracy of a commercial pure GPS system is approximately 15 meters and can be improved to about 2 meters if using other compensation techniques like differential GPS. GPS performs well outdoors for tracking automobiles and vessels but it cannot be used indoors as the RF signal cannot penetrate buildings.

2.3.2 Radio Frequency based location system

A Microsoft Research group has developed a radio-frequency (RF) based system
called RADAR system for locating and tracking users inside buildings [10]. RF signal strength information is gathered at multiple receiver locations and the user’s position is obtained through triangulation. Using three RF base stations in a 1000 square meters office environment, the median resolution of the RADAR location sensing system is in the range of 2 to 3 meters.

The tracking system is based on the IEEE 802.11 WaveLAN wireless network technology which operates in a 2.4 GHz ISM band. In order to obtain the RF signal strength information, a wireless LAN client has to be installed in each of the mobile objects. As the signal strength distribution is different for each RF base station and client pair, costly and time consuming calibration has to be done to construct the predefined signal-strength database. The performance of the whole location system depends on the accuracy of the database.

2.3.4 Ultrasonic location system

Ultrasonic sensors have been widely applied to develop a precise and economical sensing system for object positioning systems. Bat ultrasonic location system [11], developed by AT&T Laboratories Cambridge, and Cricket location system [12], developed by Cambridge use ultrasonic pulse time of flight to provide a high precision 3-dimensional positioning system in the indoor environment. The main
The difference between the two systems is the system architecture. The Bat system uses moving transmitter architecture and the Cricket system uses moving receiver architecture. The illustrations of the two architectures are shown in Fig 2.2.

![Moving Transmitter and Moving Receiver](image)

**Fig 2.2 Ultrasonic location system architectures**

### 2.3.4.1 Bat Ultrasonic Location System

The Bat ultrasonic location system is based on the principle of trilateration under the moving transmitter architecture. A short pulse of ultrasound is emitted from a transmitter (a Bat) attached to the object to be located, and the time of flight (TOF) of the ultrasonic pulse will measured through a ultrasonic receiving sensors array mounted at known points on the ceiling. By making use of the velocity of the ultrasound and of TOF of the pulse, the distances from the Bat to sensor array can be calculated. Given three or more of such distances, the 3D position of the Bat can be obtained through trilateration.

Under the moving transmitter architecture, the infrastructure requires a large scale of fixed-sensor array throughout the ceiling and the sensor array has to be precisely
calibrated. Thus, the scalability, ease of deployment, and the setup cost are a challenge for researchers and still cannot be solved.

2.3.4.2 Cricket Location System

The Cricket system uses the combination of RF and ultrasonic technologies to provide location information to the attached object. In contrast to the moving transmitter architecture, beacons that transmit ultrasonic signals are mounted at the corner of the sensing area. For each time step, the main control center transmits an RF advertisement and the beacon transmits a concurrent ultrasonic pulse simultaneously. The receiver mounted on the mobile object listens for RF signals and the corresponding ultrasonic pulse. When the pulses arrive, the receiver obtains a distance estimate for the corresponding beacon by measuring the time of difference arrival between the RF signal in the velocity of light and the ultrasound in velocity of sound. The position of the mobile object will be calculated based on the distances obtained.

Under the moving receiver architecture, beacons need to advertise one by one to avoid collision. Thus the distances that the object obtains are asynchronous and the accuracy for locating a mobile object is less than that of the moving transmitter architecture.
2.4 Chapter Summary

Besides the traditional AGV navigation systems, various location systems have been developed to serve different applications. To increase the flexibility of an AGV system, free-ranging navigation is necessary but the commercial free-ranging navigation systems suffer the problem of high cost. Ultrasonic approaches for location determination provide a precise positioning with low cost. In the next chapter, the feasibility of using ultrasonic for AGV navigation will be investigated and discussed.
Chapter 3

Ultrasonic Positioning System

Using the ultrasonic approach for position determination has been addressed extensively by researchers. C. Randell [13] proposed a low cost indoor positioning system which is accurate within 25cm. Wehn and Belanger [14] point out that the main obstacle to precise range measurements is the presence of air turbulence and convection currents. A.R. Jimenez [15] designed an ultrasonic portable rod for localization of archaeological findings. The influences of strong wind on position estimated have also been investigated. Nissanka B. Priyantha et al. [16] developed an ultrasonic positioning system which provides the ability to determine the orientation of a device with 5 degrees using a “V” shaped sensor array. Among these works of research, few focus on tracking AGV using the ultrasonic approach. A low cost and precise ultrasonic positioning system for AGV navigation is proposed and discussed in this chapter.

3.1 Ultrasonic range measurement system

Ultrasonic sensors are widely applied for range detection in mobile robot applications. The principle of ultrasonic range detection is based on the properties of ultrasonic propagation in that the time taken for the ultrasonic pulse to propagate
from transmitter to receiver is proportional to their range. Solutions of measuring a reflected signal or using a transmitter-receiver pair have been developed for range measurement. Both systems have their advantages and drawbacks depending on the particular application.

### 3.1.1 Reflected signal detection

This is the simplest method of range measurement as the whole measurement can be done using single module. The working illustration is shown in figure 3.1. When the ultrasonic signal is generated and transferred to a piezoelectric transducer, an ultrasonic wave will travel outward from the transducer until it reaches a physical surface. The ultrasonic wave is then reflected back in the opposite direction until it reaches the transducer. The time-of-flight (TOF) of the ultrasonic wave propagation is counted. The distance between the reflector and the transducer can be obtained from the equation: \( d = \frac{TOF \cdot c}{2} \) where \( c \) is the velocity of sound. The drawback of this configuration is that the accuracy level depends on the reflection surface. The ultrasonic wave will be easily distorted by a rough and non-parallel reflection surface.
3.1.2 Direct signal detection

The configuration is shown in Fig 3.2. In this configuration, the ultrasonic sensing is separated into transmitter and receiver. The ultrasonic receiver detects the direct signal from the transmitter instead of the reflected signal. The distance equation is:

\[ d = TOF \cdot c \]. As the ultrasonic wave is not affected by the reflection surface, both the accuracy and the reliability are higher than the reflected signal detection configuration. In order to measure the time-of-flight of the ultrasonic wave, the receiver has to be aware when the transmitter sends the signal. Therefore, a synchronization device has to be installed on both parties. In contrast to the reflected signal detection, the complexity and the total cost of the system are higher in this configuration.
3.1.3 Signal Detection

Signal detection is an important process in the range measurement as it determines the accuracy of the time-of-flight measurement. In a typical indoor environment, ultrasound will easily be reflected by the wall or other obstacle, as shown in fig 3.3.

To tackle the indirect signal problem, the thresholding technique is applied. A trigger is used to distinguish between the desired signal and the undesirable signal. Fig. 3.4 shows the illustration of the thresholding: wave B is the targeted signal and wave C
is the reflected signal. The reflected signal arrives later than the direct signal and has lower amplitude as it travels for a longer time. The presence of wave A may be caused by a noise like jiggling a bunch of keys or an ultrasonic signal that is reflected many times. These kinds of signals normally have no predicted pattern with very low amplitude. The trigger level is set so that wave A will be eliminated and wave B can be detected easily. Once the system detects the signal, the following undesirable wave within the same reception window will be ignored.

![Ultrasonic Signal Detection Diagram](image)

**Fig 3.4 Illustration of ultrasonic signal detection**

Thresholding also suffers the problem that the accuracy level decays when the distance between the transmitter and the receiver increases. Fig. 3.4 shows the
received ultrasonic signal taken using an oscilloscope. An ultrasonic receiver is a piezoelectric device that converts ultrasonic waves (kinetic energy) into electronic signals (electricity). When the ultrasonic receiver is far away from the ultrasonic signal source, it needs more time for the electronic signal to build up in order to reach the trigger level. As shown in fig 3.5, the time for the received signal to reach the trigger level \((T_1 \text{ and } T_2)\) increases as the distance increases, and it induces error to the time-of-flight determination.

![Fig 3.5 oscilloscope observation of the received ultrasonic signal taken at 7000mm and 1500mm apart from the transmitter](image)

To solve this problem, a zone-crossing compensation is applied together with the
thresholding detection. An experiment is conducted to investigate the relation between the range and the measured time-of-flight error. Fig 3.6 shows the result of the experiment where the x-axis represents the distance between the transmitter and receiver, and the y-axis represents the measured time-of-flight error which is caused by thresholding the signal with different slope of the rising edge. The blue line shows a position correlation between the measured time-of-flight and the range and can be represented by the regression model \( y = 16.37 + 0.016x \) and shown in the black line. Given the prior knowledge about the range of the object, the accuracy level of the range measurement can be increased by compensation.

![Graph showing the relationship between measured time error and range](image)

**Fig 3.6 Relationship between measured time error and range**

### 3.1.4 Velocity of ultrasound

To obtain the range measurement, both the time-of-flight of the ultrasonic signal and the velocity of the ultrasound are required. The velocity of the ultrasound does not
depend on its frequency but on what material it is traveling in. It travels faster in
dense materials and slower in sparse materials. An approximate velocity of
ultrasound travel in air at a particular temperature can be calculated from the
following equation:

\[ C_T = C_0 \sqrt{1 + \frac{T}{273}} \]

Where:

- \( C_T \) : Velocity of ultrasound in air at specified temperature
- \( C_0 \) : Velocity of ultrasound in air at 0°C
- \( T \) : Temperature in degrees Celsius

And \( C_0 = 331.5 \text{ m/s} \)

Typically the temperature and the propagation material are the main factors that
affecting the velocity of ultrasound. Other factors such as air turbulence, convective
currents, atmospheric pressure, and humidity also affect the sensor readings but the
influential is insignificant and can be ignored in normal working environments.
3.2 Two-Dimensional Position Determination

For free-ranging vehicle navigation, the two-dimension coordinate of the vehicle with respect of a frame of predefined reference has to be determined. Based on the range measurements obtained from the object to the fixed reference, trilateration can be applied to determinate the position of the object. In chapter 2, two kinds of time-of-flight based trilateration architecture have been discussed, which are moving transmitter architecture and the moving receiver architecture. In our system, the moving receiver architecture is used as it gives better scalability and incurs lower deployment cost.

3.2.1 Geometrical Illustration for Trilateration

Generally, the position of the object in the 2D space can be determined by measuring its distances from three references at known positions. The working principle of trilateration is shown in fig 3.7 and fig 3.8.

![Nominal positions](image)

**Fig 3.7 Two range measurements obtained**
For each range measurements \((r_i)\) obtained, a circle with radius \(r_i\) can be drawn with the center at the reference point. The circumference of the circle indicates the possible location of the tracked object. Assume two range measurements \((r_i \text{ and } r_j)\) are obtained and the tracked object is not in line with the reference points. Two intersections are formed when drawing the two circles and the possible position of the tracked object is located at either one of the intersections. In order to determine the true position, a third range measurement has to be obtained.

![Diagram showing two circles with intersections for two range measurements and a true position for a third measurement](image)

**Fig 3.8 Three range measurements obtained**

Assume the third reference point is not in line with the first two reference points.

When the third circle is drawn using the third range measurement \(r_3\), it will intersect with one of the nominal positions and the true position of the tracked object can be determined.
3.2.2 Mathematical Model for Trilateration

Consider the following configuration shown in figure 3.9 that consists of an object being tracked at \((u, v)\) and three reference points located at \((x_1, y_1)\), \((x_2, y_2)\) and \((x_3, y_3)\), respectively. Based on the range measurement, distances between the tracked object and the reference points \((l_1, l_2, l_3)\) can be obtained. By simple geometry, a family of three equations \(l_i = \sqrt{(x_i - u)^2 + (y_i - v)^2}\) for \(i = \{1, 2, 3\}\) can be formed. After solving the equations, the position of the object being tracked \((u, v)\) can be determined.

![Diagram](image)

Fig 3.9: An example of Trilateration configuration

3.3 Chapter Summary

The development of an ultrasonic based 2-dimensional positioning system is presented in this chapter. Position of the object is determined based on trilateration with moving receiver architecture. Trilateration is performed which makes use of three range measurements between the object being tracked and three reference
points with known positions. An accurate range measurement system is critical for trilateration. In our proposed system, range measurement is achieved by using the time-of-flight of the ultrasonic propagation from the transmitter to the receiver. Thresholding with compensation is used to determine the time-of-flight of the ultrasound, and RF signal is used as a trigger to synchronize the measurement clock.
Chapter 4

Ultrasonic Positioning System Prototype Development

Based on the ultrasonic positioning scheme proposed, a prototype of the system is implemented. An Experiment and the evaluation of the proposed system are presented at the end of this chapter.

4.1 Prototype Development

The operating principles of the ultrasonic positioning system rely on the time-of-flight method discussed in chapter 3. The prototype was developed to test the concept and the resolution of the positioning.

4.1.1 System Architecture

To perform trilateration, at least three transmitter-to-receiver range measurements are required. When the fourth range measurement is available, an estimate of the error of the positioning result can be obtained. The error of the positioning result can be used to estimate the performance of the system and we can make use of the data to increase the accuracy. In our prototype system, four reference points (beacons) are placed at the four corners of the testing environment equipped with ultrasonic transmitter module. An AGV equipped with the ultrasonic receiver module is placed
in the testing environment. A computer is linked to the system for sending commands and data acquisition. An illustration of the system architecture is shown in figure 4.1.

![System architecture diagram]

**Fig 4.1: System architecture**

For each cycle, the central computer sends a command to ask the beacon to broadcast ultrasounds one after the other for every 50ms using the RF signal. At the same time, the receiver module mounted on the vehicle receives the RF signal and starts the internal timer in the microprocessor. After the signal detection circuitry receives the ultrasound from the beacon, the timer stops and the time-of-flight of the ultrasound will be measured and sent back to the central computer. The 50ms waiting time for each ultrasonic broadcast is to avoid collision of the ultrasounds.
4.1.2 Hardware Implementation

Figures 4.2 and 4.3 show the hardware architectures for transmitter module and receiver module. The major difference between these two modules is that the transmitter module uses a signal generator and the receiver module uses signal detection.

Fig 4.2: Hardware architecture for beacon

Fig 4.3: Hardware architecture for vehicle

The circuitry consists of the following components:

**Microprocessor**: A 8051 compatible AT89C52 microprocessor by ATMEL is used in our system. The processor operates at 24 MHz. The built-in timer is used to measure the time-of-flight.

**RF Module**: A dual channel (315/433 MHz) RF module is used for communication. Timer triggering and data communication are the major functions of the module.
**Ultrasonic Transducer:** A piezoelectric open-air ultrasonic transducer is used in the system. The transducer can convert ultrasonic signal to electricity and vice versa. A 40 kHz 12V signal is used to drive the transducer.

**Amplifier:** A two-step amplifier with 100x amplification is used to amplify the ultrasonic signal.

**Signal Generation:** A 40 kHz 12V signal is generated to drive the ultrasonic transducer.

**Signal Detection:** A comparator is used to compare the received signal to the preset trigger level. Once the signal is detected, the processor timer is stopped.

### 4.1.3 Software Implementation

Ultrasonic positioning system software was developed using LabVIEW and is shown in figure 4.4. The software provides the following functions:

1. Calibration of the beacons
2. Communication with the microprocessor at the transmitter and receiver module using RF signal
3. Performs trilateration to calculate the position of the Light Load AGV
4. Motion control of the AGV
4.1.4 **Pseudo Omni-Directional Ultrasonic Sensor Array**

Figure 4.5 shows the radiation pattern of an ultrasonic transducer. The received signal strength drops when the receiver-transmitter pair is not in line. To maintain at least 50% of the received signal (-6dB), the receiver-transmitter pair should be aligned within ±30°. This kind of angular limitation of the ultrasonic transducer creates a “dead zone” in the sensing environment and downgrades the positioning performance.
Fig 4.5: Radiation Pattern of an ultrasonic transducer

To overcome the angular limitation of the sensor, a special arranged sensor array is designed and shown in figure 4.6. The sensor array consists of seven sensors and the angle between each two sensors in the three dimensional space is 60°. Under this configuration, the ultrasonic signal strength can be maintained to at least 50% of the maximum signal strength for the whole hemisphere area.

Fig 4.6: Omni-directional ultrasonic sensor array
4.1.5 Agile Calibration for the beacon

Various types of ultrasonic location systems have been proposed but very few of them address the problem of beacon calibration. Trilateration makes use of the range measurements between the reference points and the object being tracked to calculate the object position. The accuracy of the position of the fixed reference point strongly affects the performance of the trilateration. No matter which ultrasonic architecture is used, a time consuming and costly manual calibration has to been performed before the system begins its operation. To replace the manual calibration, an agile calibration process is developed using a specially designed calibration device.

Figure 4.7 shows the geometry illustration of the calibration. To calibrate the position of the beacons, a calibration device is placed in the testing environment. The calibration device consists of two ultrasonic receiver modules mounted at fixed separation $l$. By taking the range measurements $r_1$ and $r_2$, the position of the beacon can be obtained by the following equations:

$$x_b = \frac{r_1^2 - r_2^2 - l^2}{2l}$$
$$y_b = \sqrt{r_1^2 - x_b^2}$$

Where: $x_b$ is the x-axis displacement of the beacon from $C_i$

$y_b$ is the y-axis displacement of the beacon from $C_i$
Fig 4.7: Calibration process

After applying the calibration process, the relative location of all four beacons to the calibration device can be obtained.

4.1.6 Geometry Model of Trilateration

Since the object being tracked is assumed to be inside the boundary of the beacons, only two range measurements are needed to determine the object position. The geometry model for solving the object position based on two range measurements is presented. By applying the model, a total of eight position readings are generated.

Consider the following geometric configuration for positioning. In the calibration process, the coordinates of the beacons are collected and transformed to the system coordinate frame. By the range measurement system, \( r_{b1} \) to \( r_{b4} \) can be obtained
Fig 4.8 Geometric Configuration

First, the angular information is retrieved using cosine law:

\[
\theta_{1a} = \frac{r_{b1}^2 + (x_{b1} - x_{b4})^2 + (y_{b1} - y_{b4})^2 - r_{b4}^2}{2 \cdot r_{b1} \cdot \sqrt{(x_{b1} - x_{b4})^2 + (y_{b1} - y_{b4})^2}}
\]

\[
\theta_{1b} = \frac{r_{b1}^2 + (x_{b1} - x_{b2})^2 + (y_{b1} - y_{b2})^2 - r_{b2}^2}{2 \cdot r_{b1} \cdot \sqrt{(x_{b1} - x_{b2})^2 + (y_{b1} - y_{b2})^2}}
\]

\[
\theta_{2a} = \frac{r_{b2}^2 + (x_{b2} - x_{b1})^2 + (y_{b2} - y_{b1})^2 - r_{b1}^2}{2 \cdot r_{b2} \cdot \sqrt{(x_{b2} - x_{b1})^2 + (y_{b2} - y_{b1})^2}}
\]

\[
\theta_{2b} = \frac{r_{b2}^2 + (x_{b2} - x_{b3})^2 + (y_{b2} - y_{b3})^2 - r_{b3}^2}{2 \cdot r_{b2} \cdot \sqrt{(x_{b2} - x_{b3})^2 + (y_{b2} - y_{b3})^2}}
\]

\[
\theta_{3a} = \frac{r_{b3}^2 + (x_{b3} - x_{b2})^2 + (y_{b3} - y_{b2})^2 - r_{b2}^2}{2 \cdot r_{b3} \cdot \sqrt{(x_{b3} - x_{b2})^2 + (y_{b3} - y_{b2})^2}}
\]

\[
\theta_{3b} = \frac{r_{b3}^2 + (x_{b3} - x_{b4})^2 + (y_{b3} - y_{b4})^2 - r_{b4}^2}{2 \cdot r_{b3} \cdot \sqrt{(x_{b3} - x_{b4})^2 + (y_{b3} - y_{b4})^2}}
\]

\[
\theta_{4a} = \frac{r_{b4}^2 + (x_{b4} - x_{b3})^2 + (y_{b4} - y_{b3})^2 - r_{b3}^2}{2 \cdot r_{b4} \cdot \sqrt{(x_{b4} - x_{b3})^2 + (y_{b4} - y_{b3})^2}}
\]

\[
\theta_{4b} = \frac{r_{b4}^2 + (x_{b4} - x_{b1})^2 + (y_{b4} - y_{b1})^2 - r_{b1}^2}{2 \cdot r_{b4} \cdot \sqrt{(x_{b4} - x_{b1})^2 + (y_{b4} - y_{b1})^2}}
\]

By applying the following trigonometry model shown in table 4.1, a total of eight position readings can be calculated.
\[ \theta' = \tan^{-1}\left(\frac{y_{b4} - y_{b1}}{x_{b1} - x_{b4}}\right) \]
\[ x_v = x_{b1} + r_{b1} \cdot \cos(\theta_{1a} - \theta') \]
\[ y_v = y_{b1} + r_{b1} \cdot \sin(\theta_{1a} - \theta') \]

\[ \theta' = \tan^{-1}\left(\frac{y_{b4} - y_{b1}}{x_{b1} - x_{b4}}\right) \]
\[ x_v = x_{b4} + r_{b4} \cdot \cos(\theta_{4b} + \theta') \]
\[ y_v = y_{b4} - r_{b4} \cdot \sin(\theta_{4b} + \theta') \]

\[ \theta' = \tan^{-1}\left(\frac{x_{b3} - x_{b4}}{y_{b4} - y_{b3}}\right) \]
\[ x_v = x_{b4} + r_{b4} \cdot \sin(\theta_{4a} + \theta') \]
\[ y_v = y_{b4} - r_{b4} \cdot \cos(\theta_{4a} + \theta') \]

\[ \theta' = \tan^{-1}\left(\frac{x_{b3} - x_{b4}}{y_{b4} - y_{b3}}\right) \]
\[ x_v = x_{b3} + r_{b3} \cdot \sin(\theta_{3b} - \theta') \]
\[ y_v = y_{b3} + r_{b3} \cdot \cos(\theta_{3b} - \theta') \]

\[ \theta' = \tan^{-1}\left(\frac{y_{b3} - y_{b2}}{x_{b2} - x_{b3}}\right) \]
\[ x_v = x_{b3} + r_{b3} \cdot \cos(\theta_{3a} - \theta') \]
\[ y_v = y_{b3} + r_{b3} \cdot \sin(\theta_{3a} - \theta') \]

35
\[ \theta' = \tan^{-1}\left( \frac{y_{b1} - y_{b2}}{x_{b2} - x_{b1}} \right) \]
\[ x_v = x_{b2} - r_{b2} \cdot \cos(\theta_{2a} + \theta') \]
\[ y_v = y_{b2} + r_{b2} \cdot \sin(\theta_{2a} + \theta') \]

\[ \theta' = \tan^{-1}\left( \frac{x_{b2} - x_{b1}}{y_{b1} - y_{b2}} \right) \]
\[ x_v = x_{b1} - r_{b1} \cdot \sin(\theta_{1b} + \theta') \]
\[ y_v = y_{b1} - r_{b1} \cdot \cos(\theta_{1b} + \theta') \]

Table 4.1: Summary of Trigonometry model

4.2 Effect of obstacle in positioning

When there is an obstacle appearing in the sensing area, the exact line of sight between the reference landmark and the object being tracked may be blocked. This results in a longer range measurement as the ultrasound will propagate longer to the
vehicle due to refraction. As a result, the position estimation of the object will be biased by this kind of inaccurate range measurement, as shown in figure 4.9

![Diagram showing the effect of an obstacle on positioning](image)

**Fig 4.9: Effect of the obstacle in positioning**

4.2.1 **Outlier rejection using squared error algorithm**

By applying the geometrical model of trilateration, a total of eight position readings can be obtained. This kind of redundancy provides us with the possibility to improve the performance of the system [17]. The simplest way to make use of the redundant data is to estimate the position by taking average of the data set. The averaging provides the least computational cost compared with other algorithms but the result will be easily biased by the outlier.

In our proposed positioning system, a squared error algorithm is applied to perform the outlier rejection. In the beginning of the iteration, the centroid of the data set,
which is the average of the data set, is calculated. The squared error of the position readings \((x_i, y_i)\) is defined as:

\[
se = \sum_{i=1}^{N} \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2}
\]

Where: \(N\) is the number of data in the data set

\((x_c, y_c)\) is the centroid of the data set

After the squared error is calculated, it is compared with a predefined threshold. If the squared error exceeds the threshold, it means that an outlier probably exists in the data set. Then the data set is searched and the data that is farthest from the centroid is filtered out. The algorithm is applied recursively until the calculated squared error is lower than the threshold.

The squared error algorithm can also be used to eliminate the effect of the obstacle in the sensing area. When an obstacle presents in the sensing area, one or more ultrasonic signals will be blocked by the obstacle. Due to the refractive property of the ultrasonic wave, the receiver will receive the refracted signal even if the transmitter-receiver pair can not maintain a line-of-sight. The time-of-flight of the signal will become longer as the propagating length of the refracted signal is longer than the real distance and the error will degrade the performance of the positioning system. By applying the squared error algorithm, this kind of time-of-flight error will be treated as an outlier and rejected.
4.2.2 Line-of-sight detector for the case of multiple obstacles

The proposed squared-error algorithm provides an iterative means to eliminate outlier, possibly erroneous signals due to the presence of single obstacle. In the case of multiple obstacles existing in the sensing area, more than one reference landmark may be blocked by the obstacles. In this case, the squared-error algorithm may fail. One possible way to tackle the problem may be to add a CMOS image captor in each reference landmark and a light source in the vehicle. By detecting the light emitted from the vehicle, a higher weighting can be assigned to the signal with exact line-of-sight so that the case of multiple obstacles can be solved.

4.3 Experiment

The ultrasonic positioning system experiment is carried out in the laboratory room, which is assumed to have a flat floor plane. An Ultrasonic receiver module is equipped on a Light Load AGV and four transmitter modules (beacons) are fixed at the four corners of the testing area. The setup of the experiment is shown in figure 4.10.
4.3.1 AGV Positioning Experiment

To evaluate the performance of the ultrasonic positioning system, the static position of the AGV is estimated by the positioning system while the AGV follows a predefined trajectory. The experimental positioning result is shown in Fig 4.11.
Fig 4.11: Result of AGV positioning

The black line represents the true trajectory of the AGV and the red line is the estimated AGV position obtained from our proposed positioning system. The result of the positioning experiment is promising. The figure shows that the position obtained from the system can estimate the true trajectory accurately. The error mean is the position estimation is 6.8mm with standard deviation of 5.4mm.

4.3.2 Outliner rejection experiment

To evaluate the effectiveness of the outliner rejection algorithm, an obstacle is placed in front of one of the beacons, as shown in figure 4.12. As we discussed in the previous chapter, the existence of an obstacle will create a longer time-of-flight
reading which is treated as an outlier. The estimated position of the AVG is calculated based on the averaging and squared error algorithm respectively. Both cases with and without the existence of the obstacle are studied. The result of the experiment is shown in figure 4.13.

Fig 4.12: Photo of the experiment setup with obstacle
Fig 4.13: Result of outlier rejection experiment

When there is no obstacle in the testing environment, all the time-of-flight measurements represent the true distance of the transmitter-receiver pair. The figure shows that the estimated positions of the two algorithms are similar. When an obstacle is placed in front of a beacon, the time-of-flight measured from this beacon becomes an outlier. When the averaging algorithm is used, the estimated position of the AGV is distorted and shifted to the opposite of the obstacle. The estimated position of the AGV is similar to the case without obstacle. It shows the effectiveness of the squared error algorithm in outlier rejection.
4.4 Chapter Summary

A precision positioning system based on the ultrasonic time-of-flight range measurement and trilateration is proposed. The positioning system is implemented and a prototype of the system, including both hardware and software, is developed. Various measures, including outlier rejection and omni-direction transducer array are used to improve the performance of the system. An experiment is performed to evaluate the performance of the positioning system and the results show the system can estimate the position of an AGV accurately. Table 4.2 and 4.3 summarize the comparison among the existing positioning systems and AGV navigation system.

<table>
<thead>
<tr>
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<th>Active Bat</th>
<th>Cricket</th>
<th>Our proposed system</th>
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<tr>
<td>Accuracy</td>
<td>30mm</td>
<td>20mm</td>
<td>6.8mm</td>
</tr>
<tr>
<td>Scalability on</td>
<td>Deploying</td>
<td>Cycle time</td>
<td>Improved by</td>
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<td>individual</td>
<td>increases with no.</td>
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<tr>
<td></td>
<td>system in each sensing</td>
<td>of landmarks</td>
<td>configuration</td>
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<td></td>
<td>zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scalability on</td>
<td>Cycle time</td>
<td>Estimating all</td>
<td>Estimating all</td>
</tr>
<tr>
<td>number of device</td>
<td>increases with no.</td>
<td>object positions at</td>
<td>object positions at</td>
</tr>
<tr>
<td></td>
<td>of device being</td>
<td>the same time</td>
<td>the same time</td>
</tr>
<tr>
<td></td>
<td>tracked</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ease of deployment</td>
<td>Complex</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td></td>
<td>infrastructure</td>
<td></td>
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</tr>
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</table>

Table 4.2: Comparison with existing ultrasonic positioning system
<table>
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<th>Inductive wire guidance</th>
<th>Laser guidance</th>
<th>Our proposed system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible routing</td>
<td>poor</td>
<td>Good</td>
<td>good</td>
</tr>
<tr>
<td>Cost</td>
<td>Low hardware cost/high installation cost</td>
<td>High hardware and installation costs</td>
<td>Low hardware and installation costs</td>
</tr>
<tr>
<td>Ease of deployment</td>
<td>Guided wire has to be embedded into the floor</td>
<td>Complex calibration device installation</td>
<td>easy</td>
</tr>
</tbody>
</table>

Table 4.3: Comparison with existing AGV navigation systems
Chapter 5

Dynamic Positioning

In the last chapter we show that the ultrasonic positioning system can achieve a high precise level positioning when the vehicle is in a static state. In static positioning, the location of the vehicle can be easily computed as all the range measurements obtained reflect the distance between the beacons and stationary vehicle. In contrast, for the case of dynamic positioning, the vehicle is moving around. At different time steps, the range measurements obtained do not represent the same position of the vehicle, but rather different snapshots of the moving vehicle, creating an asynchronous problem. The concept of the problem is shown in figure 5.1.

![Diagram](image)

**Fig 5.1: Asynchronous problem**

To solve the problem of the asynchronous range measurement in the dynamic positioning, we designed a recursive Kalman Filter for estimating the position of the vehicle.
The Kalman Filter is a set of mathematical equations that provide an efficient recursive means to estimate the state of a process, in a way that minimizes the mean of the squared error [18]. The Kalman Filter updates the estimate about the state of the vehicle every time a new range measurement is acquired. Then the most recent distance sample and its state are used to project ahead and produce an estimate of where the vehicle might be in the next time-step. After obtaining the distance sample at the next time-step, the Kalman Filter will first correct the state of the vehicle based on the actual distance sample. The covariance matrix of the vehicle’s state will be updated as time goes by.

5.1 Position-velocity Kalman Tracking Filter

5.1.1 Mathematical Model

Dynamic Model

\[ X_{n+1} = \Phi X_n \]

Where:

\[
X_n = \begin{bmatrix}
    x_n \\
    y_n \\
    \dot{x}_n \\
    \dot{y}_n
\end{bmatrix}
\]
\[ \Phi = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

\[ X_n : \text{Vehicle state matrix consists of position and velocity components at scan } n. \]

\[ x_n : x \text{ coordinate of the vehicle.} \]

\[ y_n : y \text{ coordinate of the vehicle.} \]

\[ \dot{x}_n : x \text{ direction velocity component of the vehicle.} \]

\[ \dot{y}_n : y \text{ direction velocity component of the vehicle.} \]

\[ \Phi : \text{State transitional matrix of the model.} \]

\[ \Delta t \text{ Time difference between scan } n \text{ and } n-1 \]

**Measurement Model**

\[ Z_n = HX_n \]

Where:

\[ Z_n = \begin{bmatrix} x_{m(n)} \\ y_{m(n)} \end{bmatrix} \]

\[ H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \]

And,

\[ x_{m(n)} : x \text{ coordinate obtained by triangulation at scan } n \]
$y_{m(n)}$: $y$ coordinate obtained by triangulation at scan $n$

$Z$: Actual measurement obtained by triangulation.

$H$: Observation matrix.

The tracking geometry illustration is shown in fig 5.2.

**Fig 5.2: Two-dimensional tracking geometry**
\[ x_{m(n)} = x_{b1} - r_{b1(n)} \cdot \cos \left( \theta_{1(n)} + \text{sign}(y_{b1} - y_{b4}) \cdot \tan^{-1} \left( \frac{y_{b4} - y_{b1}}{x_{b4} - x_{b1}} \right) \right) \]

\[ y_{m(n)} = y_{b1} - r_{b1(n)} \cdot \sin \left( \theta_{1(n)} + \text{sign}(y_{b1} - y_{b4}) \cdot \tan^{-1} \left( \frac{y_{b4} - y_{b1}}{x_{b4} - x_{b1}} \right) \right) \quad \text{for } n=1,5,9,\ldots \]

\[ x_{m(n)} = x_{b2} - r_{b2(n)} \cdot \sin \left( \theta_{2(n)} + \text{sign}(x_{b2} - x_{b1}) \cdot \tan^{-1} \left( \frac{x_{b1} - x_{b2}}{y_{b1} - y_{b2}} \right) \right) \]

\[ y_{m(n)} = y_{b2} + r_{b2(n)} \cdot \cos \left( \theta_{2(n)} + \text{sign}(x_{b2} - x_{b1}) \cdot \tan^{-1} \left( \frac{x_{b1} - x_{b2}}{y_{b1} - y_{b2}} \right) \right) \quad \text{for } n=2,6,10,\ldots \]

\[ x_{m(n)} = x_{b3} + r_{b3(n)} \cdot \cos \left( \theta_{3(n)} + \text{sign}(y_{b2} - y_{b3}) \cdot \tan^{-1} \left( \frac{y_{b2} - y_{b3}}{x_{b2} - x_{b3}} \right) \right) \]

\[ y_{m(n)} = y_{b3} + r_{b3(n)} \cdot \sin \left( \theta_{3(n)} + \text{sign}(y_{b2} - y_{b3}) \cdot \tan^{-1} \left( \frac{y_{b2} - y_{b3}}{x_{b2} - x_{b3}} \right) \right) \quad \text{for } n=3,7,11,\ldots \]

\[ x_{m(n)} = x_{b4} + r_{b4(n)} \cdot \sin \left( \theta_{4(n)} + \text{sign}(x_{b3} - x_{b4}) \cdot \tan^{-1} \left( \frac{x_{b2} - x_{b3}}{y_{b2} - y_{b3}} \right) \right) \]

\[ y_{m(n)} = y_{b4} - r_{b4(n)} \cdot \cos \left( \theta_{4(n)} + \text{sign}(x_{b3} - x_{b4}) \cdot \tan^{-1} \left( \frac{x_{b3} - x_{b4}}{y_{b3} - y_{b4}} \right) \right) \quad \text{for } n=4,8,12,\ldots \]

Where:

\[ x_{bi} : x \text{ coordinate of beacon } i \]
\[ y_{bi} : y \text{ coordinate of beacon } i \]
\[ r_{bi(n)} = r_{mbi(n)} + v(n) \]
\[ r_{bi(n)} : \text{Range measurement between beacon } i \text{ and the vehicle at scan } n \]
\[ r_{mbi(n)} : \text{Measured range between beacon } i \text{ and the vehicle at scan } n \]
\( \nu(n) \): Random noise on range measurement at scan \( n \)

\[
\theta_{1(n)} = \cos^{-1} \left( \frac{(x_{b1} - x_{b4})^2 + (y_{b1} - y_{b4})^2 + r_{b1(n)}^2 - r_{b4(n)}^2}{2 \cdot \sqrt{(x_{b1} - x_{b4})^2 + (y_{b1} - y_{b4})^2} \cdot r_{b1(n)}} \right)
\]

\[
\theta_{2(n)} = \cos^{-1} \left( \frac{(x_{b2} - x_{b1})^2 + (y_{b2} - y_{b1})^2 + r_{b2(n)}^2 - r_{b1(n)}^2}{2 \cdot \sqrt{(x_{b2} - x_{b1})^2 + (y_{b2} - y_{b1})^2} \cdot r_{b2(n)}} \right)
\]

\[
\theta_{3(n)} = \cos^{-1} \left( \frac{(x_{b3} - x_{b2})^2 + (y_{b3} - y_{b2})^2 + r_{b3(n)}^2 - r_{b2(n)}^2}{2 \cdot \sqrt{(x_{b3} - x_{b2})^2 + (y_{b3} - y_{b2})^2} \cdot r_{b3(n)}} \right)
\]

\[
\theta_{4(n)} = \cos^{-1} \left( \frac{(x_{b4} - x_{b3})^2 + (y_{b4} - y_{b3})^2 + r_{b4(n)}^2 - r_{b3(n)}^2}{2 \cdot \sqrt{(x_{b4} - x_{b3})^2 + (y_{b4} - y_{b3})^2} \cdot r_{b4(n)}} \right)
\]
5.1.2 Kalman Filter Operation Procedure

The operation cycle of the Kalman Filter can be classified into three steps, which are shown in figure 5.3.

![Diagram of Kalman Filter operation cycle]

**Fig 5.3: Kalman Filter operation cycle**

**Initialization step**

In the initialization step, since we do not have prior knowledge about the state, a null 4x1 matrix will be assigned to the initial state matrix. The covariance matrix $P_n$ will tend to a steady state quickly and then remains constant given that $Q$ and $R$ are constant [19]. So we can either compute the $P_0$ by running the system offline or a random generated $P_0$ matrix can be used.

**Prediction step**

In the prediction step, the Kalman Filter will make use of the most recent position sample and its internal state to project ahead to calculate the estimate position and
velocity of the vehicle at the next time-step.

**Filtering equations for Prediction step**

Projection of the state ahead:

\[ X_n^{(-)} = \Phi X_{n-1}^{(+)} \]

\[ \dot{x}_n = (x_n - x_{n-1}) / \Delta t \]

\[ \dot{y}_n = (y_n - y_{n-1}) / \Delta t \]

Where:

\( X_n^{(-)} \): State estimate at scan \( n \) before processing the measurement \( Z_n \)

\( X_n^{(+)} \): State estimate at scan \( n \) given the knowledge of the measurement \( Z_n \)

Projection of the error covariance ahead:

\[ P_n^{(-)} = \Phi P_{n-1}^{(+)} \Phi^T + Q \]

Where:

\( P_n^{(-)} \): Covariance matrix of estimation errors before processing the measurement \( Z_n \)

\( P_n^{(+)} \): Covariance matrix of estimation errors given the knowledge of the measurement \( Z_n \)

\( Q = \sigma_p^2 \): Covariance of the process noise
Filtering equations for the correction step

Calculation of the Kalman gain:

\[ K_n = P_n^{(-)} H^T (H P_n^{(-)} H^T + R)^{-1} \]

Where:

\[ R = \sigma_m^2 \]: Covariance of the measurement noise

\[ K_n \]: Kalman gain used to weight the output between the predicted state and the actual measurement

Update the state estimate:

\[ X_n^{(+)} = X_n^{(-)} + K_n (Z_n - H X_n^{(-)}) \]

Update the error covariance:

\[ P_n^{(+)} = (I - K_n H) P_n^{(-)} \]

6.2 Simulation

In order to investigate the performance of the Kalman filter in dynamic positioning, a simulator that provides us with the necessary functionality to analyze the Kalman Filter using different system settings is implemented.
A simulation program is developed using MatLab to simulate the effect of the Kalman Filter in dynamic positioning. In the simulation model, the standard deviation of the range measurement error is set as 10mm. The object being tracked is placed at the starting point and follows a defined pathway to the end point. In imitating to the actual environment, variation will be included into the speed and the bearing of the object. The result of the simulation is shown in figure 5.4.

![Graph showing trajectory](image)

**Fig 5.4 Trajectory of the object with velocity of 2m/s**

The result shows that although trilateration by moving receiver architecture can be applied to track the position of the object when the object is moving, the positioning accuracy is bounded by the working principle of the architecture. To avoid the signal collision, each beacon can only broadcast the signal after the previous beacon’s signal is diminished, and it induces the asynchronous range measurement problem to
the position system. To increase the accuracy of dynamic positioning, the Kalman filter is implemented and the results are promising. By predicting the state of the object and correcting the measurement by the prediction, the accuracy for dynamic position is increased.

![Graph showing Squared Error distribution for a vehicle with velocity of 2m/s.](image)

Fig 5.5 Squared Error distribution for a vehicle with velocity of 2m/s.
Fig 5.6 Squared Error distribution for an object with velocity of 1m/s

Fig 5.7 Squared Error distribution for an object with velocity of 0.5m/s
Figures 5.5, 5.6 and 5.7 show that the effect of the Kalman-filter increases when the velocity of the object increases. One should notice that Kalman filter has to undergo a "warm-up" period as the prior knowledge about the state of the object at the very beginning. That is the reason why the positioning error is great for the first few time steps.

Fig 5.8 Error means comparison under different velocities

Fig 5.9 Error S.D. comparison under different velocities

Figures 5.8 and 5.9 show the comparison of dynamic positioning under different velocities. When the result of the "warm up" period is ignored, a great improvement can be found when using the Kalman filter to perform dynamic positioning. At the
velocity of 2m/s, the error mean for using trilateration is 220mm and can be improved to 186mm when combining the Kalman filter technique.

5.2 Chapter summary

The ability to create a reliable and accurate dynamic positioning system is important for vehicle navigation in AGV systems. Although trilateration using moving receiver architecture can provide good scalability and multiple object tracking, it suffers the asynchronous range measurement problem in dynamic positioning. By applying the Kalman filter technique into trilateration using moving receiver architecture, the performance of dynamic positioning can be improved.
Chapter 6

Scalability Analysis

For an AGV system that operates in an industrial environment, it is anticipated that a large number of vehicles will require location information for navigation in a large area. In the previous chapter, a prototype of the ultrasonic positioning system was developed and it demonstrates the feasibility of using ultrasound for AGV navigation.

In this chapter, the scalability issue of the system is discussed.

6.1 Scalability on number of tracked objects

In the moving transmitter architecture, the objects being tracked need to broadcast an ultrasonic signal one by one to avoid signal interference and collision. In contrast, the moving receiver architecture scales better as the density of objects increases. This is because the RF and ultrasonic channel use depends on the number of beacons and is independent of the number of objects being tracked.

6.2 Scalability on location sensing area

The maximum propagation length for an ultrasonic signal is about ten meters. This limits the maximum location sensing area when developing the ultrasonic positioning system. For our developed prototype, the maximum sensing area is 8m X 8m.
6.2.1 Context aware application

For the location system that targets context aware applications like the Cricket and Active Bat Systems, this limitation can be removed as the system is applied in an office environment, which is segmented into different zones.

A stand-alone system is used for each office room to determine the local position and send the information to the central computer system. The global position can be calculated in the central computer. The working principle of the multiple room tracking is shown in figure 6.1.

![Diagram of multiple room tracking for Active Bat System][1]

**Fig 6.1: Multiple rooms tracking for Active Bat System [20]**

Under this segmented architecture, the boundary of the sensing area depends on the network infrastructure that connects the receiver matrixes to the central database.
6.2.3 Vehicle navigation application

Unlike the context aware applications, position of the vehicle has to be obtained throughout the whole area in vehicle navigation application. For our proposed system, to deploy the location system in a typical workshop sized 50m X 50, a 6 X 6 sensor matrix has to be installed. For each of the ultrasonic beacons, 50ms is needed to broadcast its position every cycle. This includes 30ms for the ultrasonic propagation diminishing and 20ms overhead. If every receiver has to broadcast separately, the cycle time for positioning comes 1.8s. This means that only a 0.56Hz refresh rate can be achieved. Under such a low positioning refresh rate, the dynamic positioning performance will be degraded heavily and precision vehicle control is hard to achieve.

One may wonder, “Can multiple beacons be broadcast simultaneously?” The problem of multiple beacons being broadcast simultaneously is shown in figure 6.2. When the object being tracked is passing through the red zone stated in the figure, beacon signals from two different beacons will reach the receiver module at the same time. The system cannot determine at which side the object should be located.
To increase the scalability of the location sensing area, the system infrastructure
should have the ability to extend without affecting the overall performance. In order
to achieve the goal, the system infrastructure should consist of the following abilities:

1. For every signal broadcasting, no collision should occur.
2. The system configuration is repeatable
3. At least three beacon range measurements can be obtained anywhere inside the
   sensing area.

6.3 Sensor deployment using honey-comb configuration

A honey-comb configuration design is developed to solve the scalability issue.

Instead of using four beacons in the corners, six beacons are used and a honey-comb
structure is formed using this configuration. Figure 6.3 shows the illustration of the
honey-comb configuration. Each color in the figure represents a beacon group that broadcasts at a time step. The overall system configuration is repeatable and figure 6.4 shows the layout of the expanded infrastructure with a total of 19 sensing zones consisting of 54 beacons. At each of the time steps, 9 beacons will broadcast their position simultaneously without colliding with each other.

Fig 6.3: Honey-comb system configuration
Fig 6.4: Expanded infrastructure

To determine the exact position of the vehicle, at least 3 beacon range measurements are needed to perform the trilateration. One of the properties of the honey-comb configuration is that at least 3 beacon range measurements can be obtained anywhere in the sensing zone. The maximum sensor coverage the configuration can achieve is six when the object being tracked is located at the center of the sensing area. The sensor coverage map can be found in figure 6.5.
6.4 Sensor deployment using two-dimensional triangulation

Triangulations appeared originally in the category of topology and now they play an important role for computing fixed point position [21]. There is a wide variety of triangulation methods available and the most common one is the two-dimensional algorithm [22]. The two-dimensional algorithm is modular with two main modules: point generation and mesh construction, and is shown in figure 6.6. Although the two-dimensional triangulation provides a sensor deployment with a minimal number of nodes, the group broadcasting assignment is complex to avoid signal collision. Due to this reason, the honey-comb sensor deployment layout is used in our proposed system.

6.5 Chapter Summary

Scalability is an important issue in vehicle navigation. For the scalability of the
number of tracked object, as our proposed system uses the moving receiver architecture, a satisfying scalability can be achieved. For the scalability of the sensing area, a honey-comb system configuration is developed to solve the fundamental problem of ultrasonic positioning, which is the limited propagation range of ultrasound.
Chapter 7

Flexible Light Load Automated Guided Vehicle

7.1 Introduction

The classical use of AGV is for material handling of large loads in extensive manufacturing plants or warehouses. The AGV can pick up and drop off loads and transfer them automatically. Various types of AGV, including Towing, Unit load, Pallet type and Fork lifting vehicles have been developed to handle different types and sizes of loads. In light industries like consumer electronics and apparel industry, loads are usually small in size and in bundle form. Production and assembly are usually performed at bench-top workstations with operators being seated. For such a manufacturing environment, the classical AGV system is no longer suitable for the material handling duty and a new kind of AGV has to be developed to fit the special need [21].

For this reason, the concept of a flexible light load AGV has been developed. The purpose of the flexible light load AGV is to handle small parts, bundles, or other light loads through a light manufacturing environment with agile path changing ability. They are specially designed to operate in areas with limited space.
7.2 The Design of the Light Load AGV

The basic configuration of the AGV is a two-wheeled vehicle with two supportive omni-directional ball pivots, as shown in figure 7.1.

![Fig 7.1: Basic configuration of the AGV](image)

7.2.1 Flexible Turning Radius

For most of the classical AGV's available in the market, a four-wheeled vehicle design is used, as is shown in figure 7.2.

![Fig 7.2: Classic forklift vehicle design](image)

The main drawback of this design is the complicated kinematics model of the motion.
and poor control. Unlike the standard four-wheeled AGV design, the light load AGV is specially designed to improve the performance of working in limited space. In the new design, all the motor-driven wheels and pivot wheels of the vehicle are mounted along the x and y axis. This special configuration of the wheels can provide the AGV the ability to travel in limited space. By independent control of the rotating velocity of the wheels, steering with flexible turning radius can be achieved and the operating illustration is shown in figure 7.3.

Fig 7.3: Steering control of the AGV

The advantage of the new design is that it gives the vehicle the ability to be operated in limited spaces like narrow tunnels and right-angle paths. The overall flexibility and ease of vehicle control can also be increased.

7.2.2 Interchangeable Load Handling Module

In different industries, the form of the load is different so the mechanism to handle
the load has to be specially designed too. With the interchangeable load handling module design, a special designed load handling module can be mounted on the AGV to perform different material handling duties. With different load handling units, the AGV can pick up and drop off different kinds of loads automatically using storage baskets, fork attachments, conveyors, thread guidance etc. Illustrations of different load handling modules are shown in figure 7.4.

![Fig 7.4: Different load handling modules](image)

This kind of modulated design can increase the agility for the flexible manufacturing system. The production and maintenance cost can also be reduced.

7.3 Chapter Summary

AGV is the core component of an AGV system and it plays an important role in the
system's overall performance. With the new design of the vehicle driving system and
the interchangeable load handling module, our Light Load AGV can facilitate the
operation of the flexible manufacturing system in light industries.
Chapter 8

Conclusion

After describing the design, implementation and evaluation of the proposed local positioning system, this chapter summarizes the challenges encountered when implementing an indoor location system and the contributions made by this research. The possible future directions for improving the performance of the positioning system are also discussed.

8.1 Challenges

In developing an indoor positioning system that is suitable for AGV navigation application, there are three major challenges.

Accuracy: To perform AGV navigation tasks like following a virtual path and docking to a workstation, a position estimation accuracy of a few centimeters is required. The harshness of indoor environments like signal reflection and obstacle blocking makes it difficult for the positioning system based on ultrasonic propagation to achieve the required accuracy level. Also, the positioning system requires the ability to trace mobile objects.
Ease of deployment:

The positioning system deployment, configuration and maintenance process should be easy to perform. To minimize the affect to the manufacturing flow, the amount of manual configuration and precise placement time should be as little as possible.

Scalability:

An AGV system requires controlling a large number of automated vehicles operating in a large area. Hence, an indoor location system needs to scale well with the number and the density of users of the system.

8.2 Contributions

This thesis proposed a positioning system based on ultrasonic propagation. It consists of beacons that are mounted on the ceiling of the sensing area, with the receiver module mounted on the automated vehicles. Each beacon periodically broadcasts its location information by transmitting an ultrasonic signal together with the RF message. The receiver module measures the distances to nearby beacons using the different arrival times of the RF and ultrasonic signals. The estimated position of the vehicle is obtained using the corresponding range measurements by trilateration.

The thesis makes the following contributions that tackle the above challenges.
**Accuracy:**

A precise range measurement between the beacon and the vehicle is critical to the accuracy of the position estimation. A unique arrangement of sensors is used to solve the angular limitation of the ultrasonic sensors. To deal with the influence of the reflected signal and the signal decay over range, the thresholding and compensation technique is applied. In the trilateration process, a squared error filter is applied to the model to reject the outlier and eliminate the obstacle blocking effect. In addition, a Kalman filter is applied in the system to increase the performance of dynamic positioning.

**Ease of deployment:**

Most of the positioning systems based on ultrasonic propagation rely heavily on a precisely installed sensor infrastructure to achieve accurate position estimation. A self calibration process has been developed to obtain the location information of the beacons.

**Scalability:**

In our proposed positioning system, moving receiver infrastructure is used such that all the vehicles are able to obtain their position simultaneously. A novel honey-comb
arrangement of the beacon is proposed to solve the scalability problem of the sensing area due to limited ultrasonic range. Under the honey-comb system configuration, at least 3 beacon range measurements can be obtain anywhere in the sensing zone and the configuration can be expanded by duplication without affecting the positioning refresh rate.

8.3 Future research directions

The ultrasonic positioning system proposed in this thesis is a prototype that demonstrates the feasibility of using the positioning system for AGV navigation. Future work is needed before it can be deployed in the manufacturing environment.

Future research directions are summarized as follows.

8.3.1 Accuracy improvement for range measurement

In chapter 3, various techniques like thresholding and compensation are used to obtain an accurate time-of-flight. Since compensation uses empirical data which varies with different environments and receiver-transmitter pairs, the calibration process is time consuming and costly. To further increase the accuracy and eliminate the calibration, other kind of signal processing techniques can be studied. One of the possible solutions is to use local maxima detection to take several time-of-flight
measurements and use these measurements to perform curve-fitting and find the zero-crossing point.

**8.3.2 Supporting control system development**

In the operation of an AGV system, after obtaining the location information about the automated vehicle, the central control system needs to perform different functions like path assignment, vehicle control, and collision handling. The development of a control system that supports our proposed positioning system is challenging and needs further investigation.
Reference:


[10] P.Bahl and V. Padmanabhan, "RADAR: An In-Building RF-Based User Location and Tracking System", INFOCOM 2000,


