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A high precision ultrasonic docking system used for automatic guided vehicle

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Abstract

With the more and more wide applications of automatic guided vehicle (AGV) in the material handling of modern manufactory system, its docking techniques have drawn extensive attention. The objective of this paper is to investigate the ultrasonic sensor based AGV 2D docking. As an established and cost-effective method, the application of classic ultrasonic sensor still faces certain drawbacks, e.g., low accuracy. In the present work, a novel high-precision, low-cost ultrasonic docking system is developed to locate the AGV relative to the docking workstation. In the proposed scheme, with electromagnetic wave used as system synchronization to trigger the time of flight (TOF) counter, the docking system consists of the ultrasound reception and emission beacons positioned at the same height of docking workstation and AGV, respectively. The 2D position of AGV is obtained from the TOF of ultrasonic signal from the emitter to two receivers. To ensure docking accuracy on low-cost narrow bandwidth ultrasonic transducer, a transducer equalizer based on the adaptive training algorithm is employed to realize high ranging precision (1 mm). Experimental results obtained on a demo AGV are presented and discussed, confirming the validity of the proposed solution, with an AGV docking precision of around ±3 mm in x and y, ±1° in bearing.

Keywords: AGV; Docking; Equalization; Ultrasonic ranging

1. Introduction

Material handling is a significant part of the manufacturing process, both in terms of cost and time. Indeed, statistics show that the processing time only occupies 5% of the manufacturing time of a typical job, the remainder is spent in storage and transportation processes [1,2]. With advantages such as mobility, flexibility, efficiency and so on, the automatic guided vehicles (AGV) are playing a more and more important role in modern manufactory system. Thus the research of AGV technology makes important sense for the industrialization of automatic handling system.

The main task of AGV is to transport materials from one workbench to another in industrial environment. During the stage of running, AGV need to locate its 2D position, traditionally depending on electrical wires buried in the floor, or reflecting laser from fixed position.

When AGV runs near to a workbench, it enters docking mode. A more difficult problem raised upon the docking of AGV is that both the position and the bearing relative to the workbench must be controlled. Meanwhile, to meet the need of mechanical interface, the precision needed in docking procedure is much higher than that in simply running. This topic has been extensively addressed by several researchers. Vaz et al. [3] developed an infrared sensor and reflector based docking system for mobile robot with an accuracy of ±5 mm in x and y, ±1° in bearing. Using ultrasonic sensors and CCD-line-camera, Roth's docking system [4] claims accuracy in orientation and distance of less than 5 mm.

Ultrasonic sensors are widely used in mobile robot applications. For ultrasound based docking solution, the ac-

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curacy of docking is in essence dependent on the precision of point–point ultrasonic ranging. Generally characterized as limited precision, there have been several ultrasonic devices that possess high accuracy. Polaroid claims a ranging unit with a resolution of ±1% for a range of 10.7 m [5]. A transmitter–receiver pair developed by Figueroa yields an accuracy of ±0.152 mm for a range of 0.9 m [6].

Nonetheless, few previous systems addressed the effect of low-bandwidth transducer on ranging precision. Consider the low-bandwidth characteristics of the transducer, the classical correlation method will lead to poor accuracy of time delay measurement. To cope with this problem, the deconvolution strategy can offer a feasible countermeasure by removing the influence of band limited transducer [7,8]. But the main drawback of the direct deconvolution method is that the operation involves a division process, which is very sensitive to data errors, especially when divided by a small value. Though the inclusion of a compensator parameter can alleviate the effect of small value, unfortunately, optimal selection of this parameter proved to be difficult [9]. In the present study, with the adoption of an adaptive equalization processing to mitigate the negative factors above-mentioned, the design of a high-precision, low-cost ultrasonic docking scheme is presented. Consider its great propagation speed compared to ultrasound, the electromagnetic wave is adopted as the trigger signal for measuring TOF of ultrasonic wave.

The remainder of the present paper is organized as follows. First, the theoretical basis of the described position and bearing estimation scheme is introduced. Next, the high precision processing method, system hardware and software design are outlined. Finally, experimental studies are carried out with the use of a demo AGV platform in the laboratory. The results obtained demonstrate the satisfactory performance of proposed scheme.

2. Theoretical basis and system description

As an established technique, ultrasonic sensor systems have been widely used in positioning system of mobile robot [10–12]. These systems can be divided into two categories, one is pulse–echo mode, and the other is transmitter–receiver mode. Systems of transmitter–receiver mode can avoid the problem of identifying the target reflecting surface and get better reliability. Mahajan and Figueroa [13], Tesch [14], Martin et al. [15] have developed transmitter–receiver mode ultrasonic navigation systems for mobile robot. To reach high reliability and precision, transmitter–receiver mode is employed in the proposed scheme. The whole docking system consists of two parts: the transmitter beacons mounted on AGV and the receiver beacons at workbench. Both the emission and reception beacons are positioned at the same height to simplify the docking into a problem of 2D position discrimination. Meanwhile, the electromagnetic wave is used as system synchronization to trigger the TOF measuring.

2.1. Principle of position and bearing measurement

The triangulation scheme is adopted to estimate the 2D position of AGV conveniently. By the measurement of ranges D_{CA} and D_{CB} between emitter C on AGV and receiver beacons A and B on known position, AGV's 2D location can be determined as shown in Fig. 1a.

The 2D location calculation is as follows:

$$y_C = \frac{D_{CA}^2 - D_{CB}^2}{4L} \tag{1}$$

$$x_C = \pm\sqrt{\frac{D_{CA}^2 + D_{CB}^2 - 2L^2 - 2y^2}{2}} \tag{2}$$

Accurately docking needs both high precision localization and bearing measurement. Bearing measurement is performed based on the localization output. Because two points can define a line, with two transmitters F, H mounted on the AGV (shown in Fig. 1b) located by receiver beacons D, E at workstation respectively, we can measure the AGV's bearing relative to the workstation. The bearing calculation is as follows:

$$\alpha = arctg\frac{y_F - y_H}{x_F - x_H} \tag{3}$$

To assure the accuracy of bearing measurement, transmitter beacon M is firstly located to the centerline of E, D points prior to the AGV begins the bearing measurement.

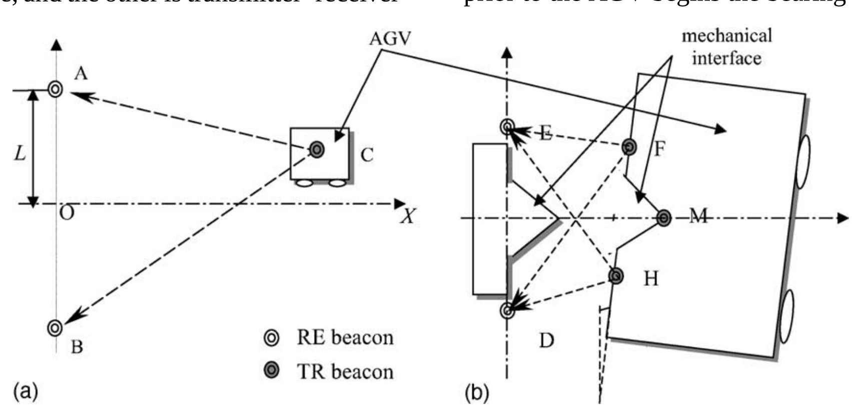

Fig. 1. Principle of 2D localization and bearing measurement.

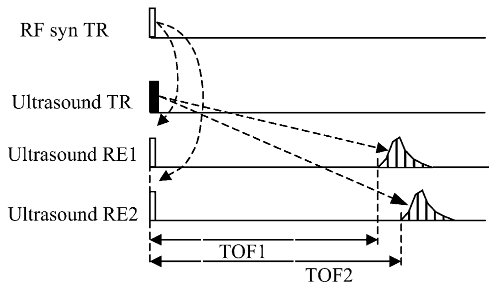

Fig. 2. Synchronization timing of system.

2.2. System synchronization design

The electromagnetic wave is used as system synchronization to trig the TOF counter. Synchronization principle (shown in Fig. 2) is that: at the same time of transmitter beacon emitting an ultrasonic pulse, wireless transmitter module emits an electromagnetic synchronization pulse, reception side triggers a counter once receiving the synchronization pulse, then waits the receiving of ultrasonic pulse to stop the counter and record the TOF. The TOF values from different reception positions (See TOF1 and TOF2 in Fig. 2) are used as the parameters for the calculation of AGV position or bearing in Eqs. (1–3).

3. Research of high precision ultrasonic ranging

3.1. Accuracy consideration

The principle of localization and bearing measurement in the above section means that the precision of AGV navigation is up to the precision of ultrasonic ranging. However, ultrasonic ranging method is traditionally characterized as low accuracy.

It is generally understood that there are several factors such as air turbulence, humidity, temperature dependence, transducer misalignment and bandwidth of transducer that limit the accuracy of ultrasonic ranging. Among them, the bandwidth of transducer is a main reason. The signal obtained from transducer with a small bandwidth climb slowly from its beginning to its peak in time-domain, which causes a low ranging precision. According to the Cramer–Rao theory, the lower bound of time estimation variance of band limited measurement system is [16]:

$$\sigma_{\mathrm{CR}}^2 \approx \frac{3}{4\pi^2 T}\frac{1}{\mathrm{SNR}}\frac{1}{f_{\mathrm{H}}^3 - f_{\mathrm{L}}^3} \tag{4}$$

where T is width of measurement time, SNR is the signal to noise ratio of received signal, f_{L} and f_{H} is lower and higher bound of bandwidth of system, respectively.

It is recognized that, compared to the bandwidth of emission signal and air medium, bandwidth of the transducer is the main limitation of the whole system bandwidth. As a result, under the same SNR, low bandwidth transducer leads to low ranging accuracy. In this work, base on the analysis that the small bandwidth of ultrasonic transducer is the main reason of low ranging precision, an equalization processing method is employed to reach high ranging accuracy with low-cost, band limited ultrasonic transducer.

3.2. Transducer equalization

A transducer equalizer is an inverse filter used to counterpoise the small bandwidth of transducer to widen the system bandwidth. With the aid of a deconvolution filter, the effect of transducer can be mitigated by compensating its impulse response h_{TR}, using an inverse system, h_{de}. Ideally, the cascade of the transducer and its inverse filter will simply be a delayed impulse:

$$h_{\mathrm{de}} * h_{\mathrm{TR}} = \delta(c) \tag{5}$$

where c is a constant delay. After the deconvolution process, the time discrimination precision of the whole system will be enhanced with the removing of transducer's band limited effect [9].

3.3. Transducer equalization based on adaptive algorithm

To avoid the drawback of direct deconvolution method mentioned in Section 1, adaptive algorithm is used to train the weights of a finite impulse response (FIR) transducer equalizer. The equalization is performed in two stages: first, the filter coefficients are trained iteratively to convergence using a reference signal; second, deconvolution is carried out with the fixed coefficients obtained from training.

In the training stage, transmitter and receiver transducers are positioned at fixed positions, with a very small distance (set at 0.5 m), in order to get receiving signal $x(k)$ with high SNR. Feeding emitting impulse $d(x)$ into transmitter transducer, received signal from receiver transducer acts as the input of training process. Reference signal is the delayed impulse signal (Fig. 3). Then the weights W_k of the FIR equalizer are trained according to the least mean square (LMS) algo-

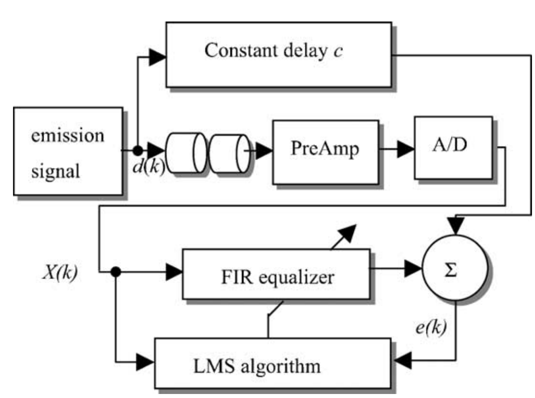

Fig. 3. Training process of the equalizer with LMS adaptive algorithm.

rithm. The iteration formula of coefficients W_k updating is [17]:

$$W_{k+1} = W_k + 2\mu e_k X_k \quad k = 1, 2, \ldots N \tag{6}$$

$$e(k) = d(k) - X_k^T W_k \tag{7}$$

$$X_k = x(k, k+1, \ldots, k+L-1) \tag{8}$$

where μ is a gain constant used to control the convergence rate, $e(k)$ is the error of adaptive system, N is the length of input and reference signal, L is the length of filter coefficients, $d(k)$ and $x(k)$ is reference signal and input signal respectively. The constant delay c is introduced to ensure the causality of inverse modeling. See Fig. 3.

The transducer adopted in this system is the low-cost, general purpose Model T/R40-16, with a 3dB bandwidth of 3 kHz. Working on bending vibration mode with a centre frequency of 40 kHz, it is suitable for being used in air medium. However, for ultrasonic ranging system, its low bandwidth is the main factor limiting the precision. Therefore, equalization process is performed to mitigate its bandwidth to improve the ranging accuracy.

4. Experimental work

4.1. High precision ultrasonic ranging

4.1.1. Determination method of TOF

In the present work, the signals are acquired with a 1Msps 8-bit ADC. After the convergence of adaptive training process, the weights obtained are saved as the fixed taps of the transducer equalizer. Shown in Fig. 4(A) and (B) are the time histories of ultrasonic signal obtained before and after the equalization respectively. To facilitate the TOF estimation, time history obtained from transducer pairs positioned at a fixed distance (0.5 m at the current scheme) through equalization process is firstly employed as the standard signal for cross-correlation operation. Similarly, for the aim of comparison between the proposed method and the classical correlation, standard signal is also acquired directly from the transducer pairs without equalization.

After the acquirement of standard signal, the TOF between the emitter beacon on AGV and receptor beacon on workstation is determined according to the cross-correlation peak between corresponding received signal and standard signal. Illustrated in Fig. 4(C) and (D), normalized cross-correlation curves between reception signals without and with equalization and corresponding standard signals are presented. The points t_{peak} associated with the peak of cross-correlation curve are chosen as the arrival time of ultrasonic wave (marked with black arrows in Fig. 4(C) and (D)).

4.1.2. Calibration process and propagation speed adjustment

This TOF estimation method may include an offset between the t_{peak} and the real time of arrival. Provided that the form of the signal does not suffer significant variations, this offset can be considered as constant and can be calibrated once at the beginning. The calibration process is carried out by the mean result of 400 measurements with transducer pairs at a fixed distance of 2.0 m.

Besides the TOF, the accuracy of the propagation speed C of ultrasonic wave will also affect the ranging output. For simplification, only the factor of the temperature is accounted in the present study. To alleviate the ranging error caused by the C due to the variation of temperature, compensation measure is taken. According to the following relationship of the temperature T (°C) and C (m/s) [18]:

$$C = 331.45 + 0.61\,T \tag{9}$$

the propagation speed C is thus adjusted with the temperature measured at the beginning of each test.

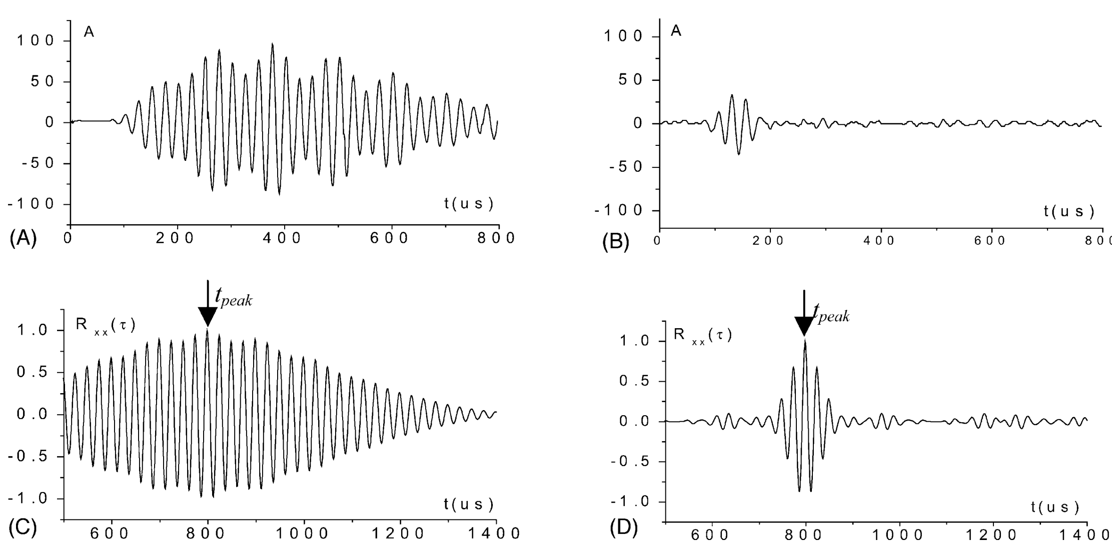

Fig. 4. Signal waveform (A) (B) and its normalized cross-correlation curve (with corresponding standard signal) (C)(D) before and after the equalization.

4.1.3. Results of equalization

Consider the original situation without the equalization, the raw signal from the T/R40-16 transducer pairs covers a big 700 μs time-width in time history (See Fig. 4(A)) and exhibits many slowly attenuating false peaks around the actual peak in cross-correlation curve (See Fig. 4(C)). On the other hand, as Fig. 4(B) illustrates, with the use of transducer equalizer, the time-width of the equalizer's output signal decreases greatly to about 100 μs, associated with a easily identified correlation peak in cross-correlation curve (Fig. 4(D)). Accordingly, the enhancement of arrival time discrimination accuracy can be straightforwardly predicted with the much less influence of false cross-correlation peaks resulting from the adoption of equalizer.

4.1.4. Improvement of ranging precision with equalization

After calibration and propagation speed adjustment, the precision curves are obtained by the smoothing of measurement errors at 7 different distances from 2 to 9 m using proposed and classical correlation method respectively. The comparison results between the ranging accuracy before and after the transducer equalization process is plotted in Fig. 5. It is noted that both of the errors depend mainly on the distance, exhibiting general agreement with Eq. (4) as the SNR will drop with the increasing of distance. Similarly, because the use of transducer equalizer broadens the bandwidth of whole system, ranging precision is obviously improved compared to classical method by about 1–3 mm at different distance.

It can be concluded that the ranging precision of this system is ±0.5 mm within 3 m, which can meet the precision requirement of AGV workstation docking.

4.2. Experiment of AGV docking [11,18]

Docking experiments are carried out in the lab with the help of a demo AGV. The experimental environment is the laboratory room, which is assume to have a 2-D floor plane and composed of walls and corners. The results are as follow:

4.2.1. Test bed for docking experiments

For the purpose of navigation experiments, a demo AGV named "XD-AGV1" shown in Fig. 6 is developed as navigation experiment platform. It is equipped with two driving wheels (left and right wheel) and a passive wheel (front wheel). Each driving wheel is activated by a step motor. Such design facilitated the AGV to adjust its position and bearing relative to workstation accurately.

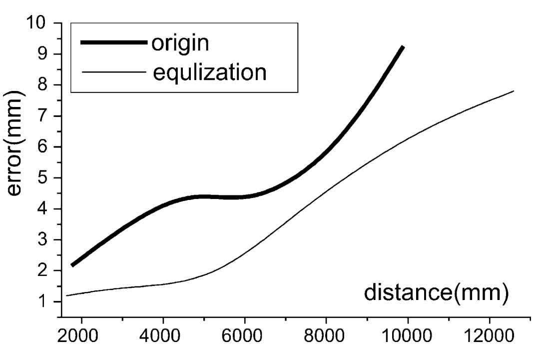

Fig. 5. Ranging precision before and after the equalization.

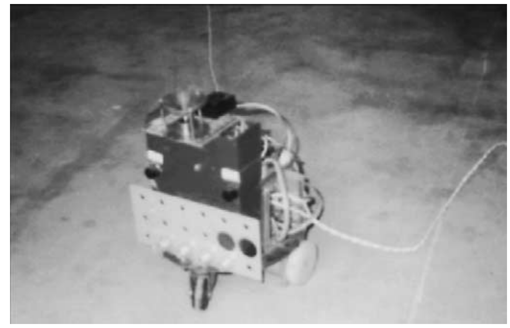

Fig. 6. Photo of demo AGV "XD-AGV1".

4.2.2. AGV 2D localization

Accurately localization experiment is carried out after the AGV enters a docking area, which is about 1 m away from the midpoint of two workstation beacons, about ±5 cm near the centerline of these two beacons. The experimental localization results before AGV's docking mode are shown in Fig. 7. The mid-point *O* of the workstation (See Fig. 1) is stationed at the (0,0) point in Fig. 7. It thus can be seen that with the increasing distance of AGV with respect to the reception

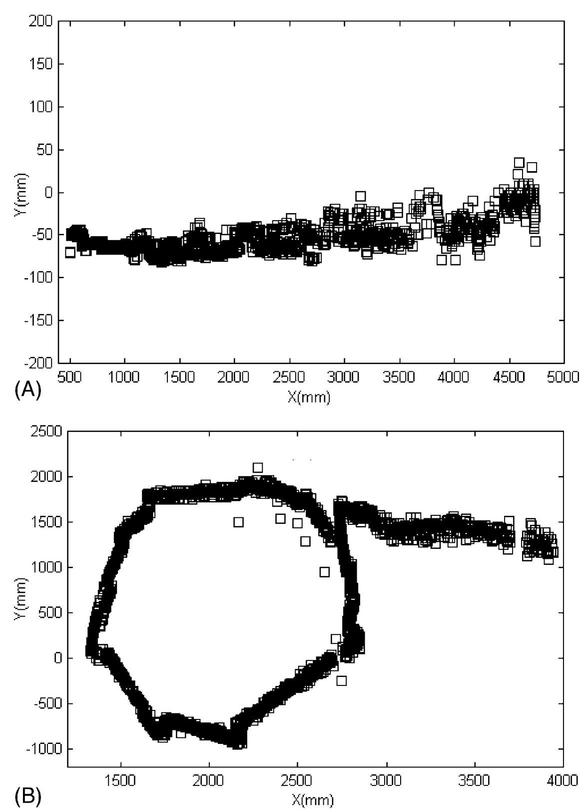

Fig. 7. Result of AGV 2D localization.

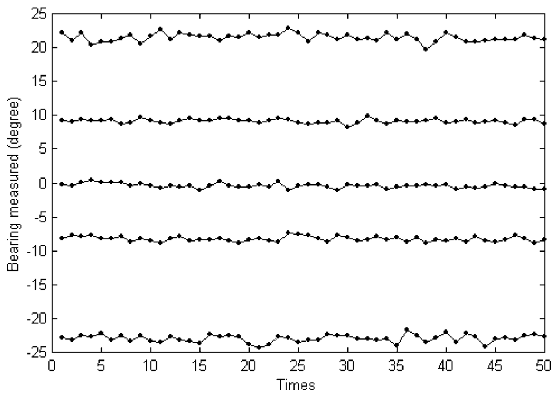

Fig. 8. Result of 50 measurements at five different bearings.

beacons, the error of localization also exhibits an increasing trend, due to the weakening of SNR mentioned at the previous section.

With the setting of $L = 750$ mm, under the condition of both silent and fluctuation air medium (generated by electric fan, with signal amplitude fluctuation degree 3.28dB), an accurate 2D localization precision not more than ± 3 mm is achieved on the test bed AGV with the proposed scheme. This precision is superior to that of some similar commercially available AGV systems, e.g., Transrobot-H750-24 type AGV of Germany Blechert and SIA-AGV-T500/T1000 of China [18].

4.2.3. Bearing measurement

After AGV is accurately located to the centerline of two workstation beacons, it begins the bearing measurement for the final docking operation. Two ultrasonic beacons on AGV transmit ultrasonic signals, the TOFs of which are estimated in receptors and used to calculate the angle between AGV and the workstation according to Eq. (3). Shown in Fig. 8 are the 50 measurement results of bearing at five different angles.

As seen from Fig. 8, when the AGV is located at a relatively big angles (around $\pm 20^\circ$, See Fig. 8) with respect to the workstation, the angle discrimination errors are bigger that that from small angles (less than $\pm 20^\circ$, See Fig. 8), due to the strong waveform deformation caused by the misalignment between ultrasonic transducer pairs. Consider the final bearing measurement precision will be dependent on the estimation results at small angles in docking operation, a precision of $\pm 1^\circ$ is achieved, as confirmed in Fig. 8.

4.2.4. Index of AGV docking performance

- 2D position location precision: ± 3 mm
- Bearing measurement precision: $\pm 1^\circ$.

5. Conclusion

In the present work, an innovative ultrasonic 2D localization system has been developed to be used for the docking of AGV. The classical triangulation scheme is employed to calculate the 2D position and the bearing is determined by the positioning results of two points on the AGV. Consider the TOF estimation of ultrasonic wave, in light of the drawbacks of traditional ultrasonic solution, special attention is given to the high precision in 2D localization and bearing measurement by adopting a transducer equalization process.

Adopting the transmitter–receiver mode TOF ranging method, electromagnetic wave synchronization and transducer equalization process, satisfactory reliability and precision are achieved in the docking experiments on a test bed AGV. The final docking precision index obtained on the test bed AGV is ± 3 mm in 2D localization, $\pm 1^\circ$ in bearing measurement.

The described docking scheme, which is low-cost, robust and has high-precision, has the potential of being developed into a practical docking system for the AGVs as well as other similar mobile vehicles. Further work will be carried out to investigate the effect of misalignment of transducer pairs on measurement errors for the development of new method with higher precision.

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Biographies

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