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High Accurate Two-Dimensional Geo-Location System for Social Safety Robot

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Abstract: In this paper, we propose an efficient two-dimensional geo-location system for social safety robot, where its location is obtained by direction of arrival (DOA) and time of arrival (TOA) of the radio signal. The proposed system requires two reference signals while the conventional systems generally deploy more than three reference signals. For estimating TOA and DOA information together, we employ a multiple signal classification (MUSIC) algorithm. The simulation results show that the proposed geo-location system achieves accuracy within 3 meters error in 2 kilo-meters coverage which is constraint for mobile social safety robot.

Keywords: MUSIC, TOA, DOA, Location

1. INTRODUCTION

Recently, the role of unmanned robot is getting more important than ever in public security. In particular, the security robot which patrols the defence area has been attracted much attention of many researchers due to its usefulness in next generation unmanned defence system. To control the robot in the central station, location awareness of the robot is one of the most important factors. That is, localization technique of the robot should be well-developed to assure the information between the robot and the central station.

Localization techniques can be roughly categorized into two groups: range based estimation and range free one. The range based estimation [L. Girod [2002]][A. Harter [1999]]uses the distance between the devices for finding the location. On the other hand, the range free algorithm[Tian He [2003]] does not require the distance between nodes. Although the range based location estimation method requires high quality of hardware, it is more reliable than the range free one. Thus, we focus on the range based techniques. Received signal strength indication (RSSI), time of arrival (TOA) and time difference of arrival (TDOA) are the most popular techniques to acquire the ranging information from processing the radio signal. There are some location finding method based on ranging information such as trigonometric methods. Among them, the trilateration method uses the three range information, ie. only the distance information is used to find the location of the target object. Next, we consider hybrid method which needs just two reference information, range and direction. We can find the range through one of the range method, RSSI, TOA, and TDOA, and the direction information using the angle of arrival (AOA) method. Such system requires only the angle and distance of two devices, which is so called two-dimensional localization.

Two-dimensional localization methods have been suggested in some literatures. For instance, Kambiz et al. proposed a joint positioning method using matrix pencil [Kambiz [2003]]. It was shown therein that arrival time and angle of the radio signal are estimated using matrix pencil algorithm. In general, the matrix pencil requires less processing power and computational complexity compared to the MUSIC algorithm. Nevertheless, the MUSIC algorithm can be preferable to some application such as the social safety robot. In case of the social safety robot, its accuracy of the localization information must be guaranteed.

In this paper, we propose a high accurate two-dimensional geo-location system, where the location of the mobile robot is obtained from DOA and TOA of the radio signal. The proposed system requires two reference signals while the conventional system based on popular trigonometric method generally deploys more than three reference signals. To estimate both TOA and DOA together, we

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employ the MUSIC algorithm such that the accuracy of system is enhanced. The simulation results show that the proposed geo-location system achieves accuracy within 3 meters error in 2 kilo-meters coverage which is constraint for mobile social safety robot. Therefore, we conclude that the proposed system can be applied for location system of the mobile robot.

The rest of this paper is organized as follows. In Section 2, we present the system description. Section 3 describes the principles of MUSIC algorithm for TOA and DOA estimation. In section 4, we present the two-dimensional location finding method for a social safety robot. The simulation results with relevant discussion will be given in section 5. Finally, we reach the conclusion about the proposed geo-location algorithm in section 6.

2. SYSTEM DESCRIPTION

We consider a location finding system with one-to-one relationship between a robot and a target object. We assume that the robot has multiple linear omnidirectional antennas to detect directions such that any directional signal can be covered. It also has other antenna to find the delay component, as shown in Fig. 1. To find the location of the object, the RF signal is periodically transmitted. Then, the robot detects the first arrival time and direction of the first signal.

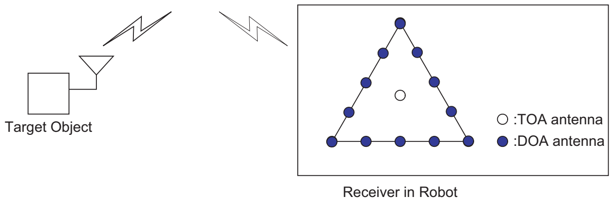

Fig. 1. Location finding system model

When the robot receives the desired signal, the received signal model can be expressed as

$$\begin{aligned} \mathbf{x} &= \mathbf{SH} + \mathbf{w}, \\ \mathbf{S} &= [s_N(1), s_N(2), \cdots, s_N(M)], \\ \mathbf{H} &= [h(1), h(2), \cdots, h(M)]^T, \end{aligned} \tag{1}$$

where $\mathbf{x}$ is the received signal vector which is composed of three terms, i.e., signal matrix $\mathbf{S}_{N\times M}$, channel matrix $\mathbf{H}_{M\times 1}$, and the additive white Gaussian noise vector $\mathbf{w}$. N and M denote total number of samples and the number of data which should be found.

3. EISTIMATION METHOD

3.1 MUSIC Algorithm Overview

The MUSIC algorithm has been generally appreciated as one of the most popular techniques to estimate the desired data. It is based on the eigen decomposition of the autocorrelation matrix for the received signal vector in (1). The autocorrelation matrix is represented as

$$\mathbf{R}_{xx} = E\{\mathbf{x}\mathbf{x}^H\} = \mathbf{R}_s + \mathbf{R}_w, \tag{2}$$

where the superscript H denotes the Hermitian transpose operation. From (2), we see that the autocorrelation matrix $\mathbf{R}_{xx}$ can be written as the sum of signal and noise autocorrelation matrices, $\mathbf{R}_s$ and $\mathbf{R}_w$. Here, $\mathbf{R}_s$ is clearly $N \times N$ matrix with rank M. Thus, each $N - M$ eigenvector which corresponds to the noise vector has the zero eigenvalue. Consequently, M highest signal eigenvectors are orthogonal to the noise vector. It is the basic principle of the MUSIC algorithm. The desired number of data can be determined by the *pseudo-spectrum* defined as

$$S_{MUSIC}(v) = \frac{1}{\sum_{m=1}^{N-M} \|P_w s(t)\|^2}. \tag{3}$$

It means that the signal space projects into the noise one P_w orthogonally. In this case, the eigenvalue have the near zero value. From (3), the estimated data have the M peaks in the pseudo-spectrum [Xinrong [2004]]. So far, we reviewed the MUSIC algorithm generally. In the following subsections, we extend the MUSIC Algorithm for detection of the delay and direction required to find the location.

3.2 TOA Estimation Method

A wireless multipath channel containing the L_p path components can be modeled by

$$h(t) = \sum_{k=0}^{L_p-1} \alpha_k \delta(t - \tau_k). \tag{4}$$

In practice, TOA using the MUSIC is estimated in the frequency domain to obtain the discrete frequency channel response. For the TOA estimation based frequency domain system, the harmonic signal model can be represented as [Manolakis [2000]]

$$H(\tau) = \sum_{k=0}^{L_p-1} \alpha_k e^{-j2\pi f_k \tau}. \tag{5}$$

Then, the sampled frequency domain channel response which is divided into L equally spaces is expressed as

$$\begin{aligned} x(l) &= \hat{H}(f_l) = H(f_l) + w(l) \\ &= \sum_{k=0}^{L_p-1} \alpha_k e^{-j2\pi(f_0 + l\Delta f)\tau_k} + w(l), \end{aligned} \tag{6}$$

where $l = 0, 1, \cdots, L$, and $w(l)$ is white Gaussian noise with zero mean and variance σ_w^2. Here we divide the channel matrix H into delay matrix $\mathbf{a}$ and the other matrix $\mathbf{V}$ to find the channel delay term.

$$\mathbf{x} = \mathbf{H} + \mathbf{w} = \mathbf{Va} + \mathbf{w} \tag{7}$$

where

$$\mathbf{V} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ e^{-j2\pi(1)\Delta f \tau_0} & e^{-j2\pi(1)\Delta f \tau_1} & \cdots & e^{-j2\pi(1)\Delta f \tau_{L_p-1}} \\ e^{-j2\pi(2)\Delta f \tau_0} & e^{-j2\pi(2)\Delta f \tau_1} & \cdots & e^{-j2\pi(2)\Delta f \tau_{L_p-1}} \\ \vdots & \vdots & \vdots & \vdots \\ e^{-j2\pi(L-1)\Delta f \tau_0} & e^{-j2\pi(L-1)\Delta f \tau_1} & \cdots & e^{-j2\pi(L-1)\Delta f \tau_{L_p-1}} \end{bmatrix} \quad (8)$$

$$\mathbf{a} = \begin{bmatrix} \alpha_0 e^{-j2\pi f_o \tau_0} \\ \alpha_1 e^{-j2\pi f_o \tau_1} \\ \vdots \\ \alpha_{L_p-1} e^{-j2\pi f_o \tau_{L_p-1}} \end{bmatrix}, \quad \mathbf{w} = \begin{bmatrix} w(0) \\ w(1) \\ \vdots \\ w(L-2) \\ w(L-1) \end{bmatrix}$$

Since the MUSIC algorithm uses the eigenvalue decomposition of autocorrelation matrix, the autocorrelation matrix of the received signal can be written as

$$\mathbf{R}_{xx} = E\{\mathbf{x}\mathbf{x}^H\} = \mathbf{V}\mathbf{A}\mathbf{V}^H + \sigma_w \mathbf{I}. \quad (9)$$

As shown in (9), the autocorrelation of the received signal can be regarded as signal space and noise one. Thus, we can detect the delay component by finding the peak point of pseudo-spectrum, which have zero valued denominator because the signal value projecting into the noise space is zero.

3.3 DOA Estimation Method

In this subsection, we consider the DOA estimation method using the MUSIC algorithm. The system uses a uniform linear antenna array with N elements for each distinguishable direction M. The steering vector associated with an angle ϕ is given by

$$s(\phi_i) = \left[\, 1,\ e^{jkd\cos\phi_i},\ e^{j2kd\cos\phi_i},\ \cdots\ e^{j(N-1)kd\cos\phi_i} \,\right] \quad (10)$$

where $i = 1, 2, \cdots, M$, $k = 2\pi/\lambda$ where λ is wavelength of light, and d is inter-antenna-element space. The received signal can be represented by

$$\begin{aligned} \mathbf{x} &= \mathbf{S}\mathbf{a} + \mathbf{n} \\ \mathbf{S} &= [s(\phi_1), s(\phi_2), \cdots, s(\phi_M)] \\ \mathbf{a} &= [\alpha_1, \alpha_2, \cdots, \alpha_M]^T \end{aligned} \quad (11)$$

where $\mathbf{a}$ denotes an amplitude matrix of each different path. To detect the direction information, we use the MUSIC algorithm by decomposition of the autocorrelation matrix. Thus, the autocorrelation matrix of the received signal can be written by

$$\mathbf{R}_{xx} = E\{\mathbf{x}\mathbf{x}^H\} = \mathbf{S}\mathbf{A}\mathbf{S}^H + \sigma_w \mathbf{I}. \quad (12)$$

Then, we can also detect the direction of the received signal by applying the MUSIC algorithm as in 3.1 subsection.

4. TWO-DIMENSIONAL LOCATION SYSTEM

For two-Dimensional location system, angle and distance information together are required to find the position of the target object. At first, an optimum training sequence is transmitted to estimate channel. The frequency domain representation of channel impulse response is processed by the MUSIC method. Then, multiple array antenna system estimates the direction of first arrival path by using also MUSIC method.

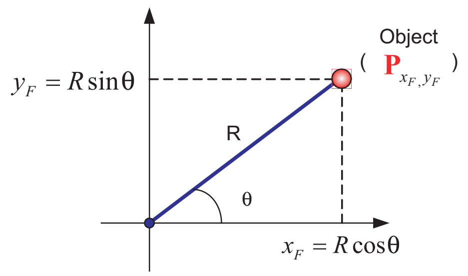

Fig. 2. Relationship between distance and angle for target object

The TOA estimator defines a circle around the target object with radius $R = TOA \times c$, c is the speed of light. And the DOA estimator defines a direction between robot and object. Thus the position of the target object can be easily found as shown in Fig. 2. When the initial robot position is x_I, y_I, the final position (the position of target object) x_F, y_F is obtained as

$$\begin{bmatrix} x_F \\ y_F \end{bmatrix} = \begin{bmatrix} x_I \\ y_I \end{bmatrix} + \begin{bmatrix} R \times \cos(DOA) \\ R \times \sin(DOA) \end{bmatrix} \quad (13)$$

The main advantage of 2-Dimensional location system over other is that it needs only one range information. Thus it can not only reduce the computational load but also provide more accurate location information. The TOA estimation method should grasp the multipath components as accurate as possible. Otherwise it critically affects its location error. If we find the direction using the multiple antenna, the location is estimated more accurately since the high gain antenna gives a narrow beam [Yoshihiko [1999]].

5. SIMULATION RESULTS

In this section, we consider the social safety robot equipped with the location system, under the constraints of the 3m location error in a radius 2km. Fig. 3 shows the

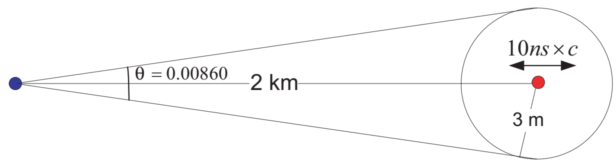

Fig. 3. Required finding location system

requirements to satisfy the location error bound in the social safety robot system. To meet the 3m range error bound, the delay term should variate within 10ns, i.e., TOA$\cdot 3 \cdot 10^8$m/s $= 3$m. Also the direction error also should be within $0.0086°$, i.e., $2\pi \cdot 2000 \cdot \frac{\text{DOA}}{360} = 3$m.

We provide the simulation results to illustrate the validity of the proposed algorithm within the requirements. we assume 2-tap channel model which has [100ns, 300ns] tap delay and [0.9, 0.3] tap envelope. The antenna array at the receiver is placed with equal space $d = \lambda/2$, and the simulation runs are performed repeatedly (100 times).

Fig. 4 shows the location error according to different SNR when maximum seven antennas are used. It is observed

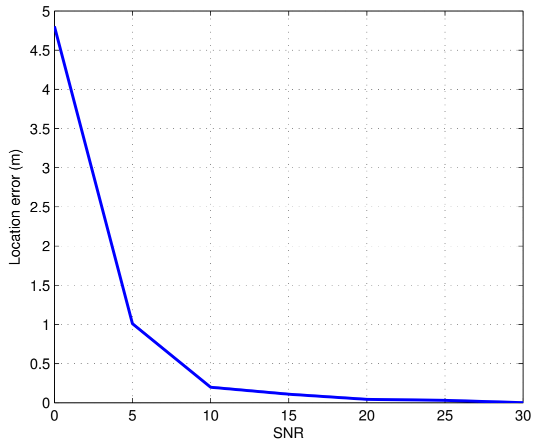

Fig. 4. Location error according to the SNR

that the location error of two-dimensional location system exists within the 3m error boundary at about 2.5dB. Specifically, TOA has much less error (0ns-0.2ns) than the theoretical error bound (10ns). For DOA, its error is between 0° and 0.1170°. From this simulation results, we can see that the location error performance more depends on the DOA estimation than TOA. Besides, the performance is improved as SNR increases. At over 20dB, the location error is approximately zero.

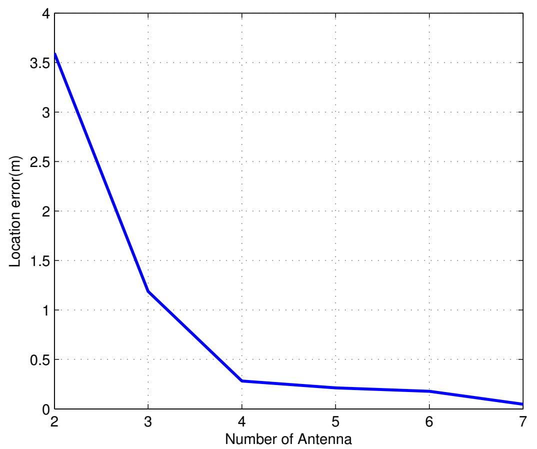

Fig. 5. Location error according to the number of antennas

Fig. 5 provides the location error as the number of antennas increases. In this case, the simulation was performed at SNR of 20dB. As we expected, the location error is reduced according to the increased number of antenna. When more than seven antennas are used, the location error does not exist. In detail, TOA estimation error is 0.1ns which is less than theoretical error bound (10ns). The DOA error is between 0.001° and 0.1030°.

6. CONCLUSION

In this paper, we have proposed the high accurate two-dimensional geo-location system for social safety robot. Since the accuracy of the location is critical for social safety robot, we employed the MUSIC algorithm instead of matrix pencil method to estimate both DOA and TOA. The proposed system requires two reference signals while the conventional system based on popular trigonometric method generally deploys more than three reference signals. We have demonstrated the validity of the proposed scheme through simulation results. More specifically, the location error of two-dimensional location system within the 3m error boundary at 2.5dB or so when different SNR are considered. For the increased number of antenna, the location error is remarkably less than the theoretical error bound. Therefore, we expect that the proposed system can be applied for some mobile robot which needs the accuracy of the location information.

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