Distributed Communication/Navigation
Robot Vehicle Network

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ABSTRACT

This paper describes algorithms for forming a communication/navigation network of robotic vehicles inside a building. An ultrasound ranging system on each vehicle is used to determine the distance between vehicles in the network. This distance information is transformed into x,y position information using a steepest descent algorithm that minimizes the error between measured distances and estimated distances (determined from estimated x,y position). This same optimization function is also used to guide the vehicles into a desired formation specified by the desired distance between vehicles. When used for guidance, the gradient vector is used as the commanded input to each vehicle. Most importantly, the algorithm does not require knowledge of the distance between every vehicle node, only those closest to it. Therefore, the algorithm can be distributed amongst the vehicles, providing a global control for the entire system using only local control laws implemented on each vehicle.

KEYWORDS: distributed robotic vehicle navigation, guidance, indoors

INTRODUCTION

The control of multiple cooperative robotic vehicles has been a topic of considerable interest. Applications have ranged from moving large objects (1) to troop hunting behaviors (2). Conceptually, large groups of mobile robotic vehicles should display the ability to automatically perform military tasks such as formation following, localization of chemical sources, de-mining, target assignments, autonomous driving, perimeter control, surveillance, and search and rescue missions (3-7).

In this paper, we address the task of localization and navigation of multiple robotic vehicles inside a building. The purpose of creating a communication/navigation network is to allow multiple vehicles to traverse a large enclosed environment, such as inside a building, while maintaining communication and localization with respect to the base station. In an indoor environment, communication between a vehicle and the base station

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is often lost when a vehicle turns a corner and loses line-of-sight with the base station. For this reason, it is important to create a communication network where vehicles form communication nodes that allow other vehicles in distant locations of the building to route messages back to the base station through the network.

Another problem with indoor environments is that GPS is not available; therefore, precise vehicle location is difficult to achieve. However, it has been shown that relative vehicle positions can be found by combining ultrasound sensors and an RF radio in a novel approach (8). By measuring the time of flight of an ultrasound pulse between two vehicles, it is possible to determine the distance between the vehicles. An RF radio message between the vehicles is used to tell the receiving vehicle when the transmitting vehicle has sent the pulse. The length of RF transmission is negligible compared to the time of flight of the ultrasound pulse. Using three or more vehicles, it is possible to determine the relative position of the vehicles relative to two “beacon” vehicles using triangulation. Therefore, when creating a localization network it is important that the vehicles stay within acoustic range of at least two neighboring vehicles. This paper presents a decentralized control law that allows the vehicles to spread out within the building while maintaining the communication/navigation network.

We describe the localization and navigation techniques used to create a communication/navigation network for indoor environments.

**LOCALIZATION OF NETWORK**

Figure 1(a) illustrates the localization problem for three vehicles. Assuming that vehicle

1 is the origin and vehicle 2 is some distance along the x-axis, then the position of vehicle 3 with respect to vehicle 1 is given by

\[
\begin{align*}
1 \hat{x}_3 &= \frac{d_{13}^2 + d_{12}^2 - d_{23}^2}{2d_{12}} \\
1 \hat{y}_3 &= \pm \sqrt{d_{13}^2 - \left(1 \hat{x}_3\right)^2}
\end{align*}
\]

(1)

where \(d_{ij}\) is the measured distances between the vehicles. Notice that there are two possible solutions for the y position of vehicle 3. This reflection cannot be helped unless the distance sensor can measure orientation as well. Since our sensor does not have this capability, we make the assumption that vehicle 3 is always in the positive y direction.

![Figure 1. (a) Using triangulation to locate the position of vehicle 3. (b) Using triangulation to compute the location of vehicle 4.](image-url)
Figure 1(b) shows the case for four vehicles. Assuming that vehicle 4 is within ultrasound range of vehicles 1, 2, and 3, the position of vehicle 4 is given by

$$
\begin{align*}
1x_4 &= \frac{d_{12}^2 + d_{14}^2 - d_{24}^2}{2d_{12}} \\
1y_4 &= \pm \sqrt{d_{14}^2 - (1x_4)^2}
\end{align*}
$$

(2)

Again, the sign of the y direction could be positive or negative when using only the relative distances to vehicles 1 and 2. However, using the distance to vehicle 3, the sign of vehicle 4 can be chosen such that

$$
\left| d_{34}^2 - \left[ (1x_4 - 1x_3)^2 + (1y_4 - 1y_3)^2 \right] \right|
$$

is minimized.

This triangulation scheme can be repeated for any number of vehicles if the distance back to vehicles 1 and 2 are known. However, once a vehicle moves beyond the ultrasound range of the origin, a different technique must be used to locate the position of each of the vehicles. By minimizing

$$
f(\bar{x}) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} e_{ij} \left[ d_{ij}^2 - (x_i - x_j)^2 - (y_i - y_j)^2 \right]^2
$$

(5)

where

$$
e_{ij} = \begin{cases} 0, & d_{ij} \text{ not known} \\ 1, & d_{ij} \text{ known} \end{cases}
$$

(6)

we can determine the least squares solution that minimizes the squared error between the measured (possibly noisy) distance measurements and the computed x,y position of each vehicle. The iterative steepest descent solution is given by

$$
\bar{x}(k+1) = \bar{x}(k) - \alpha \nabla f(\bar{x}(k))
$$

(7)

where

$$
\bar{x} = \begin{bmatrix} \bar{x}_1 \\
\vdots \\
\bar{x}_n \end{bmatrix} \in \mathbb{R}^{2N} \quad \bar{x}_i = \begin{bmatrix} x_i \\
y_i \end{bmatrix} \in \mathbb{R}^2 \quad \nabla f(\bar{x}) = \begin{bmatrix} \frac{\partial f}{\partial \bar{x}_1} \\
\vdots \\
\frac{\partial f}{\partial \bar{x}_n} \end{bmatrix} \in \mathbb{R}^{2N}
$$

(8)

and

$$
\frac{\partial f(\bar{x}_i)}{\partial x_i} = -4 \sum_{j=1}^{N} e_{ij} \left( d_{ij}^2 - \|\bar{x}_i - \bar{x}_j\|^2 \right) (\bar{x}_i - \bar{x}_j).
$$

(9)

Simulation and experiments show that steepest descent algorithm will typically converge in less than 100 iterations with a random initial position vector. A second order conjugate gradient method has also been implemented and found to converge in half as many iterations, however, the line search used in the algorithm is quite computationally intensive. Therefore, we have found the simple first order method takes less time to compute the result. Of course, once the vehicles have found their initial positions, the location algorithm converges in one or two iterations for small changes in the positions of the vehicles.

**CONTROL OF NETWORK**

Next, let us consider the problem of N vehicles spreading out in a two-dimensional space into a specified configuration. Suppose that N vehicles are in some initial configuration
as shown in Figure 7(a), and we would like them to adjust their position relative to each other so that their final configuration is as shown in Figure 7(b). We assume that the vehicles communicate their position to each other and that each vehicle knows the specified distance that it is supposed to be from neighboring vehicles. Is there a decentralized control that will drive the group of vehicles to the desired configuration?

![Figure 7(a)](image1)

![Figure 7(b)](image2)

Figure 2. (a) Initial configuration of vehicles. (b) Desired configuration vehicles.

To solve this problem, a gradient-based control law is proposed that is the same as in Equation (7) except now the distances are the desired distances $d_{ij}^*$ and the $x, y$ positions are those determined from the previous section. We will assume the dynamics of the vehicles are essentially ignored so that the vehicle dynamics can be considered to be the control law only.

$$\dot{x}_i = -u_i, \quad i = 1, \ldots, N$$

The control input is

$$\bar{u}_i(t) = -\alpha \frac{\partial v_i(t, \bar{x}_i(t))}{\partial \bar{x}_i}, \quad i = 1, \ldots, N$$

where $\alpha > 0$ is the control gain. As shown in (9), this control law is connectively stable (10) and minimizes the vector Liapunov function

$$v(t, \bar{x}) = \sum_{i=1}^{N} v_i(t, \bar{x}_i)$$

where the individual Liapunov functions are

$$v_i(t, \bar{x}_i) = \sum_{j=1}^{N} e_{ij} \left[ (d_{ij}^*)^2 - (x_i - x_j)^2 - (y_i - y_j)^2 \right]^2$$

and $e_{ij} = e_{ji}$ for all $i, j \in N$.
Figures 3 and 4 show the results of two MATLAB simulations. Figure 3 illustrates a group of 20 vehicles that start in a tightly clustered position. They are tasked with the goal of spreading out uniformly while maintaining a specified ultrasound ranging distance $d_{ij}^*$ from their neighbors. The vehicles execute the gradient strategy outlined above using the position of only their three nearest neighbors, which changes continually throughout the motion. The results in Figure 3 show that the vehicles do spread out the specified distance after 225 iterations. Figure 4 illustrates a similar situation with the difference being that there are walls forming a hallway and a side corridor that restrict the vehicles from spreading out in certain directions. Infrared proximity sensors on all 4
sides of each vehicle detect the presence of walls, obstacles, and other vehicles. When an obstacle is detected, a repulsive vector is added to the gradient-based control, which pushes the vehicle away from the obstacle. Figure 4 shows that the vehicles achieve fairly uniform coverage of the hallways while still maintaining the ultrasound ranging distance needed to create a navigation network. The solution converges after 500 iterations.

CONCLUSION

This paper presents distributed algorithms for localization and navigation of multiple vehicles inside of a building. A group of 20 robotic vehicles (see Figure 5) was built to test the algorithms. Results of preliminary hardware tests will be shown at the conference.

REFERENCES