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Leader-follower formation control of multiple mobile robots

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Abstract: *this article discusses the problem of controlling a group of mobile robots by a leader's follow-up method. A process implementation algorithm, a mathematical model of a non-holonomic mobile robot, navigation and communication methods are presented. The presented algorithm and control method contribute to the correct positioning and reaching of set targets by a group of mobile robots. The results show robust robots behaviour and good accuracy.*

Keywords: *multiple robot control, leader-follower, mobile robots, navigation and localization*

1. Introduction

A robot team can perform tasks that are difficult for one single robot. Some examples are group hunting [1, 2], large area exploration [3], surveillance [4], object transportation [5, 6], and spacecraft interferometry tasks [7].

It is well known that the robustness of multiple mobile robot systems is strictly related to the control structure used to organize the robots and to obtain the desired formation behaviours. In the field of mobile robots formation control, the control structures can be identified as centralized control structure and distributed control structure. In the centralized control structure, a single computational unit processes all the information needed to achieve the desired control objectives. Therefore, they can ideally yield superior performances and optimal decisions for both the individual members and the formation as a whole [8].

In recent years, many of the related studies on formation control for multiple mobile robots with centralized control structure have been discussed. In reference of [9], a coordination strategy for moving a group of robots in a desired formation over a given trajectory was proposed. In reference of [10], a centralized path planning method for a group of unmanned aerial vehicles (UAVs) in a desired formation was proposed. In reference of [11], a centralized trajectory computation scheme that uses kinetic energy shaping was developed. The advantages of a centralized structure typically include faster convergence and enhanced stability. These benefits come with a greater financial cost due to the required processing and communications resources needed by the single computational unit. Although these guarantee a complete solution, centralized control schemes require higher computation power and are less robust due to the heavy dependence on a single controller. Additionally, architectures involving a single computational unit typically do not work well for large systems due to limited communication range and limited processing power of the single computational unit [12].

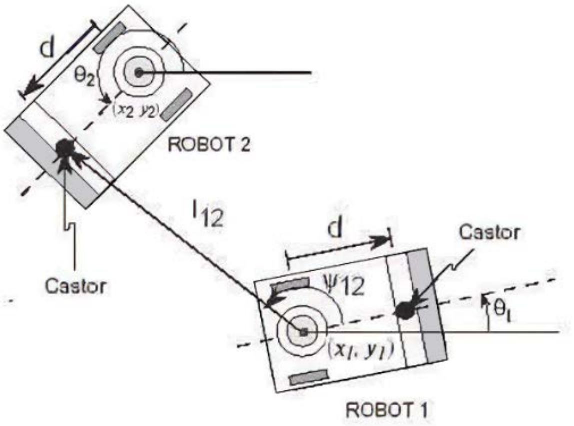

Figure. 1. Leader and one follower

In the leader-follower approach [13, 14, 15, 16], one robot acts as leader that generates the reference trajectory for the group of robots, and the rest of robots in the group act as followers that must keep the desired separation and relative bearing with respect to the leader. In fact, once the motion of the leader is given, the desired separation and the desired relative bearing of the follower with the leader can be achieved by choosing a local control law on each follower based on its relative position dynamics. Then the stability of the formation is also guaranteed, i.e. the entire group can achieve and maintain the desired formation. Based on the above observation, formation control problem can be essentially viewed as a natural extension of the traditional trajectory-tracking problem. To the best of my knowledge, just few researchers have considered the trajectory-tracking problem when dealing with the multi-robot formation problem. [15, 17] presented a feedback linear control method for the formation of non-holonomic mobile robots using the leader-follower approach, and proposed two control algorithm: $l-\varphi$ control and $l-l$ control. The $l-\varphi$ control aimed to control and maintain the desired separation l_{12}^{d} and relative bearing φ_{12}^{d} between the leader and the follower robot as shown in Fig. 1 for two non-holonomic wheeled mobile robots. The $l-l$ control considered the relative position of three mobile robots, a follower and two leaders, by keeping the desired separation to its two leaders. The aim is to control and maintain the desired separations l_{13}^{d} and l_{23}^{d} between the follower and its two leaders, as shown in Fig. 2.

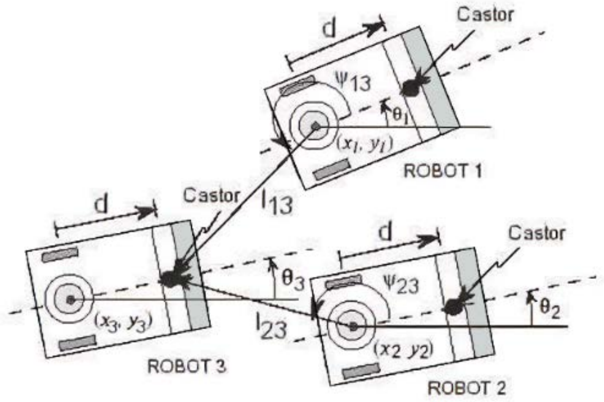

Figure 2. Two leaders and one follower

2. Mathematical model of non-holonomic mobile robot

Consider a group of n non-holonomic mobile robots. For simplicity, we assume that each robot has the same mechanical structure as shown in Fig. 3. The posture of the $i-th(1\leq i\leq n)$ robot (named robot R_i) in a cartesian frame OXY is specified by $p_i=[x_i,y_i,\theta_i]^T$, where (x_i,y_i) denotes the front coordinate of the robot R_i, θ_i is the heading angle.

The mobile robot with two driven wheels shown in Fig. 2.1 is a typical example of non-holonomic mechanical systems. Under the hypothesis of pure rolling and nonslipping [18], the kinematic constraint of the non-holonomic mobile robot R_i is given as

$$\dot{y}_i \cos\theta_i - \dot{x}_i \sin\theta_i = d\dot{\theta}_i, \tag{1.1}$$

where d is the distance from the rear axle to the front of the robot.

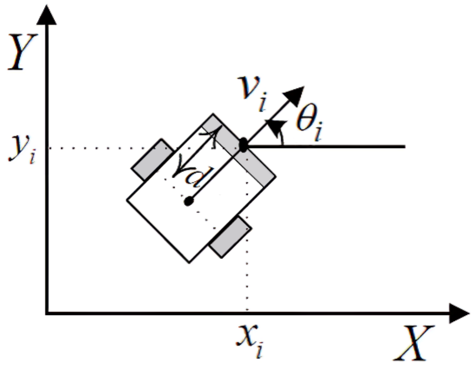

Fig. 3 Non-holonomic mobile robot

From the kinematic constraint (2.1), the kinematics model of the non-holonomic mobile robot R_i can be written as

$$\dot{p}_i = \begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\theta}_i \end{bmatrix} = \begin{bmatrix} \cos\theta_i & -d\sin\theta_i \\ \sin\theta_i & d\cos\theta_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix}, \tag{1.2}$$

where v_i and w_i are the linear velocity and the angular velocity.

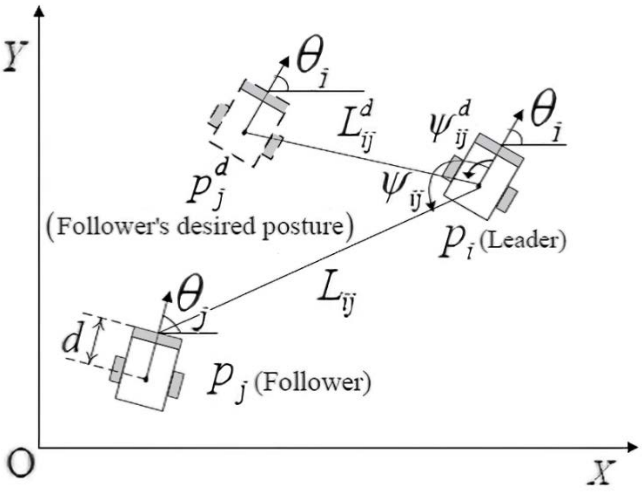

Fig. 4. Leader follower formation.

From the formation control scheme shown in Fig. 2.2, the robot R_j follows its leader R_i with desired separation L_{ij}^d, desired bearing ψ_{ij}^d and desired orientation θ_j^d. Here $\theta_j^d = \theta_i$. Note that $p_i = [x_i, y_i, \theta_i]^T$ is the actual posture of leader robot R_i,

$p_j = [x_j, y_j, \theta_j]^T$ is the actual posture of follower robot R_j , $p_j^d = x_j^d, y_j^d, \theta_j^d]^T$ is the desired posture of follower robot R_j , Lij and ij are the actual separation and the actual bearing between follower R_j and its leader R_i, and L_{ij}^d and ψ_{ij}^d represent the desired separation and the desired relative bearing respectively.

Through the geometrical relation between robots, it is easy to obtain that the desired posture p_j^d of the follower robot satisfies

$$p_j^d = x_j^d, y_j^d, \theta_j^d]^T = \begin{bmatrix} x_i - d\cos\theta_i + L_{ij}^d \cos(\psi_{ij}^d + \theta_i) \\ y_i - d\sin\theta_i + L_{ij}^d \sin(\psi_{ij}^d + \theta_i) \\ \theta_i \end{bmatrix}, \tag{1.3}$$

The actual posture p_j of the follower R_j satisfies

$$p_j = [x_j, y_j, \theta_j]^T = \begin{bmatrix} x_i - d\cos\theta_i + L_{ij} \cos(\psi_{ij} + \theta_i) \\ y_i - d\sin\theta_i + L_{ij} \sin(\psi_{ij} + \theta_i) \\ \theta_i \end{bmatrix}, \tag{1.4}$$

Project the relative distance Lij along the X and Y directions by Cartesian coordinates as

$$L_{ij} = \sqrt{L_{ijx}^2 + L_{ijy}^2}, \tag{1.5}$$

where $L_{ijx}(t)$ and $L_{ijy}(t)$ denote that the actual relative separations between leader and follower project along X and Y direction by Cartesian coordinates respectively, and satisfy

$$L_{ijx} = x_i - x_j - d\cos\theta_i = -L_{ij}\cos(\psi_{ij} + \theta_i), \tag{1.6}$$

$$L_{ijy} = y_i - y_j - d\sin\theta_i = -L_{ij}\sin(\psi_{ij} + \theta_i).$$

Taking the derivative of (2.6) along (2.2) gives

$$\dot{L}_{ijx} = \dot{x}_i - \dot{x}_j + d\dot{\theta}_i \sin\theta_i = v_i\cos\theta_i - v_j\cos\theta_j + dw_j\sin\theta_j,$$

$$\dot{L}_{ijy} = \dot{y}_i - \dot{y}_j - d\dot{\theta}_i \cos\theta_i = v_i\sin\theta_i - v_j\sin\theta_j - dw_j\cos\theta_j,$$

where v_i and w_i denote the linear velocity and angular velocity of the leader R_i, v_j and w_j denote the linear velocity and angular velocity of the follower R_j.

Taking the derivative of (2.5) along (2.2) yields

$$\dot{L}_{ij} = \frac{1}{\sqrt{L_{ijx}^2 + L_{ijy}^2,}} \left(L_{ijx}.\dot{L}_{ijx} + L_{ijy}.\dot{L}_{ijy}\right)$$

$$
\begin{aligned}
&= \frac{1}{L_{ij}}\left\{v_i\left(L_{ijx}\cos\theta_i + L_{ijy}\sin\theta_i\right)\right\} \\
&\quad - \frac{1}{L_{ij}}\left\{v_j\left(L_{ijx}\cos\theta_j + L_{ijy}\sin\theta_j\right)\right\} \\
&\quad + \frac{1}{L_{ij}}\left\{-dw_j\left(-L_{ijx}\sin\theta_j + L_{ijy}\cos\theta_i\right)\right\} \\
&= -v_i\cos\psi_{ij} + v_j\cos\gamma_{ij} + dw_j\sin\gamma_{ij}, \qquad (1.7)
\end{aligned}
$$

where $\gamma_{ij} = \psi_{ij} + \theta_i - \theta_j$.

From Fig. 2 $\psi_{ij} = \arctan(L_{ijy}/L_{ijx}) - \theta_i + \pi$. Let us take the derivative of the relative bearing,

$$
\begin{aligned}
\dot{\psi}_{ij} &= \left[\tan\left(\frac{L_{ijy}}{L_{ijx}}\right) - \theta_i + \pi\right]' \\
&= \tfrac{1}{L_{ij}}\left\{v_i\sin\psi_{ij} - v_j\sin\gamma_{ij} + dw_j\cos\gamma_{ij}\right\} - w_i. \qquad (1.8)
\end{aligned}
$$

Hence, the kinematic model of the leader-follower formation is

$$\dot{L}_{ij} = -v_i\cos\psi_{ij} + v_j\cos\gamma_{ij} + dw_j\sin\gamma_{ij}, \qquad (1.9)$$

$$\dot{\psi}_{ij} = \tfrac{1}{L_{ij}}\left\{v_i\sin\psi_{ij} - v_j\sin\gamma_{ij} + dw_j\cos\gamma_{ij}\right\} - w_i. \qquad (1.10)$$

3. Algorithm for leader follower method

The proposed algorithm aims to establish the consistency of the group control process, as well as to improve the movement of mobile robots. Of course, to implement such an algorithm, certain predefined criteria must be met. The criteria are as follows:

- We have to have the mathematical model of the robots;
- We have to determine the odometry errors;
- We have to set up controllers for control of every robot;

Assuming that all the robots that we use will have the same mobile platforms, respectively, they will be controlled in the same way, it will have to calculate the respective parameters for only one robot and be used for all. This will reduce the need for large computational power, which is a drawback in this type of group control. The proposed algorithm is shown in Figure 5.

All robots are connected in the same Wi-Fi network, so they can communicate each other. The leader robot receives date from the sensors of the other robots then send back control command. To implement the proposed algorithm we use ROS. In ROS we can use Web socket protocols for send and receive data. Every robot is represented as ROS ‘node’. That mean that the leader will compute the control parameters for each follower and sends them for performing. Each follower will be numbered. The numbering is as follows: even numbers will be on the right side, odd numbers will be on the left side.

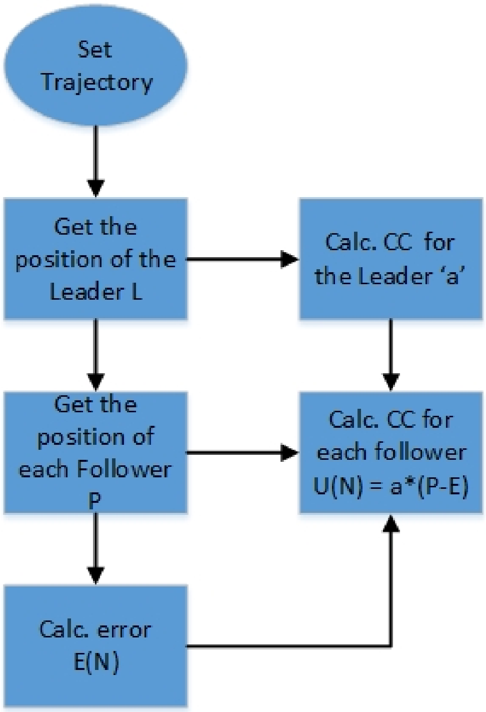

Fig. 5. Leader Follower algorithm.

For the autonomous navigation, we are using ROS Navigation Stack. It provides functions and algorithms for mapping and autonomous navigation. When we have the robot models and controllers, we put them in the navigation algorithms the navigation is ready to be used. The leader will follow the trajectory from the Navigation stack and the other agents will follow the same trajectory by adding the corresponding offset. The error will be calculated by determining the localization of each robot according to the localization of the leader. In case of detection of obstacle, the formation will follow the trajectory of the leader without offset and the numbering will do the sequence.

4. Conclusion

The proposed algorithm permits the контрол of a group of robots by the leader's follow-up method. Robots communicate directly on a local network. Each agent sends as a feedback its localization to the leader. The leader’s computer performs calculations. For each robot, ROS is executing a node that calculates the necessary control signals. High data rates and the performance of the Leader PC make it possible to achieve robust robot control, positioning accuracy, and trajectory

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Лидер-последователь формирования контроля нескольких мобильных роботов

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Аннотация: *В статье рассматривается проблема управления группой мобильных роботов по методу наблюдения последователья на лидера. Представлены алгоритм реализации процесса, математическая модель неголономного мобильного робота, методы навигации и связи. Данный алгоритм и методь управления способствуют правильному позиционированию и достижению заданных целей группой мобильных роботов. Результаты показывают надежное поведение роботов и хорошую точность.*

Ключевые слова: *управление несколькими роботами, лидер-последователь, мобильные роботы, навигация и локализация*