Leader-Follower Formation Tracking Of Multiple Mobile Robots With Constant Leader Velocity

M. Latif
Electrical Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
Mechatronics Department, University of Trunojoyo Madura, Bangkalan, Indonesia
latif.utm@gmail.com

Abstract. This research presents a tracking formation by multiple mobile robots. The formation used is leader follower approach. Formation control is designed based on the robot kinematics model. Follower is controlled to track the position of the specified formation. Triangle shape is used to the goal formation. Experiments carried out with two scenarios. First, leader moves to a point with linear motion. Second, leader moves along the circular trajectory. Leader motion is constantly with the aim that the formation is rigidly formed while moving towards the goal. Experiments show that robots can perform and maintain formation while achieving goals.

Keywords; Formation Tracking, Leader Follower, Mobile Robot

1. Introduction
Formation control is one of the many research topics currently being carried out. That is because it has complex difficulties and can be implemented. Sometimes a task such as a rescue mission, moving large objects, hunting activities, forming and clustering satellites is too difficult or impossible to do by a single robot [1]. Formation control of a group of robots can be implemented to complete a job, for example; agriculture [2], surveillance [3] and transportation [4]. Formation control problem is formation tracking takes a long time or desired formation cannot be achieved. Another problem is the chaotic formation that occurs during the journey to the goal, this is caused by disturbances. For example, follower velocity is slow compared to leader velocity or due to other problems. Several approaches have been proposed in the literature for formation control in mobile robots (see [5]-[10]). This approach can be proven with assumption that all position values are guaranteed to be used in formation control. One of the formation control approach is follower leader method. The method consists of one or more robots as a leader and several robots as followers who track the leader. In this field of research, generally, it is assumed to have active communication between the Leader and the Follower. Formation problems can be solved based on graph theory concepts (see [11] - [14], for example). Other study in leader followers formation control have been carried out by [15]. The study conducted experiments with two robots. The controller used in the follower is the PID method.

This study discusses formation tracking using the leader follower approach with triangle shape formation. Leader velocity is constantly regulated, while each follower velocity are controlled using robot kinematics model. The constant movement of the leader aims to produce a reliable and rigid formation. The follower is controlled to track the reference point that has been determined to reach the formation, while the leader is controlled to track a point or trajectory. This study is organized as follows; in section 2 is discussed about leader follower formation control on mobile
robots. In section 3 is discussed the control design based on robot kinematics models. In section 4 is discussed experiments results to validate the controller that have been designed. Then the experimental results are concluded in section 5.

2. Leader-Follower Formation Control
Leader follower formation control structure has a robot that acts as leader, and the other robot acts as a follower who follows the leader in his position. Follower must know his own position towards the leader in order to achieve and maintain formation. Follower must always maintain distance error and angle error against the leader is equal to zero. Formation control using leader follower approach is shown in Figure 1, with the following variable;

![Figure 1. Leader follower formation control structure](image)

where;
- $d_r$: Distance reference
- $\theta_r$: Angle reference
- $(x_L, y_L)$: Leader Position
- $(x_{d_F}, y_{d_F})$: Follower Position Reference
- $(x_F, y_F)$: Follower Position
- $e_x, e_y$: Position error

3. Control Design
The robot used in this study is a type of mobile robot that is driven by two rear wheels. Motion control is designed based on kinematic models of mobile robot. Model of robot dynamics used refers to research has conducted by De la Cruz [16]. Mobile robot model is shown in Figure 2 with assuming there is no disturbances of robot dynamics. The purpose of this control will produce linear velocity and angular velocity that will be given to the follower. Control structure is shown in Figure 3. The kinematics equation of the mobile robot used is written as follows;

![Figure 2. Model of mobile robot](image)

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\phi}
\end{bmatrix} = \begin{bmatrix}
\cos\phi & -\sin\phi \\
\sin\phi & \cos\phi \\
0 & 1
\end{bmatrix} \begin{bmatrix}
u \\
\omega
\end{bmatrix}
\]

where;
- $\nu$: Linear velocity
- $\omega$: Angular velocity
- $\phi$: Robot heading
- $\rho$: Distance between axle and center of coordinates
4. Experimental Result

Experiment is conducted on the controller designed for leader follower formation control. Experiments carried out by simulations using MATLAB. Simulation consisted of three robots and formed a triangle formation as shown in Figure 4. Robot parameters used in the experiment are shown in Table 1. Experiment were carried out with two different scenarios. First scenario is leader moves linearly to the specified destination and second scenario is leader follows a circle-shaped trajectory.

Table 1. Robot parameter

| Parameter | Leader | Follower1 | Follower2 |
|-----------|--------|----------|----------|
| $k_x$     | 0.5    | 0.5      | 0.5      |
| $k_y$     | 0.5    | 0.5      | 0.5      |
| $s_x$     | 0.4    | 0.4      | 0.4      |
| $s_y$     | 0.4    | 0.4      | 0.4      |
| $a$       | 0.2 m  | 0.2 m    | 0.2 m    |

4.1. Linear motion

Experimental scenario with linear motion, the leader moves to the specified point and moves linearly. Follower will move towards the reference position in order to reach the specified formation. The formation used is a triangle shape. Leader's destination point is $x = 6, y = 0$. The initial position of each robot has not formed a triangle formation. The initial values of the position of each robot and the formation parameters are determined according to Table 2. In this experiment, formation error or
distance error of each follower reaches a steady state at time $s = 4$. Formation error for each follower is obtained using Equation (2). Formation error is shown in Figure 5. Linear velocity of two followers close to leader occurs at time $s = 4$, while the angular velocity occurs at time $s = 25$, as shown in Figure 6. Trajectory of leader and follower during linear motion is shown in Figure 7. Based on this experiment, formation control design has been successful in achieving the desired formation. Even though the leader and follower move to the goal after formation is reached, formation is well maintained and there is no chaos in the formation.

### Table 2. Formation parameter

| Parameter | Leader | Follower1 | Follower2 |
|-----------|--------|-----------|-----------|
| $x_{\text{initial}}$ | 1      | 0.5       | 0         |
| $y_{\text{initial}}$ | 0      | 0         | 0.5       |
| $\phi_{\text{initial}}$ | 0      | 0         | 0         |
| $\text{dist}_l$ | -      | 0.5 m     | 0.5 m     |
| $\theta_{\text{r}}$ | -      | 0.785 rad | -0.785 rad |

\[
e_D = \sqrt{(e_x + e_y)^2}
\]

(2)

**Figure 5.** Formation error in linear motion

**Figure 6.** Linear and angular velocity in linear motion

**Figure 7.** Robot trajectory in linear motion
4.2. Tracking circle trajectory.
In the second scenario, leader motion follows a circle shape trajectory. As long as leader follows trajectory, follower goes to reference point and makes a triangle formation. Initial position in the second scenario is the same as the first scenario experiment. Initial position values of each robot and formation parameters according to Table 1. In this experiment, the formation error of each follower reaches a steady state at time $s = 3$, as shown in Figure 8. Linear velocity of two followers close to leader occurs at time $s = 4$, while the angular velocity occurs at time $s = 35$, as shown in Figure 9. Figure 10 shows the leader and follower trajectories. Based on the second experiment, showed that controller was designed is work properly. Formation is well maintained and there is no chaos in formation even though leader follows circular trajectory.

![Figure 8. Formation error in tracking trajectory](image)

![Figure 9. Linear and angular velocity in tracking trajectory](image)

![Figure 10. Robot trajectory in tracking trajectory](image)

5. Conclusions
This paper proposed formation tracking on a group of mobile robots with a leader follower approach. Controller is designed based on robot mobile kinematics model. Leader velocity is determined by a constant value. Formation used in the experiment is a triangle shape. Effectiveness of the controller in achieving formation is verified in simulation. Based on experiments, the proposed controller can run successfully. Formation can be achieved and maintained even though the leader makes a linear movement or follows a circular trajectory. Further research can be developed by conducting experiments on real robot.
Acknowledgment
The authors wish to thank LPDP-BUDI Kemenristekdikti for funding this research.

References
[1] P. K. and Y. B. Shtessel, “Time-varying linear controllers for exponential tracking of nonholonomic systems in chained form”, Int. J. Robust Nonlinear Control, vol. 17, no. 7, pp. 631–647, 2007.
[2] P. Cartade, R. Lenain, B. Thuilot, B. Benet, and M. Berducat, “Motion Control of a heterogeneous fleet of mobile robots: Formation control for achieving agriculture task”, in AGENG 2012 5th Automation Technology for Off-Road Equipment Conference, 2004, pp. 2–7.
[3] Z. Tang and Ü. Özgüner, “Motion Planning for Multitarget Surveillance”, IEEE Trans. Robot., vol. 21, no. 5, pp. 898–908, 2005.
[4] G. Loianno and V. Kumar, “Cooperative Transportation using Small Quadrotors using”, IEEE Robot. Autom. Lett., vol. 3, no. 2, pp. 680–687, 2018.
[5] L. consolini, F. Morbidi, D. Prattichizzo, and M. Tosques, "Leader-Follower Formation Control of nonholonomic mobile robots with input constraints“, Automatica, 44(5):1343-1349, 2008.
[6] . Shao, G. Xie, J. Yu and L. Wang, "Leader-Following Formation Control of Multiple Mobile Robots", Proceedings of the 20th IEEE International Symposium on Intelligent Control, ISIC '05 and the 13th Mediterranean Conference on Control and Automation, MED '05, vol. 2005 (Limassol, Cyprus), pp. 808-813, 2005.
[7] T. Balch and R. C. Arkin, "Behavior-based formation control for multirobot team", IEEE Trans. Robot. Automat., vol. 14, no. 6, pp. 926-939, December 1998.
[8] J. Fredslund and M. J. Mataric, "A general algorithm for robot formations using local sensing and minimal communication", IEEE Trans. Robot. Automat., vol. 18, no. 5, pp.837-846, October 2002.
[9] A. K. Das, R. Fierro, V. Kumar, J. P. Ostrowski, J. Spletzer and C. J. Taylor, "A vision-based formation control framework", IEEE Trans. Robot. Automat., vol. 18, no. 5, pp. 813-825, October 2002.
[10] P. O"gren, M. Egerstedt and X. Hu, "A control Lyapunov function approach to multi-agent coordination", IEEE Trans. Robot. Automat., vol. 18, no. 5, pp. 847-851, October 2002.
[11] H. Rezaee, F. Abdollahi, M. B. Menhaj, “Model-free fuzzy leader follower formation control of fixed wing uavs”, in: Proceedings of the Iranian Fuzzy Systems Confrance, Qazvin, Iran, 2013, pp. 1–5.
[12] Z. Lin, W. Ding, G. Yan, C. Yu, and A. Giua, “Leader-follower formation via complex laplacian”, Automatica, vol. 49, no. 6, 2013, pp. 1900–1906.
[13] H. Rezaee and F. Abdollahi, "Motion synchronization in unmanned aircrafts formation control with communication delays", Communications in Nonlinear Science and Numerical Simulation, vol. 18, no. 3, 2013, pp. 744–756.
[14] M. Cao, A. S. Morse, C. Yu, B. D. O. Anderson, S. Dasgupta, “Maintaining a directed, triangular formation of mobile autonomous agents”, Communications in Information and Systems vol. 11, no. 1, 2011, pp. 1–16.
[15] I. S. Choi, J. S. Choi, and W. J. Chung, “Leader-follower formation control without information of heading angle”, in 2012 IEEE/SICE International Symposium on System Integration, SII 2012, 2012, pp. 842–846.
[16] C. De la Cruz, R. Carelli, C. D. La Cruz, and R. Carelli, “Dynamic Modeling and Centralized Formation Control of Mobile Robots”, in IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on, 2006, pp. 3880–3885.