Decentralized Formation Control for Multiple Leaders and Followers ⋆

Leonardo A. Fagundes-Junior * **Denise Cristina H. de Freitas** ** **Mário Sarcinelli-Filho** *** **Alexandre S. Brandão** **

* *Department of Informatics, Federal University of Viçosa, MG, (e-mail:* `leonardo.fagundes@ufv.br`*).*
** *Department of Electrical Engineering, Federal University of Viçosa, MG, (e-mails:* `denise.henrique@ufv.br`, `alexandre.brandao@ufv.br`*)*
*** *Department of Electrical Engineering, Federal University of Espírito Santo, ES, (e-mail:* `mario.sarcinelli@ufes.br`*)*

Abstract: This work describes a control scheme proposed for guiding a leader-follower formation of mobile robots. In our approach, there is no information sharing, emphasizing a decentralized approach. The follower robot uses a laser scanner mounted on it to get and estimate information of its leader, such as its location and velocities. The proposed strategy can be applied in scenarios with several agents, in the possibility of having several leaders and also several followers. To validate this proposal, four robots are used, first in a diamond-shaped formation with one leader and three followers; then in a line-shaped formation, containing three leaders and three followers. The system stability can be verified through the asymptotic convergence of the formation variables to the desired values during the experiments, which is in accordance with the theoretical analysis performed in the controller design.

Resumo: Este trabalho descreve uma proposta de controle para uma formação líder-seguidor de robôs móveis terrestres. Nesta estratégia não há compartilhamento de informação, enfatizando uma abordagem descentralizada. O robô seguidor utiliza um sensor laser montado no mesmo para obter e estimar informações do seu líder, tais como a sua localização e velocidade. A estratégia proposta pode ser aplicada em cenários com vários agentes, na possibilidade de ter vários líderes e também vários seguidores. Para validar esta proposta, são utilizados quatro robôs, primeiro numa formação em forma de diamante com um líder e três seguidores; depois numa formação em forma de linha, contendo três líderes e três seguidores. A estabilidade do sistema pode ser verificada através da convergência assimptótica das variáveis de formação para os valores desejados durante os experimentos, o que está de acordo com a análise teórica realizada no projeto do controlador.

Keywords: Robots Cooperation, Decentralized Control, Navigation, Line Structure.

Palavras-chaves: Cooperação de Robôs; Controle Descentralizado; Navegação; Estrutura Linear.

1. INTRODUCTION

In robotics fields, particular tasks are executed in a better way by a group of robots working cooperatively instead of a single robot. This may be due to the specific nature of the task or to the associated cost if the task is executed by a specialized robot, which is usually a more expensive equipment. Examples of the most compatible tasks for a group of mobile robots to perform include load transport (Shirani et al., 2019; Hawley and Suleiman, 2019; Tuci et al., 2018; Farivarnejad et al., 2021), search and rescue of people in rubble (Chatziparaschis et al., 2020; Arnold et al., 2018; Cardona and Calderon, 2019; Queralta et al., 2020), cooperative search and mine disarming task (Wong et al., 2020; Rango et al., 2017; Florez-Lozano et al., 2020), mapping of large regions and areas (Lee, 2020; Zhang et al., 2019; Masehian et al., 2017), and so on.

Among the coordinated control approaches involving co-operation of mobile robots, three distinct techniques can be mentioned: leader-follower formation, virtual structures method, and behavior-based method (Soni and Hu, 2018). In the leader-follower structure, a robot named leader is responsible for guiding all the other robots that compose the formation in order to bring them to their desired positions and keep them in formation during the entire movement (Yang et al., 2020; Li et al., 2020). Dealing with a virtual structure, the robot leader is no longer the main entity, but the entire formation. In order to keep a desired virtual geometric structure, multiple mobile robots system must work at a cooperation framework, which is considered a rigid body that moves to establish a predefined geometric shape (Miao et al., 2018; Liu et al., 2020). Finally, in the behavior-based approach, each robot is controlled by a

⋆ This work was supported by CAPES, CNPq, FAPES and FAPEMIG.

predefined behavior (Lee and Chwa, 2017). This method is easy to implement and reacts fast to environmental change, but it needs predefined behaviors and it is hard to maintain the stability of the formation.

Regarding the control strategy, it can be carried out in a centralized or decentralized way (Dai et al., 2020; Tanveer and Kadri, 2018). For the centralized control strategy, there is an agent responsible for all information concerning the group, such as relative positions of all the others and computation of all control signals required to establish the formation. On the other hand, a decentralized control strategy is understood as that without such a centralized information unit. In this sense, the robots that make up the formation have their own sensors designed to report their current position in the environment, the state of the workspace, the current pose of the other robots, and, by themselves, to constitute the formation.

The advantages and disadvantages of centralized or decentralized control schemes have been the subject of discussion in the scientific community (Ismail and Sariff, 2019). Centralized control systems, for example, can manage global information about the environment and optimize coordination between robots or mission accomplishment by reducing and/or smoothing the trajectories (or paths) to be covered. Furthermore, they can easily identify and manage failures of some of the robots. On the other hand, the information centralizing unit presents itself as a limiting factor of the system, in terms of computational and communication requirements. In other words, its eventual failure compromises the entire system. In contrast, decentralized control systems do not present a rigid computational constraint, since each agent performs its control independently, with a common global objective. In addition, such systems are inherently more stable and robust, since task accomplishment can be achieved even if a failure (or misbehavior) occurs in one of the robots in the formation. However, the difficulty in localization and global mapping makes it difficult to coordinate and optimize the formation's coordination during mission execution (Ismail and Sariff, 2019). In this sense, therefore, the choice of formation control strategy is up to the designer, who must analyze the characteristics of the task to be performed by the group of robots.

In such a context, this paper presents a proposal for decentralized control of a leader-follower formation. The platoon is composed by four unicycle-like robots, which do not share information with each other. The follower is responsible for positioning relatively to its leader. For this approach, the leader carries a predefined and known pattern, while the follower has a laser scanning sensor installed on board it. In possession of current and desired formation variables, a control law is designed according to the theory of Lyapunov and applied to the follower robot (emphasizing decentralized control) so that it achieves the pose in the semi-structured environment that guarantees the formation shape. Moreover, using the same strategy, an extension is proposed handle considering the possibility of having one leader and several followers and also several leaders and several followers.

The text is organized as follows: Section 2 illustrates the robot used as an experimental platform, as well as the formation variables involved in the leader-follower linear structure and the state equations of the system. In addition, it shows the design of the decentralized formation controller and its stability analysis according to Lyapunov, and then highlights the strategy used to obtain the formation variables based on the on-board sensory system of the follower robot. Afterwards, Section 3 discusses the extension of the strategy to multi-robot formation by considering two distinct possible structures: leader-followers and leaders-followers. Next, Section 4 highlights the numerical experimental results and pertinent discussions regarding the proposed formation control laws. Finally, Section 5 presents the main conclusions and suggestions for future work.

2. LEADER-FOLLOWER FORMULATION

This section presents the formation variables involved in the proposed decentralized leader-follower formation control, as well as the necessary details regarding the robots used for strategy validation.

2.1 The Robot Model

In this work, we used the Pioneer P3-Dx, a unicycle like mobile robot shown in Figure 1. Considering that navigation occurs only in a horizontal plane, the robot pose is $\mathbf{x} = [x\ y\ \psi]^\intercal$, in which x and y are the coordinates of the control point located at the center of the virtual axle that joins its wheels, and ψ is its heading with respect to its x axis, based on the inertial frame $\langle o \rangle$. Also, v and ω are the linear and angular velocities of the robot, respectively.

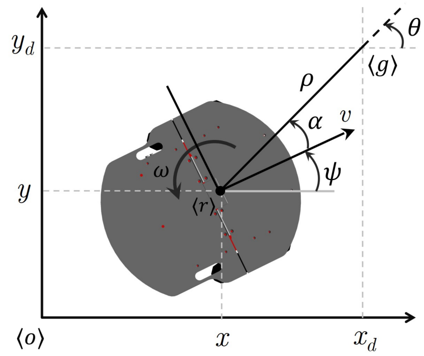


Figure 1. Spatial unicycle type robot representation (Brandão et al., 2013).

The system of equations describing the motion of the robot over time in the Cartesian plane can be written as follows

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi & 0 \\ \sin\psi & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}, \quad (1)$$

whose nonholonomic condition is given by

$$\dot{y}\cos\psi - \dot{x}\sin\psi = 0,$$

indicating that the robot cannot displace laterally.

2.2 The Leader-Follower Formulation

The formation variables involved in decentralized leader-follower formation control can be represented by the state vector $\mathbf{q} = [\rho_{LF}\ \beta_{LF}\ \theta_{LF}]^\intercal$, which represent, respectively, the distance between the leader and follower robots ($\rho_{LF} \in \mathbb{R}^+$), the angle between the line connecting the two robots and the follower's x-axis ($\beta_{LF} \in (0, \pi)$ rad), and the orientation error between the robots ($\theta_{LF} \in [-\pi/2, \pi/2]$ rad). All these variables are shown in Figure 2, to illustrate the formulation in (Brandão et al., 2013). It is worth noting that throughout the paper, variables with subscript L refer to the variables of the *leader* robot, as well as, variables with subscript F will be used to describe the *follower* robot states.

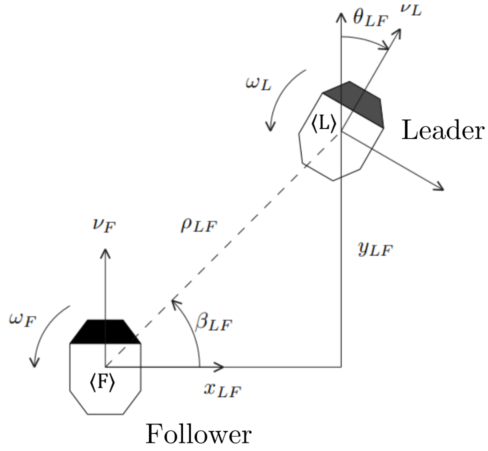


Figure 2. The formation geometry and the description of the control variables.

As described in our previous work (Brandao et al., 2009), the state equations for the follower robot, based on the formation variables, are given by

$$\dot{\rho}_{LF} = u_L \sin(\beta_{LF} - \theta_{LF}) - u_L \sin \beta_{LF} \tag{2a}$$

$$\dot{\beta}_{LF} = \frac{1}{\rho_{LF}}[u_L \cos(\beta_{LF} - \theta_{LF}) - u_F \cos \beta_{LF}] - \omega_F \tag{2b}$$

$$\dot{\theta}_{LF} = \omega_L - \omega_F \tag{2c}$$

In order to design a controller, we define the following formation errors: $\tilde{\rho}_{LF} = \rho_d - \rho_{LF}$ and $\tilde{\beta}_{LF} = \beta_d - \beta_{LF}$. The proposed controller goal is to make $\rho_{LF} \to \rho_d$ and $\beta_{LF} \to \beta_d$, and, consequently $\tilde{\rho}_{LF} \to 0$ and $\tilde{\beta}_{LF} \to 0$ when $t \to \infty$, keeping θ_{LF} bounded. Notice from (2a) that the change in the orientation error θ depends only on the difference between the angular velocities of the leader and follower robots.

Following the control signals make the system stable and reach at the equilibrium point asymptotically

$$v_F = \frac{v_L \sin(\beta_{LF} - \theta_{LF}) - k_1 \tanh \tilde{\rho}_{LF}}{\sin \beta_{LF}} \tag{3a}$$

$$\omega_F = \frac{v_L \sin \theta_{LF} + k_1 \tanh \tilde{\rho}_{LF} \cos \beta_{LF}}{\rho_{LF} \sin \beta_{LF}} - k_2 \tanh \tilde{\beta}_{LF}, \tag{3b}$$

with $k_1 > 0$ e $k_2 > 0$ real, positive gains. In summary we get $[\tilde{\rho}_{LF}\ \tilde{\beta}_{LF}]^\intercal = [0\ 0]^\intercal$ in $t \to \infty$.

To conclude this section, it is important to comment on two features associated with the proposed control law. The first one concerns to the speed of the leader robot, which must be estimated by the follower during navigation. The second one refers to the two singularities of the proposed controller. The first highlights that the distance between the robots must not be equal to zero, $\rho_{LF} = 0$. This is a singularity that is perfectly respected in the leader-follower structure, because one robot cannot be overlapping the other. The third one concerns the values of $\beta_{LF} = n\pi$, which means that formation cannot be performed with side-aligned robots. This uniqueness is caused by the sensory limitation of the follower robot, as its on-board laser sensor only sees the front of its workspace.

2.3 The Sensing Approach

This subsection presents a proposal for estimating the values of the formation variables $\mathbf{q} = [\rho_{LF}\ \beta_{LF}\ \theta_{LF}]^\intercal$ from the scanning measurements of the laser sensor installed onboard the follower robot (see Figure 3). Initially, a semi-cylinder with diameter equal to 200 mm is mounted on the leader robot of the formation for its identification in the environment. Then, by geometric methods, the equations that govern the calculation of the formation variables are obtained. This way, it is possible to obtain the current state of the leader-follower structure without the need to share information among the robots (decentralized control).

Figure 3 illustrates the distance measurements between the laser sensor mounted on the follower robot and the beginning and end of the pattern seen by this sensor, represented by ρ_1 and ρ_2, which are taken, respectively, at the β_1 and β_2 angles of the laser scan. The controllable formation variables ρ_{LF} and β_{LF}, whose values must be estimated, are also presented in this figure.

Considering that noise in the laser scan measurements can introduce a large error in the calculation of the virtual pattern dimension, due to the large metric discrepancy between the distance separating the robots and such dimension, and knowing that the angular scanning of the sensor used is discrete (1° intervals), the following approximation is feasible for the control variables:

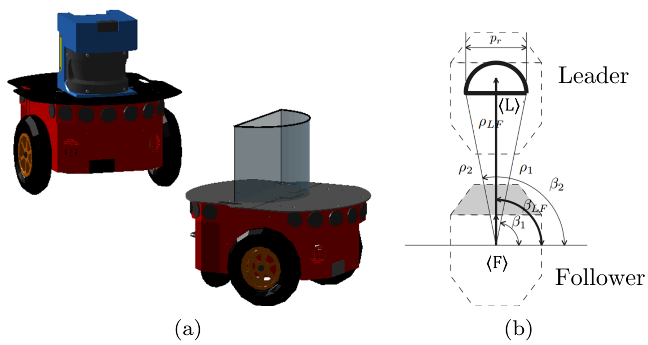


Figure 3. The pattern on board the leader robot. (a) Simulation environment of the leader-follower formation. (b) Distance ρ_{LF} between the robots as a function of laser measurements.

$$\rho_{LF} \approx \frac{\rho_1 + \rho_2}{2} \tag{4a}$$

$$\beta_{LF} \approx \frac{\beta_1 + \beta_2}{2}, \tag{4b}$$

$$\theta_{LF} \approx \arctan\left(\frac{\rho_1 \sin\beta_1 - \rho_2 \sin\beta_2}{\rho_1 \cos\beta_1 - \rho_2 \cos\beta_2}\right), \tag{4c}$$

2.4 Positioning Controller for the Leader

Considering the situation where a robot does not follower any other, i.e., it is a natural leader, we use the controller presented in (Brandão et al., 2013), to guide it in a positioning task, and the variables involved are shown in Figure 1. So, the control signals of the leader are

$$v_L = v_{max} \tanh(\rho) \cos\alpha, \tag{5a}$$

$$\omega_L = \omega_{max}\alpha + v_{max}\frac{\tanh(\rho)}{\rho} \sin\alpha\cos\alpha. \tag{5b}$$

It is worth-mentioning that the controller described by Brandão et al. (2013), guides the robot from a starting point to a desired goal, making it stay at the target point without worrying about its final heading. There the stability analysis can also be found.

3. EXTENDED MULTI-ROBOT FORMATION

The proposed control strategy is scalable and it can be applied to a decentralized formation with several leaders and followers. This section outlines how the extension of the decentralized formation controller proposed in Section 2 can be extended for a Leader-Followers structure and a Leaders-Followers one, since all agents have an on-board scanning laser sensor on them and also a pattern, when required.

3.1 Leader-Followers Structure

When the task to be performed requires the mobile robots to establish a predefined geometric structure, it is essential that the followers position themselves relative to a elected leader. The first strategy refers to a leader-followers structure, where there is only one leader and several followers that seek the pattern mounted on it.

The final structure, with n robots, is based on the generation of $n-1$ leader-follower formations in which the $n-1$ followers take reference from only one leader, which carries on itself a semi-circular pattern for identification. Each follower robot is a decentralized structure responsible for collecting and processing data about the leader, as well as to calculate its control signals. Figure 4 illustrate this structure for a diamond-shape formation.

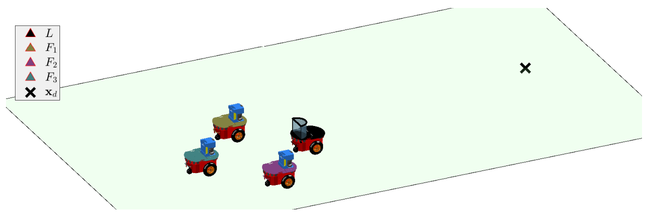


Figure 4. Diamond-shape multi-Robot formation.

3.2 Leaders-Followers Structure

The second approach considers a leader-follower structure, in which all the robots that make up the formation have a pattern mounted on them. One of the robots is the natural leader, which will guide the whole formation to a predefined target. The other robots have to establish the linear structure, seeking for the nearest leader.

Unlike the leader-followers structure, this one does not require that each follower robot to seek their posture in relation to a unique (particular) leader. For this, all robots has a pattern mounted on it, as well as a sensor capable of extracting the formation variables through the identification of this pattern mounted on the closest leader.

In the leaders-followers structure, it is essential that one of the robots is assigned the role of natural leader. Therefore, it is up to the leader to fulfill the mission of reaching the target, while it is up to the followers to seek the closest leader and establish with it the desired formation. Figure 4 illustrate this structure for a line-shape formation.

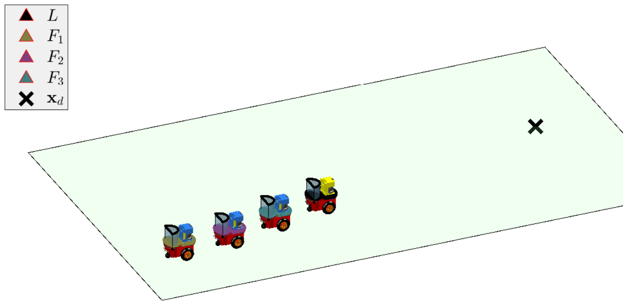


Figure 5. Line-shape multi-robot formation.

4. RESULTS AND DISCUSSION

This section starts describing the experimental setup used to evaluate the proposed decentralized formation control considering an extension for multiple leaders and followers. We have four ground unicycle-like mobile robots, model Pioneer P3-DX, as well a laser scanner mounted on them, whenever is necessary. All leaders have a pattern with well-know dimensions mounted on them. The followers look for such a pattern, in order to localize its relative leader and establish the predefined formation shape with it. Figure 3 illustrates the leader-follower formation for a pair of robots.

Since the laser sensor provides only a two-dimensional information, the pattern must be distinct from other objects in the semi-structured environment. Otherwise, the follower cannot determine correctly the leader, or it can consider some static object in the scene as the leader.

In order to prevent saturation of robot motor speeds, we adopt $k_1 = 0.25\ \mathrm{m\,s^{-1}}$ and $k_2 = 0.5\ \mathrm{rad\,s^{-1}}$ for the follower robots, according to the decentralized formation controller in (3), and $v_{max} = 0,35\ \mathrm{m\,s^{-1}}$ and $\omega_{max} = 0,44$ rad/s, for the leader robot in (5).

ISSN: 2525-8311 DOI: 10.20906/CBA2022/3175

4.1 Case Study: Leader-Followers Formation

Figure 4 illustrates the case in which the leader robot has the pattern to be identified by the three follower robots. In such numerical experiment, it is mandatory that all follower robots can visualize the pattern mounted on the leader robot, so that they can position themselves in relation to it. In this example, the followers and its leader create a diamond-shape virtual structure.

The task to be performed by the leader robot is to reach a target located at the coordinates (4, 3) m starting from the coordinates (0, 0) m, with zero initial heading. The followers, named F_1, F_2 and F_3, start from the positions (-0.750, 0.250) m, (-0.500, -1.000) m and (-1.500, -0.250) m, with the respective orientations, $\psi_{F_1} = -15$ °, $\psi_{F_2} = -45$ °, and $\psi_{F_3} = 15$ °. In order to obtain a diamond formation, the desired values for the formation variables were established, namely: for the first follower, it was defined $\rho_d = 0.700$ m and $\beta_d = 60$ °, for the second, $\rho_d = 0.700$ m and $\beta_d = 120$ °, and for the third $\rho_d = 1.200$ m and $\beta_d = 90$ °.

The results presented in Figure 6 demonstrate the possibility of extending the leader-follower structure to a formation containing more than two robots. This is possible because each leader-follower pair can be treated as a distinct linear structure, which will result in the desired global shape, in this case a diamond-shape one. Figure 6(a) illustrates the path taken by the platoon to reach the desired formation. One can easily see that the robots have successfully organized themselves into a diamond structure, thus fulfilling the task's objective. It is also worth noting that the leader robot reached the target that was proposed to it. The formation robots were plotted at 10s intervals.

The time evolution of the follower robots formation variables can be seen in the Figure 6(b). There all the robots converge asymptotically to the same desired value of ρ_{LF}, for distinct angles β_{LF}, also stable, while maintaining a smooth bounded angle θ_{LF}.

Figure 6(c) presents the control signals sent to the formation robots. It is possible to verify that, once in steady state, the linear and angular velocities sent to the followers practically overlap those sent to the leader of the formation, thus resulting in a smooth movement of the entire platoon. This same figure still illustrates the linear velocity v_L of the leader as well that esteemed by each follower. Despite the visible fluctuations, the estimates follow the variable's trend, which is fundamental for the fulfillment of the tracking task.

It is important to keep in mind that, in this work, the leader search and formation control strategy does not contemplate the avoidance of obstacles, so there may be collisions between agents during the composition of the formation. Therefore, this intra-formation collision must be avoided when the initial and desired conditions are defined.

4.2 Case Study: Leaders-Followers Formation

An example of a leaders-followers structure can be seen in Figure 5, where each robot located immediately in front of another robot becomes the leader of the latter, until all the leader-follower formation pairs are defined. It is worth noting that the robot positioned ahead of everyone else is the natural leader.

Validating the structure proposed here, a numerical experiment was run and the Figure 7 presents their results. In this case, the natural leader runs the positioning controller describe in (5) and must reach the position (4, 3) m in the **XY** navigation plane, starting from the initial position (0, 0) m, with orientation $\psi_L = 0$ °. The other robots execute the decentralized formation controller, described by (3), and all of them have the desired values $\rho_d = 0.700$ m and $\beta_d = 90$ °.

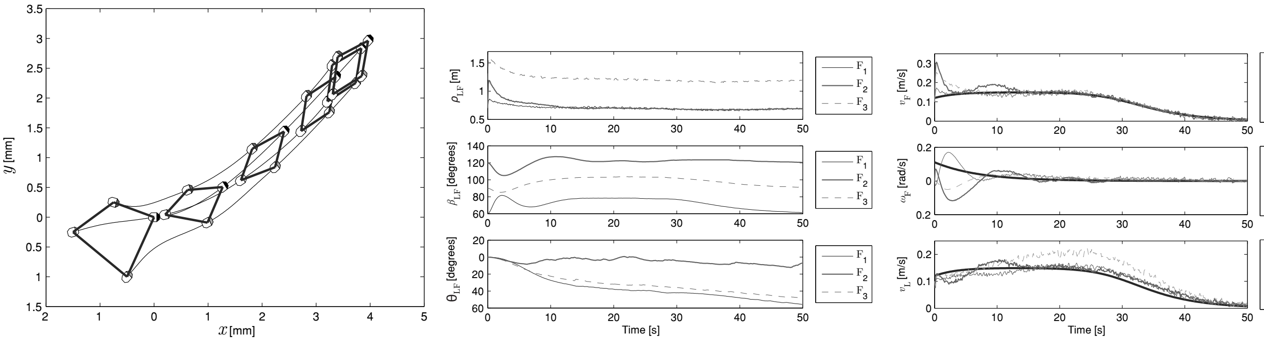
Figure 7(a) illustrates the path taken by the robots in order to form the leader-follower line-shape structure. The formation robots were plotted at 15 s intervals. The traced paths suggest that the followers of the natural leader should have the same path traveled by it. However, as there are several leaders, each follower seeks its closest one and establishes the formation with it. The time evolution of all formation variables is shown in Figure 7(b), which highlights the fact that the formation variables converge asymptotically to the desired values for all followers.

The control signals sent during the positioning task can be seen in Figure 7(c). It is possible to see that, in the vicinity of the target, the control signals tend to zero, indicating, therefore, the asymptotically stable fulfillment of the positioning task, and, consequently, of the tracking task. Note also that upon reaching the target, the followers remain in formation. Additionally, in Figure 7(c), it is presented the linear velocity v_L estimated by followers. Once again it is clearly seen that the estimation by the follower robots is efficient in monitoring the evolution of v_L.

5. CONCLUDING REMARKS

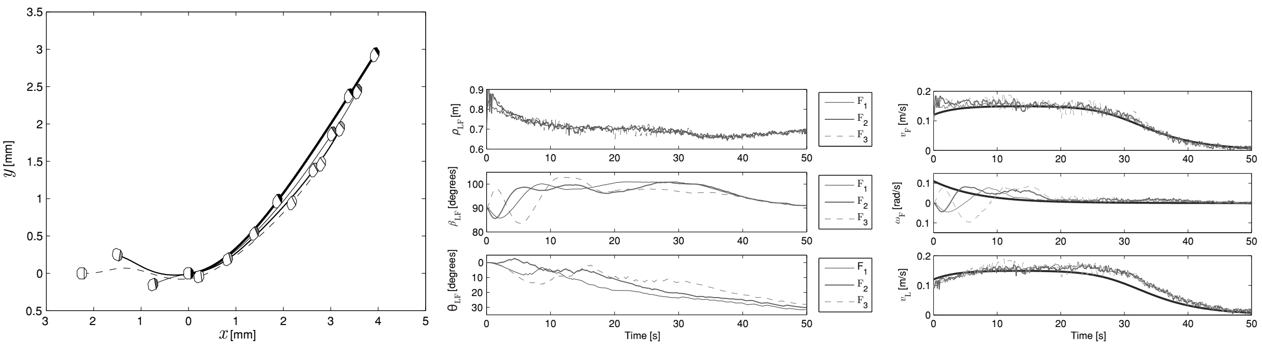
This work proposed a decentralized multi-leader-follower formation. The search strategy provides the formation variables involved in the Leader-Follower structure. A suitable sensor onboard the follower robot and a pattern mounted on the leader robot are enough to keep working the formation shaping, hence the formation variables ρ and β can be computed. One can, however, use another type of sensor, as long as it allows estimating the ρ_{LF} and β_{LF} variables, which determine the formation structure. This work proposes and numerically validates an extended decentralized leader-follower strategy for a set of four ground robots.

Considering the extension of the L-F strategy, first, a leader-followers approach is characterized by the presence of a natural leader and followers who refer to it. This type of multi-robot cooperation strategy can be used in cargo transport tasks, where prior knowledge of the robots' posture in the formation is essential, and this positioning must be ensured during all navigation. After all, any deformation could compromise the performance of the task, as it would cause the load to drop. Secondly, a multi-robot navigation using the leaders-followers structure can be used to map the environment, as a possible deformation would not compromise the execution of the task, or to seek



(a) (b) (c)

Figure 6. Simulation: leader-follower structure with diamond shape. (a) Path covered by the formation, (b) Evolution of formation variables, and (c) Control signals and estimated linear velocity v_L of the leader robot.



(a) (b) (c)

Figure 7. Simulation: leader-follower structure in linear formation. (a) Path taken by the formation, (b) Evolution of formation variables, and (c) Control signals and estimated linear velocity v_L of the leader robot.

and disarm land mines, as if one agent is lost, the others can perfectly handle and fulfill the mission.

Finally, the stability of the whole group can be verified through the asymptotic convergence of the formation variables to the desired values during the experiments, which is in accordance with the theoretical analysis.

ACKNOWLEDGMENT

The authors thank CNPq - Conselho Nacional de Desenvolvimento Científico e Tecnológico, an agency of the Brazilian Ministry of Science, Technology, Innovations and Communications, and FAPEMIG - Fundação de Amparo à Pesquisa do Estado de Minas Gerais, for the support given to this research. Mr. Fagundes also thanks CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, for the scholarship granted to him, which allowed him to dedicate all his time to the Master studies.

REFERENCES

Arnold, R.D., Yamaguchi, H., and Tanaka, T. (2018). Search and rescue with autonomous flying robots through behavior-based cooperative intelligence. *Journal of International Humanitarian Action*, 3(1), 1–18.

Brandão, A.S., Sarcinelli-Filho, M., and Carelli, R. (2013). An analytical approach to avoid obstacles in mobile robot navigation. *International Journal of Advanced Robotic Systems*, 10(6), 278.

Brandao, A.S., Sarcinelli-Filho, M., Carelli, R., and Bastos-Filho, T.F. (2009). Decentralized control of leader-follower formations of mobile robots with obstacle avoidance. In *2009 IEEE International Conference on Mechatronics*. IEEE.

Cardona, G.A. and Calderon, J.M. (2019). Robot swarm navigation and victim detection using rendezvous consensus in search and rescue operations. *Applied Sciences*, 9(8), 1702.

Chatziparaschis, D., Lagoudakis, M.G., and Partsinevelos, P. (2020). Aerial and ground robot collaboration for autonomous mapping in search and rescue missions. *Drones*, 4(4), 79.

Dai, S.L., He, S., Chen, X., and Jin, X. (2020). Adaptive leader–follower formation control of nonholonomic mobile robots with prescribed transient and steady-state performance. *IEEE Transactions on Industrial Informatics*, 16(6), 3662–3671.

Farivarnejad, H., Lafmejani, A.S., and Berman, S. (2021). Fully decentralized controller for multi-robot collective transport in space applications. In *2021 IEEE Aerospace Conference (50100)*, 1–9. IEEE.

Florez-Lozano, J., Caraffini, F., Parra, C., and Gongora, M. (2020). Cooperative and distributed decision-making in a multi-agent perception system for improvised land mines detection. *Information Fusion*, 64, 32–49.

Hawley, L. and Suleiman, W. (2019). Control framework for cooperative object transportation by two humanoid robots. *Robotics and Autonomous Systems*, 115, 1–16.

Ismail, Z.H. and Sariff, N. (2019). A survey and analysis of cooperative multi-agent robot systems: Challenges and directions. In *Applications of Mobile Robots*. IntechOpen.

Lee, G. and Chwa, D. (2017). Decentralized behavior-based formation control of multiple robots considering obstacle avoidance. *Intelligent Service Robotics*, 11(1), 127–138.

Lee, H. (2020). One-way observation-based cooperative robot mapping. In *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, 900–905. IEEE.

Li, Z., Yuan, Y., Ke, F., He, W., and Su, C.Y. (2020). Robust vision-based tube model predictive control of multiple mobile robots for leader–follower formation. *IEEE Transactions on Industrial Electronics*, 67(4), 3096–3106.

Liu, A., Zhang, W.A., Yu, L., Yan, H., and Zhang, R. (2020). Formation control of multiple mobile robots incorporating an extended state observer and distributed model predictive approach. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 50(11), 4587–4597.

Masehian, E., Jannati, M., and Hekmatfar, T. (2017). Cooperative mapping of unknown environments by multiple heterogeneous mobile robots with limited sensing. *Robotics and Autonomous Systems*, 87, 188–218.

Miao, Z., Liu, Y.H., Wang, Y., Yi, G., and Fierro, R. (2018). Distributed estimation and control for leader-following formations of nonholonomic mobile robots. *IEEE Transactions on Automation Science and Engineering*, 15(4), 1946–1954.

Queralta, J.P., Taipalmaa, J., Pullinen, B.C., Sarker, V.K., Gia, T.N., Tenhunen, H., Gabbouj, M., Raitoharju, J., and Westerlund, T. (2020). Collaborative multi-robot search and rescue: Planning, coordination, perception, and active vision. *IEEE Access*, 8, 191617–191643.

Rango, F.D., Palmieri, N., Yang, X.S., and Marano, S. (2017). Swarm robotics in wireless distributed protocol design for coordinating robots involved in cooperative tasks. *Soft Computing*, 22(13), 4251–4266.

Shirani, B., Najafi, M., and Izadi, I. (2019). Cooperative load transportation using multiple uavs. *Aerospace Science and Technology*, 84, 158–169.

Soni, A. and Hu, H. (2018). Formation control for a fleet of autonomous ground vehicles: A survey. *Robotics*, 7(4), 67.

Tanveer, F. and Kadri, M.B. (2018). A simulation framework for decentralized formation control of non-holonomic differential drive robots. In *2018 SICE International Symposium on Control Systems (SICE ISCS)*. IEEE.

Tuci, E., Alkilabi, M.H., and Akanyeti, O. (2018). Cooperative object transport in multi-robot systems: A review of the state-of-the-art. *Frontiers in Robotics and AI*, 5, 59.

Wong, W.K., Ye, S., Liu, H., and Wang, Y. (2020). Effective mobile target searching using robots. *Mobile Networks and Applications*.

Yang, Z., Zhu, S., Chen, C., Feng, G., and Guan, X. (2020). Leader-follower formation control of nonholonomic mobile robots with bearing-only measurements. *Journal of the Franklin Institute*, 357(3), 1628–1643.

Zhang, Y., Chen, L., XuanYuan, Z., and Tian, W. (2019). Three-dimensional cooperative mapping for connected and automated vehicles. *IEEE Transactions on Industrial Electronics*, 67(8), 6649–6658.