A Multi-Layer Control Scheme for Multi-Robot Formations with Obstacle Avoidance

Vinicius T. L. Rampinelli, Alexandre S. Brandão, Felipe N. Martins, Mário Sarcinelli-Filho and Ricardo Carelli

Abstract— **This paper presents a multi-layer scheme to control a formation of n mobile robots, including a strategy for obstacle avoidance. The controller adopted is able to guide the robots to compose the desired formation and to track a desired trajectory, avoiding obstacles during the navigation. Two planning layers are responsible for organizing the navigation of the individual robots towards the desired formation, minimizing energy consumption, and for changing the robots reference signals in order to avoid collisions. Stability analysis performed for the closed-loop system shows that the formation errors are ultimately bounded. Finally, simulation results for a group of four unicycle-like mobile robots are presented, which show that the proposed scheme is capable of avoiding collisions and of redefining robots' pose in order to improve system performance.**

I. Introduction

The interest in multi-robot control systems has increased, after the perception that a group of mobile robots accomplishes certain tasks with more efficiency than a single specialized robot [1]. Surveillance in a large area [2], search and rescue [3], and large-objects transportation [4] are some examples of tasks that are better tailored for a group of robots. Other tasks are simply not accomplishable by a single mobile robot, demanding a group of coordinated robots to perform it, like the problem of sensors and actuators positioning [5], and the entrapment/escorting mission [6].

Although centralized control approaches possess intrinsic problems, like the difficulty to sustain the communication between the robots and the limited scalability, they have technical advantages when applied to control formations with defined geometric forms. Therefore, there still exists significant interest on their use. As an example, in [6] a centralized multi-robot system is proposed for an entrapment/escorting mission, where the escorted agent is kept in the centroid of a polygon of n sides, surrounded by n robots positioned in the vertices of the polygon. Another task for which it is important to keep a formation during navigation is large-objects transportation, because the load has a not changeable geometric form.

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Another recent work dealing with centralized formation control is [7], where a control approach based on a virtual structure, called Cluster Space Control, is presented. There, the positioning control (or tracking control) is carried out considering the centroid of a geometric structure (a triangle) corresponding to a three-robot formation. Following this approach, this work deals with the scalability problem inherent to centralized control systems, considering the application of the multi-layer control scheme proposed in [8] to a multi-robot system. More specifically, a technique is developed that explores intrinsic generalization capabilities not discussed in [7], allowing to apply the control approach based on the centroid of the formation to a formation of $n > 3$ robots. In addition, the possibility that the controlled formation avoid obstacles is discussed, supposing that the structure is allowed to momentarily modify itself, behaving as an elastic structure.

To discuss such topics, the paper is hereinafter organized as follows: Section II describes the kinematic model of a unicycle-like mobile robot and its generalization for a multi-robot system, while Section III briefly describes the multi-layer control scheme. By its turn, Section IV presents the control law and the forward and inverse kinematics transformations for the robot formation, while Section V deals with possible ways to organize the sequence of robots and their respective position in the formation being mounted, in order to avoid intra-formation collision. In the sequel, Section VI describes a methodology applied to the formation to avoid obstacles in the trajectory of any robot in the formation, based on the concept of mechanical impedance present in the interaction formation-environment (to allow deforming the virtual structure associated to the formation so that it can left the obstacles behind). Finally, Section VII highlights the main conclusions of the work.

II. Kinematic Model of the Mobile Robot

The *i*-th robot kinematic model is given by

$$\begin{bmatrix}\dot{x}_i\\ \dot{y}_i\\ \dot{\psi}_i\end{bmatrix} = \begin{bmatrix}\cos\psi_i & -a_i\sin\psi_i\\ \sin\psi_i & a_i\cos\psi_i\\ 0 & 1\end{bmatrix}\begin{bmatrix}u_i\\ \omega_i\end{bmatrix}, \qquad (1)$$

where u_i and ω_i are, respectively, the linear and angular velocities, $\mathbf{h}_i = [x_i\ y_i]^T$ is the vector containing coordinates of the point of interest, ψ_i is the orientation and a_i is the perpendicular distance from the point of interest to the point in the middle of the virtual axis linking the traction wheels of the *i*-th robot.

Considering only the coordinates of the point of interest $\mathbf{h_i}$, the inverse kinematics is given by $\mathbf{v}_i = \mathbf{K}_{ri}^{-1}\dot{\mathbf{h}}_i$, where $\mathbf{v}_i = [u_i\ \omega_i]^T$ and

$$\mathbf{K}_{ri}^{-1} = \begin{bmatrix} \cos\psi_i & \sin\psi_i \\ -\frac{1}{a_i}sin\psi_i & \frac{1}{a_i}\cos\psi_i \end{bmatrix}, \quad \text{for} \quad a_i > 0.$$

Considering a three robots formation, one has

$$\mathbf{K}_r = \begin{bmatrix} \mathbf{K}_{r1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{r2} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{K}_{r3} \end{bmatrix},$$

where the numeric subscript stands for the i-th robot. It should be noticed that robots with different kinematic models can be used (heterogeneous formation), just by updating $\mathbf{K_{ri}}$ in the $\mathbf{K_r}$ matrix.

III. Multi-Layer Control Scheme

This section briefly describes the multi-layer control scheme used to control the multi-robot formation (Fig. 1). Such control scheme is discussed in details in [8]. Each layer works as an independent module, dealing with a specific part of the problem of formation control, and such control scheme includes a basic structure defined by the control layer, the robots layer and the environment layer. Above such layers are the planning layers, namely the off-line planning layer and the on-line planning layer. The first one is responsible for setting up the initial conditions, thus generating the trajectory to be tracked and for establishing the desired formation structure, while the last one is responsible for changing the references in order to make the formation react to the environment, e. g., to modify the trajectory to avoid obstacles. The Control Layer is responsible for generating the control signals to be sent to the robots of the formation in order to reach the desired values established by the planning layers. The robot layer represents the unicycle-like mobile robot (or the formation), and finally, the environment layer represents all objects surrounding the robots, including the robots themselves.

IV. The Formation-Control Layer

This section implements the Control Layer for a centralized formation control considering three or more unicycle-like mobile robots. The state variables used to represent the whole formation are shown in Fig. 2, as proposed in [7]. The formation pose is defined by $\mathbf{P}_F = [x_F\ y_F\ \psi_F]$ and the structure shape is defined by $\mathbf{S}_F = [p_F\ q_F\ \beta_F]$, which represent the distance between R_1 and R_2, the distance between R_1 and R_3, and the angle $R_2\widehat{R_1}R_3$, respectively. It is worth mentioning that (x_F, y_F) represents the position of the centroid of the formation, as well as that the whole formation is controlled by taking the global frame xy as the reference.

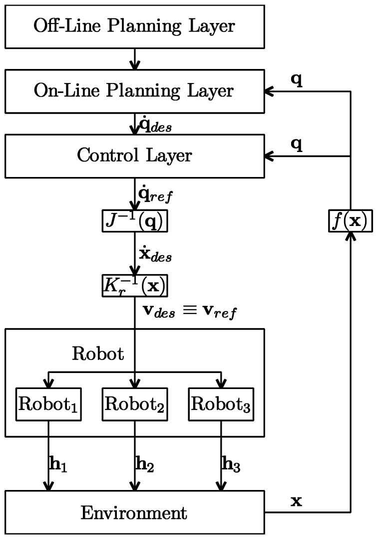

Fig. 1. The proposed Multi-layer Scheme.

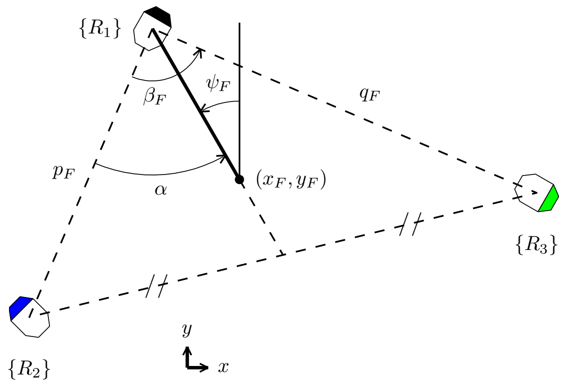

Fig. 2. Formation variables.

A. Forward and Inverse Kinematics Transformations

Before introducing the formation control law, it is necessary to express the relationship between the formation pose-shape and the robot positions $\mathbf{h}_i$, which is given by the forward and inverse kinematics transformation, i.e., $\mathbf{q} = f(\mathbf{x})$ and $\mathbf{x} = f^{-1}(\mathbf{q})$, where $\mathbf{q} = [\mathbf{P}_F\ \mathbf{S}_F]^T$ and $\mathbf{x} = [\mathbf{h_1}\ \mathbf{h_2}\ \mathbf{h_3}]^T$. It should be emphasized that the robot orientation is not considered in this proposal.

The forward kinematic transformation $f(\cdot)$, as shown in Fig. 2, is given by

$$\mathbf{P}_F = \begin{bmatrix} \dfrac{x_1 + x_2 + x_3}{3} \\ \dfrac{y_1 + y_2 + y_3}{3} \\ \arctan \dfrac{\frac{2}{3}x_1 - \frac{1}{3}(x_2 + x_3)}{\frac{2}{3}y_1 - \frac{1}{3}(y_2 + y_3)} \end{bmatrix}^T, \quad (2)$$

$$\mathbf{S}_F = \begin{bmatrix} \sqrt{(x_1-x_2)^2+(y_1-y_2)^2} \\ \sqrt{(x_1-x_3)^2+(y_1-y_3)^2} \\ \arccos\dfrac{p_F^2+q_F^2-r_F^2}{2p_Fq_F} \end{bmatrix}^T, \quad (3)$$

where $r_F = \sqrt{(x_2-x_3)^2+(y_2-y_3)^2}$.

In turn, for the inverse kinematic transformation $f^{-1}(\cdot)$, two representations are possible, depending on the disposition of the robots in the triangle formation (clockwise or counter-clockwise). Such disposition can be referenced as $R_1R_2R_3$ or $R_1R_3R_2$ sequence, hereinafter referred to as $\mathbf{ABC}$ and $\mathbf{ACB}$, respectively. Considering the first possibility, $\mathbf{x} = f^{-1}_{\mathbf{ABC}}(\mathbf{q})$ is given by

$$\mathbf{x} = \begin{bmatrix} x_F + \frac{2}{3}h_F\sin\psi_F \\ y_F + \frac{2}{3}h_F\cos\psi_F \\ x_F + \frac{2}{3}h_F\sin\psi_F - p_F\sin(\alpha+\psi_F) \\ y_F + \frac{2}{3}h_F\cos\psi_F - p_F\cos(\alpha+\psi_F) \\ x_F + \frac{2}{3}h_F\sin\psi_F + q_F\sin(\beta_F-\alpha-\psi_F) \\ y_F + \frac{2}{3}h_F\cos\psi_F - q_F\cos(\beta_F-\alpha-\psi_F) \end{bmatrix}, \quad (4)$$

where $h_F = \sqrt{\frac{1}{2}\left(p_F^2+q_F^2-\frac{1}{2}r_F^2\right)}$ is the distance from $\{R_1\}$ to the point in the middle of the segment $\{R_2\}\{R_3\}$, passing through (x_F, y_F), and $\alpha = \arccos\dfrac{p_F^2+h_F^2-\frac{1}{4}r_F^2}{2p_Fh_F}$. On the other hand, $\mathbf{x} = f^{-1}_{\mathbf{ACB}}(\mathbf{q})$ is given by

$$\mathbf{x} = \begin{bmatrix} x_F + \frac{2}{3}h_F\sin\psi_F \\ y_F + \frac{2}{3}h_F\cos\psi_F \\ x_F + \frac{2}{3}h_F\sin\psi_F + p_F\sin(\alpha-\psi_F) \\ y_F + \frac{2}{3}h_F\cos\psi_F - p_F\cos(\alpha-\psi_F) \\ x_F + \frac{2}{3}h_F\sin\psi_F - q_F\sin(\beta_F-\alpha+\psi_F) \\ y_F + \frac{2}{3}h_F\cos\psi_F - q_F\cos(\beta_F-\alpha+\psi_F) \end{bmatrix}. \quad (5)$$

Taking the time derivative of the forward and the inverse kinematics transformations we can obtain the relationship between the $\mathbf{x}$ and $\mathbf{q}$ velocities, represented by the Jacobian matrix, which is given by $\dot{\mathbf{q}} = J(\mathbf{x})\dot{\mathbf{x}}$ in the forward way, and by $\dot{\mathbf{x}} = J^{-1}(\mathbf{q})\dot{\mathbf{q}}$ in the inverse way, where

$$J(\mathbf{x}) = \frac{\partial \mathbf{q}_{n\times 1}}{\partial \mathbf{x}_{m\times 1}} \quad \text{and} \quad J^{-1}(\mathbf{q}) = \frac{\partial \mathbf{x}_{m\times 1}}{\partial \mathbf{q}_{n\times 1}},$$

for $m, n = 1,\ 2,\ \cdots,\ 6$. Note that there will be an inverse Jacobian Matrix for the $\mathbf{ABC}$ sequence, and another for the $\mathbf{ACB}$ sequence.

B. The Formation Control

The block diagram shown in Fig. 3 presents the adopted control scheme for the triangle formation illustrated in Fig. 2. The Control Layer receives from the upper layer the desired formation pose and shape $\mathbf{q_{des}} = [\mathbf{P}_{Fd}\ \mathbf{S}_{Fd}]^T$, and its desired variations $\dot{\mathbf{q}}_{\mathbf{des}} = [\dot{\mathbf{P}}_{Fd}\ \dot{\mathbf{S}}_{Fd}]^T$. Defining the formation error as $\tilde{\mathbf{q}} = \mathbf{q_{des}} - \mathbf{q}$, the proposed formation control law is

$$\dot{\mathbf{q}}_{\mathbf{ref}} = \dot{\mathbf{q}}_{\mathbf{des}} + \boldsymbol{\kappa}\tilde{\mathbf{q}}, \quad (6)$$

where $\boldsymbol{\kappa}$ is a positive definite diagonal gain matrix. Let us consider a difference $\boldsymbol{\delta}_{\mathbf{v}}$ between the desired and the real formation variations, such as $\dot{\mathbf{q}} = \dot{\mathbf{q}}_{\mathbf{ref}} + \boldsymbol{\delta}_{\mathbf{v}}$. Then, the closed loop system equation can be written as

$$\dot{\tilde{\mathbf{q}}} + \boldsymbol{\kappa}\tilde{\mathbf{q}} = -\boldsymbol{\delta}_{\mathbf{v}}. \quad (7)$$

Considering the Lyapunov candidate function $V = \frac{1}{2}\tilde{\mathbf{q}}^{\mathbf{T}}\tilde{\mathbf{q}} > 0$, its first time derivative is $\dot{V} = \tilde{\mathbf{q}}^{\mathbf{T}}\dot{\tilde{\mathbf{q}}} = -\tilde{\mathbf{q}}^{\mathbf{T}}\boldsymbol{\kappa}\tilde{\mathbf{q}} - \tilde{\mathbf{q}}^{\mathbf{T}}\boldsymbol{\delta}_{\mathbf{v}}$. Assuming perfect velocity tracking, which means $\boldsymbol{\delta}_{\mathbf{v}} = \mathbf{0}$, $\dot{V} < 0$, resulting that the equilibrium is globally asymptotically stable, i.e., $\tilde{\mathbf{q}} \to \mathbf{0}$ when $t \to \infty$. On the other hand, if $\boldsymbol{\delta}_{\mathbf{v}}$ is not null, the equilibrium will be asymptotically stable if $\tilde{\mathbf{q}}^{\mathbf{T}}\boldsymbol{\kappa}\tilde{\mathbf{q}} > |\tilde{\mathbf{q}}^{\mathbf{T}}\boldsymbol{\delta}_{\mathbf{v}}|$. A sufficient condition for that is $\|\tilde{\mathbf{q}}\| > \|\boldsymbol{\delta}_{\mathbf{v}}\|/\lambda_{\min}(\boldsymbol{\kappa})$, where $\lambda_{\min}(\boldsymbol{\kappa})$ represents the minimum eigenvalue of $\boldsymbol{\kappa}$. That means that the formation error $\tilde{\mathbf{q}}$ is ultimately bounded, and its bound depends on the velocity tracking error of the formation $\boldsymbol{\delta}_{\mathbf{v}}$ (in [8] it is shown that $\boldsymbol{\delta}_{\mathbf{v}}$ can be reduced by introducing a Dynamic Compensation Layer).

C. Control Approach for an n-Robot Formation

This sub-section proposes a way to generalize the control system associated to a formation of three robots (a triangular one) to a formation of n robots (a polygonal one). Such proposition considers the decomposition of a polygon of n vertices (the n-robots formation) into $n-2$ triangles. Then, the $n-2$ triangular formations thus generated are controlled using the controller proposed in Section IV-B.

Our approach starts by labeling the robots R_i, $i = 1, \cdots, n$, and determining the triangle that will lead the formation ($R_2\widehat{R_1}R_3$ or $R_3\widehat{R_1}R_2$, paying attention to the sequence $\mathbf{ABC}$ or $\mathbf{ACB}$). After that, new triangles are formed with the remaining robots, in such a way that the next triangle is formed by the last two robots of the former triangle and the next labeled robot (in other words, $R_j\widehat{R_{j+1}}R_{j+2}$ or $R_{j+2}\widehat{R_{j+1}}R_j$, where $j = 1, \cdots, n-2$ represents the current triangular formation). Considering the vector defining the desired formation shape, from Section IV we have to assign a set of three of such variables to each triangular formation ($\mathbf{S}_{Fj} = [p_{Fj}\ q_{Fj}\ \beta_{Fj}]$). However, one can straightforwardly see that the j-th triangular cell, $j = 2, \cdots, (n-2)$, adds just two new shape variables to the vector of desired shape variables of the n-robots formation (considering that $\mathbf{S}_{Fj} = [r_{Fj-1}\ q_{Fj}\ \beta_{Fj}]$), while the leader triangle adds three of such variables. Hence, the number of shape variables associated to the entire formation is $2(n-2)+1$.

One point that deserves mentioning here is the control signals thus generated: there will always be a redundancy in the formations with more than three robots. For example, the robots R_2 and R_3, in a formation of four robots, will receive control signals associated to the errors of the two triangular formations ($R_2\widehat{R_1}R_3$ and $R_3\widehat{R_2}R_4$, for example).

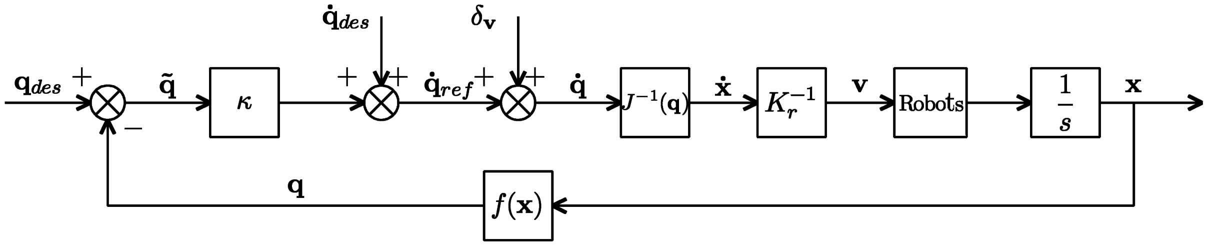

Fig. 3. Block diagram of the formation controller adopted.

In this work, however, the robot R_{j+2} will receive control signals only from the controllers associated to the j-th ($j \geq 2$) triangular formations, while the robots R_1, R_2 and R_3 will receive the signals generated by the controller associated to the leader triangle ($j = 1$). As a future work, the fusion of control signals proposed in [9] could be adopted to generate the final control signals to be sent to each robot in a triangular cell of the formation.

V. Rearranging the Assigned Final Poses for n-Robots Formations

The final (desired) pose of each robot in the formation should be assigned by the Off-Line Planning layer, considering the initial (given) poses and the task to be accomplished itself. This assignment is quite important, because of the transient positions of each robot when building the formation, which could cause intra-formation collision, mainly for large platoons.

The first step is to consider the sequence previously defined by the user. Then, depending on the case, the Off-Line Planning layer itself can reorganize this sequence, aiming at improving the performance during the maneuvers to build the formation. The choice of the approach to be adopted during an experiment (or simulation) will depend on the characteristics of the robots in the formation, e.g., if the whole platoon is composed of homogeneous robots (in terms of sensors, actuators, etc.), or if there is a diversity that allows splitting the task to be accomplished in such a way that the performance is improved (e.g., a robot having a manipulator should be in the front part of the formation when the task is to grasp any object).

To deal with this problem, this section proposes two approaches to reorganize the sequence of the robots when building the desired formation. By using one of these approaches or even considering the configuration proposed by the user, the resulting desired disposition of the robots in the formation should be reached by the robots initially randomly positioned in the workspace. Such positioning will be guided by the controller available in the layer Control, discussed in Section IV. For the first case, the traveled path can be executed as shown in Fig. 4, for which the energy spent during the positioning maneuvers is too much, and the navigation is not guaranteed to be safe, because of the possibility of intra-formation collisions (the path followed by different robots cross themselves). Therefore, the user should pay some attention to the task of defining the final position of the robots in the formation.

To rearrange the sequence of the robots in the final desired formation, the following two strategies are proposed here.

A. *With final reorganization*

In a task of loading transportation, as an example, the robots in the formation normally have identical sensing systems and actuators. Thus, the desired position of each robot in the formation can be changed, e.g. to optimize the transient arrangement of the platoon and the energy spent during such movement.

Figures 4 and 5 illustrate the initial and final positions of the robots in the formation, considering the assignments defined by the user and the rearranged ones, respectively, as well as the path traveled by each robot during the positioning task. The rearrangement of the n robots, in this case, is performed through an algorithm that identifies the most distant robot (considering the inertial frame $< O >$) and label it as R_1, with the following labels assigned to the robots so that the next robot is the one closest to the last labeled one. It should be noticed, however, that three consecutive robots cannot be in a line segment, due to the restriction that the formation should be a triangular one.

B. *With initial organization based on the final one*

Still aiming at minimizing the risk of intra-formation collision during the transient positioning of each robot to build the desired formation, another idea to rearrange the desired disposition of the individual robots in the formation is to associate to the robot R_1 of the desired formation (final position) the one in the initial configuration that is closest to it. After identifying the robot R_1 of the desired formation in the initial configuration, the other robots are labeled using a criterion of proximity (using the euclidian distance), and respecting the established sequence for the triangular formation (ABC or ACB) during the rearrangement of the desired formation. Figures 4 and 6 illustrate such strategy and show the paths each robot follows during the navigation to the desired position (the configuration initially assigned and the rearranged one, respectively).

After analyzing such figures, one can conclude that the second approach demands less energy than the first one to get the formation built. Compared to the case in which no rearrangement is done, such energy saving can be much more meaningful.

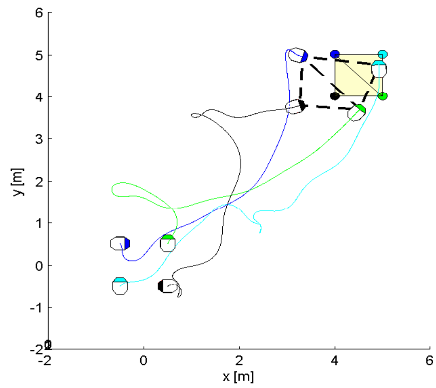

Fig. 4. Path traveled without any previous reorganization.

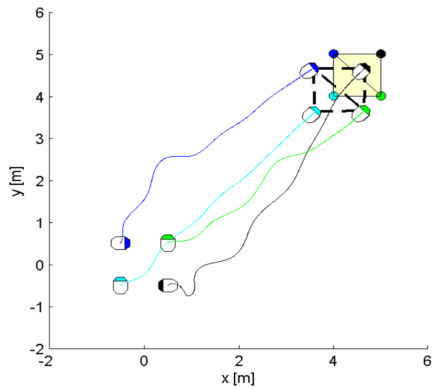

Fig. 5. Path traveled after final reorganization.

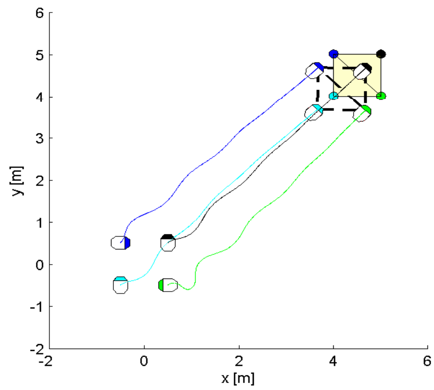

Fig. 6. Pose redefinition for the n robots in a formation.

VI. Collision Avoidance Based on Fictitious Forces

The strategy of obstacle avoidance here proposed was developed aiming at preserving the structure of the multi-layer control scheme proposed in [8], and is based on [10], which applies the concept of mechanical impedance to allow a manipulator to avoid obstacles, and in [11], which applies the same concept to modify the target position when an obstacle suddenly appears in the path a mobile robot is following when navigating towards such target. The main advantage of such strategy is that each robot in the formation may correct its trajectory independently of the other robots. As a consequence, the formation behaves as a flexible virtual structure in the presence of obstacles. It is important to mention that the implementation discussed in the sequel supposes that the application (e.g., large areas inspection with a platoon of vehicles) allows making the formation flexible.

As in [11], it is assumed here that each robot in the formation has a sensing system onboard it that allows it to measure the distance to obstacles in a certain range, in order to calculate the magnitude of the forces that define the interaction robot-obstacle.

The main idea is to associate the robot movement to virtual forces characterizing its interaction with the surrounding environment. As any obstacle should be avoided, the interaction robot-environment is characterized by the fictitious repulsion force given by

$$F_f = a - b(d - d_{min})^n, \tag{8}$$

which depends on d, the distance from the robot to the closest obstacle, d_{min}, the minimum acceptable robot-obstacle distance to avoid a crash, and n, a positive integer. Notice that the greater the distance d is, the lower the force F_f is, and vice-versa. The constants a and b in (8) correspond to system calibration, and are given by

$$a - b(d_{max} - d_{min})^n = 0, \tag{9}$$

where d_{max} is the maximum robot-obstacle distance to cause a nonzero fictitious force F_f ($F_f = 0$ if $d \geq d_{max}$).

In order to make possible for a multi-robot system to move in environments containing multiple obstacles, each robot considers two fictitious forces in the calculation of the necessary correction in its trajectory, which are associated to the least distances robot-obstacle on the right and left sides of it, as illustrated in Fig. 7. The variables d_R and d_L showed in the figure represent the least distances measured with respect to the obstacle on the right and on the left sides of the robot, and are associated to the fictitious forces F_R and F_L, respectively. To normalize the magnitude of the forces with $d_{\min} = 0.2m$ and $d_{\max} = 1.2m$, the constant values here adopted are $a = 8$ and $n = 4$.

The magnitude of the trajectory corrections associated to the fictitious forces on the right and the left sides of the robot are given, respectively, by $x_L^c = Z^{-1}F_R$ and $x_R^c = Z^{-1}F_L$, where Z represents the mechanical impedance characterizing the interaction robot-environment, which is considered as $Z = Is^2 + Bs + K$ with I, B and K being positive constants representing, respectively, the effect of the inertia, the damping and the elastic constant.

Considering the limitations associated to the movement of the unicycle-like mobile robots (nonholonomic constraints), it was decided to apply the trajectory corrections associated to the fictitious forces F_R and F_L perpendicularly to the desired trajectory. Thus, when any of the robots in the formation detects an obstacle at a distance lower than d_{max}, its desired trajectory will be changed according to a perpendicular component of magnitude and orientation given by the resultant of the corrections x_L^c and x_R^c caused by the fictitious forces.

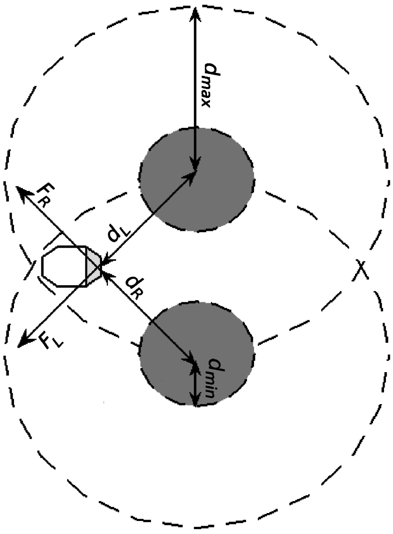

Fig. 7. The fictitious forces acting over an individual robot of the formation.

Such technique was adopted in a simulation in which a formation composed of four robots should navigate following an horizontal line, from left to right. The values $I = 10N.s^2/rad$, $B = 40N.s/rad$ and $K = 5N/rad$ define the set of impedance parameters adopted in the simulation.

Figure 8 shows three particular instants of such simulation. In the left one it is shown the desired formation; in the middle the formation has been distorted in order to avoid the two obstacles in its trajectory, and in the right the desired formation is recovered after the robots left the obstacles behind. An important observation, still considering Figure 8, is the change in the trajectory of the fourth robot of the formation. It is caused by the proximity of the third one, which is considered as an obstacle by the fourth robot, which changes its trajectory to avoid a possible collision.

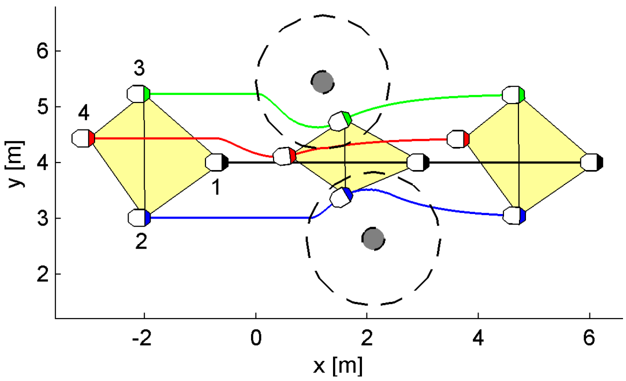

Fig. 8. The formation being distorted to avoid obstacles.

VII. Conclusion

This paper shows a generalization of a multi-layer control scheme previously proposed for a formation of three robots to a formation involving n robots. It also proposes a technique to allow the formation to distort its shape in order to avoid obstacles in its trajectory. Simulation results are shown, allowing to conclude that the proposed control scheme is effective, not only in terms of guaranteeing that the individual robots reach the desired formation but also in terms of avoiding obstacles while tracking a trajectory specified by the user.

VIII. Acknowledgement

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