Cooperative On-line Object Detection using Multi-Robot Formation

José Miguel Vilca Lounis Adouane Ahmed Benzerrouk Youcef Mezouar
Institut Pascal
Blaise Pascal University / IFMA – UMR CNRS 6602
Clermont-Ferrand, France
Jose_Miguel.VILCA_VENTURA@univ-bpclermont.fr

***Abstract*—This paper presents an online method for a cooperative mobile robots navigation using local robot's reference frame. The group of robots must navigate while keeping a geometric shape. To achieve with distributed and reactive way the Multi-Robot Formation (MRF), a cooperative object detection using range data is presented. This information will permits to detect the position of the leader robot in the formation. Indeed, in this work it is proposed that the leader can be surrounded by an ellipse and its parameters are obtained online using the sequential range data from all the mobile robots. An appropriate method is used to identify the enclosed ellipse. To perform the MRF, it is proposed to use a combination between behavior-based, dynamical virtual structure (already presented in [1] which use global reference frame) and leader-follower approach. Simulations will permit to show the efficiency of the proposed reactive and distributed cooperative navigation.**

***Keywords-component*—Multi-robot system, Formation control, Mobile robot navigation; Obstacle detection; Telemetry; Parameter identification.**

I. Introduction

In recent years, research in control and coordination of multiple mobile robots has increased significantly. Tasks that may be performed by a single complex robot can be performed more efficiently and cheaply by a group of elementary cooperating robots. Some examples of multi-robot applications can be seen in exploration [2] [3], management and platooning of autonomous vehicles [4] [5], mapping of unknown locations [6] [7], and transport or reposition of heavy objects [8] [9], etc. However, the coordination of multi-robot navigation is among the most challenging tasks.

A particular problem of multi-robot coordination is formation control, i.e., when a group of mobile robots has to navigate and keep a desired formation. In the literature, there are different approaches to deal with this problem such as: behavior-based [10], leader-follower [11] and virtual structure approach [12]. In this work we address the formation control problem using the combination between the three approaches: behavior based, dynamical virtual structure (already presented in [1]) and the leader-follower approach. Keeping a desired shape by the robots can then be achieved by considering the formation as a single virtual rigid body. The dynamic of this latter is given by one specific position of the rigid body. In the proposed work, this position corresponds to the leader of the formation. The control law of each follower robot is derived thus according to dynamic of the leader and the desired formation shape [13] [14].

In [15], virtual structures have been achieved by having all members of the formation tracking assigned nodes which moves into desired configuration. In the literature, some of the topics of cooperative detection is localization, mapping and tracking [16] [17] and [18]. In [17], the author presents a multi-robot/sensor cooperative object detection and a tracking method based on a decentralized Bayesian approach which uses particle filters. In the proposed paper, we use the range data from the group of robots to on-line cooperative object detection and localization. According to this range data, the parameters of the ellipse that enclose this range data will be obtained. The ellipse center will correspond to the position of the leader to follow.

Different approaches have been proposed in the literature to enclose the data with an ellipse [19] [20]. In [19], the author proposed a technique to obtain the smallest enclosing ellipse by a set of data using primitive operation with linear increasing time with regards to data dimension. In [20], the author presents a review of the methods to fit a set of data with an ellipse. The proposed method is based on a simple and efficient heuristic approach based on Euclidean distance estimation.

This paper presents the main concepts of current work, it is organized as follows: in the next section, the strategy of navigation in formation, its properties and representations are described. In section III, the details of the control architecture are introduced and the control law of the controllers is given. Section IV presents the methods for enclosing the range data with an ellipse. Simulation results are given in section V. Finally, conclusion and some future works are given in section VI.

II. NAVIGATION IN FORMATION

We consider a group of N robots with the objective of reaching and maintaining its positions and orientations in a desired formation while using only local perceptions.

A. *The cooperative control strategy*

The proposed strategy consists to control each robot$_i$ to track a secondary dynamical target (node) of a virtual geometrical structure (cf. Fig. 1). Each secondary target is defined according to the position and orientation of a main target (which corresponds to the leader robot in the proposed work).

Reaching or tracking a moving target has been widely explored in the literature [21], [22]. In [23], a specific set-point is designed for a mobile robot to reach a dynamical target. However, this work assumes that both the robot and the target are evolving with constant linear velocities (it is assumed that the robot goes faster than its target). Therefore, it is only proved that the robot meets the target but is not able to track it. The proposed virtual dynamical structure that must be followed by the group of robots is defined as follow:

- Define one point which gives the dynamics (v_{MT} and w_{MT} linear and angular velocities) of the applied structure. This point is called the main dynamical target (cf. Fig. 1) and here corresponds to the dynamic of the leader robot.
- Define the virtual structure to follow by defining as much nodes as necessary to obtain the desired geometry. Each node i is called a secondary target T_i and is defined according to a specific distance D_i and angle Φ_i with respect to the main target.
- The position of each secondary target w.r.t the Local Reference Frame (LRF) of the assigned robot$_i$ is given by (cf. Fig. 1)

$$\begin{cases} x_{S_i} = x_{MT_i} + D_i \cos(\theta_{MT_i} + \Phi_i) \\ y_{S_i} = y_{MT_i} + D_i \sin(\theta_{MT_i} + \Phi_i) \end{cases} \tag{1}$$

where $(x_{MT_i}, y_{MT_i}, \theta_{MT_i})$ are the position and orientation of the main target w.r.t. the LRF of the assigned robot$_i$ (cf. Fig. 1).

Note that the secondary targets are defined with respect to the main target and this later is localized according to the LRF of the assigned robot. The objective of this approach is to eliminate the dependency between each robot to a global reference frame [1]. This will permit to each robot to use only its LRF to reach its target. An example to get a triangular formation is given in Fig. 1.

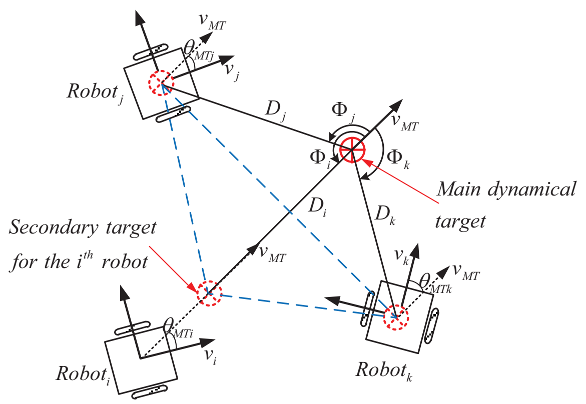

Fig. 1. Keeping a triangular formation by defining a virtual geometrical structure.

III. CONTROL ARCHITECTURE

The proposed control structure (cf. Fig. 2) aims to manage the interactions between different elementary controllers while guaranteeing the stability of the overall control as proposed in [24]. Its objective is also to insure safe, smooth and fast robot navigation. The specific blocks composing the global controller are detailed below.

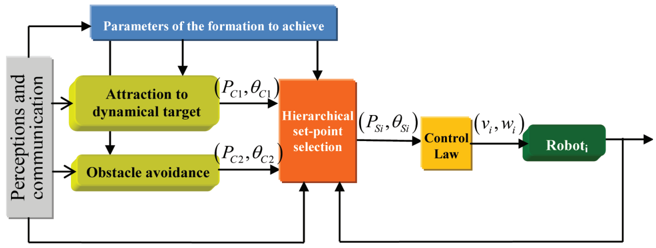

Fig. 2. Control architecture for mobile robot navigation.

The proposed control architecture uses a hierarchical action selection mechanism to manage the switches between the controllers, according to environment perception. In this paper, only the *Attraction to dynamical target* controller is considered and developed. In future works, the proposed multi-robot navigation will be applied in cluttered environment, specifically while using the obstacle avoidance controller proposed in [25].

Before describing each elementary controller, let us briefly recall the kinematic model of an unicycle robot (cf. Fig. 3)

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\theta}_i \end{bmatrix} = \begin{bmatrix} cos(\theta_i) & 0 \\ sin(\theta_i) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ \omega_i \end{bmatrix} \tag{2}$$

where x_i, y_i, θ_i are configuration state of the unicycle with respect to the global reference frame $X - Y$, v_i and ω_i are respectively the linear and angular velocity of the robot at the point O_m (cf. Fig. 3).

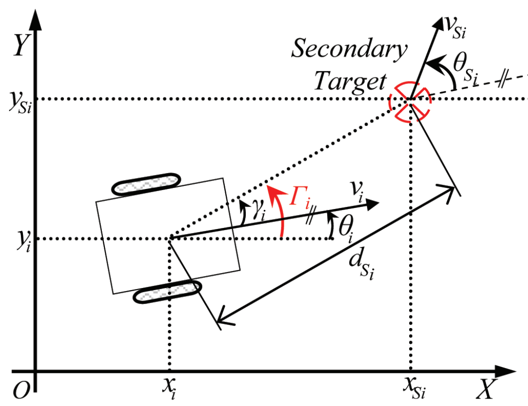

Fig. 3. Robot configuration in a global reference frame.

The strategy is to use the global reference frame to obtain the controller parameters w.r.t the local reference frame (setting $x_i = 0$, $y_i = 0$ $\theta_i = 0$), see Fig. 4.

A. Attraction to dynamical target controller

This controller guides the robot$_i$ toward its secondary dynamical target $T_i(x_{S_i}, y_{S_i})$ (cf. sub-section II-A). The kinematic model of this secondary target according to the global reference frame $X - Y$ is given by:

$$\begin{cases} \dot{x}_{S_i} = v_{S_i} \cos(\theta_{S_i} + \theta_i) \\ \dot{y}_{S_i} = v_{S_i} \sin(\theta_{S_i} + \theta_i) \end{cases} \tag{3}$$

The linear and angular velocities of the secondary target (v_{S_i} and w_{S_i}) are computed from (1). Moreover, we consider that each robot knows the velocities of the main target at each sample time. And the secondary target T_i satisfy the constraints $v_{S_i} \leq v_i$. This controller is based on the position control of the robot to the target, represented by d_{S_i} and Γ_i in Fig. 3, more details are given in [1]. The position errors are:

$$\begin{cases} e_{x_i} = x_{S_i} - x_i = d_{S_i} \cos(\Gamma_i) \\ e_{y_i} = y_{S_i} - y_i = d_{S_i} \sin(\Gamma_i) \end{cases} \tag{4}$$

where d_{S_i} is the distance of the robot to the target T_i and Γ_i is the orientation of the line passing through the robot and the target w.r.t global reference frame, it is equal to:

$$\Gamma_i = \gamma_i + \theta_i \tag{5}$$

with γ_i is the orientation of the line passing through the robot and the target w.r.t the orientation of the robot. The distance d_{S_i} and the orientation Γ_i can be defined as

$$d_{S_i} = \sqrt{e_{x_i}^2 + e_{y_i}^2} \tag{6}$$

$$\Gamma_i = \arctan\left(\frac{e_{y_i}}{e_{x_i}}\right) \tag{7}$$

The derivate of the distance d_{S_i} can be expressed as

$$\dot{d}_{S_i} = \frac{e_{x_i}\dot{e}_{x_i} + e_{y_i}\dot{e}_{y_i}}{d_{S_i}} \tag{8}$$

By using (2) and (3), $\dot{e}_{x_i}$ and $\dot{e}_{y_i}$ will be given by

$$\begin{cases} \dot{e}_{x_i} = \dot{x}_{S_i} - \dot{x}_i = v_{S_i} \cos(\theta_{S_i} + \theta_i) - v_i \cos(\theta_i) \\ \dot{e}_{y_i} = \dot{y}_{S_i} - \dot{y}_i = v_{S_i} \sin(\theta_{S_i} + \theta_i) - v_i \sin(\theta_i) \end{cases} \tag{9}$$

While using (4), (5) and (9) in (8), $\dot{d}_{S_i}$ is obtained as:

$$\dot{d}_{S_i} = v_{S_i} cos(\theta_{S_i} - \gamma_i) - v_i cos(\gamma_i) \tag{10}$$

Equation (10) shows that the variation of the distance is regardless of the parameters of the global reference frame. Similarly, the derivate of th angle Γ_i is calculated as

$$\dot{\Gamma}_i = \frac{\dot{r_{yx}}}{1 + r_{yx}^2} \tag{11}$$

where $r_{yx} = e_{y_i}/e_{x_i}$. By using (4), (5) and (9) in (11), it becomes then

$$\dot{\Gamma}_i = \frac{v_{S_i} sin(\theta_{S_i} - \gamma_i)}{d_{S_i}} - \frac{v_i sin(\theta_i - \Gamma_i)}{d_{S_i}} \tag{12}$$

To obtain the set-point robot angle θ_{SP} in order to reach its dynamical target, as described in [1], the idea is to keep Γ_i constant. In other words, we would like to have $\dot{\Gamma}_i = 0$. Under this constraint, we show that the defined set-point angle leads the robot to its target, more details are given in [1]. Equation (12) allows thus to write:

$$\frac{v_{S_i} sin(\theta_{S_i} - \gamma_i)}{d_{S_i}} - \frac{v_i sin(\theta_i - \Gamma_i)}{d_{S_i}} = 0 \tag{13}$$

The set-point angle that the robot must follow to reach its dynamical target is then given by

$$\theta_{SP_i} = \arcsin\left(\frac{v_{S_i}}{v_i} \sin(\theta_{S_i} - \gamma_i)\right) + \Gamma_i \tag{14}$$

By using (5), (14) is obtained in function of θ_i :

$$\theta_{SP_i} = \arcsin\left(\frac{v_{S_i}}{v_i} \sin(\theta_{S_i} - \gamma_i)\right) + \gamma_i + \theta_i \tag{15}$$

Equation (15) represents the desired orientation of the robot w.r.t the global reference frame.

As already cited, a close result was given in [23]. However, the two results are differently developed. In fact, in [23], the line of sight of an observer was used to build this set-point and the position of this observer affects the set-point. This work presents the formulation of the controller parameters according to the global reference frame [1] to obtain this parameters w.r.t. local reference frame. At this aim, Eq. (15) is evaluated in $\theta_i = 0$ (local reference frame) and the results will depend only on the local information of the robot and its target (cf. Fig. 4).

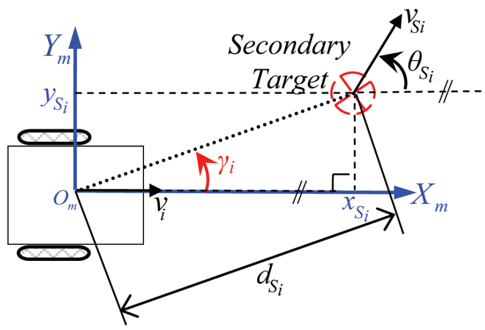

Fig. 4. Robot configuration in a local reference frame.

The proposed control law (cf. Subsection III-B) regulates the robot by accelerating or decelerating according to the robot distance d_{S_i} and γ_i. The target is then tracked whereas reached as in [23] where the goal is just to prove that the robot and its target meet each other. In [1], the proof that the robot reaches its target for two possible cases (escaping and approaching target) is demonstrated.

B. Control law

The used control law allows to robot$_i$ to converge to its set-point and it is expressed as follows [1]:

$$v_i = v_{max} - (v_{max} - v_{S_i})\, e^{-d_{S_i}^2/\sigma^2} \tag{16}$$

$$\omega_i = \omega_{S_i} + K_p\tilde{\theta}_i \tag{17}$$

where v_{max} is the maximum linear velocity of the robot, K_p and σ are the constant such that K_p and $\sigma > 0$ and, d_{S_i} is the distance between the robot and the target. $\tilde{\theta}_i$ is the angular error between set-point angle θ_{S_i} and the orientation of the robot θ_i. Like we use the local information of the robot, then $\theta_i = 0$. $\tilde{\theta}_i$ and ω_{S_i} are given by

$$\tilde{\theta}_i = \theta_{S_i} \tag{18}$$

$$\omega_{S_i} = \dot{\theta}_{S_i} \tag{19}$$

where θ_{S_i} is the set-point angle of the attraction to the target controller θ_{SP_i} and was already computed by (14).

More details about the convergence of the controller using a Lyapunov function are shown in [1].

IV. ENCLOSING DATA RANGE WITH AN ELLIPSE

During the navigation of the robots in the environment, it is important to detect and localize some specific objects to avoid or to follow it. In the proposed work, this object will correspond to the leader of the formation (cf. subsection II-A). The detection of the object could be performed more accurately if the data from all the robots are used. It is what we will show in section V.

First, let us assume that the object O can be surrounded by an elliptical box [25]. The elliptical shape is represented by its Cartesian form:

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1 \tag{20}$$

where $(h,k) \in \Re^2$ are the ellipse center coordinates and $a, b \in \Re^+$ are the semi-axes with $a \geq b$.

At this aim, the observed range data are used to surround the object with the closest ellipse. In this work, we consider that the robots exchange the information (data points) and, this data points are computed from the data range and a general frame such as GPS system. The observed range data is noiseless and without the presence of outliers. Furthermore, we consider that this data corresponds only to one object that will be enclosed by an ellipse. The segmentation method of the set of points will be used in future works to the detection of more than one object at a time.

The choice of ellipse box rather than circle is to have one more generic and flexible mean to surround and fit accurately different kind of objects shapes (longitudinal shapes) [25].

Let us consider a set of n points in $\Re^2$ with coordinates $P_i(x_i, y_i)$ (cf. Fig. 5). This set of points is computed from data range from all the robots, therefore only one ellipse will computed to enclose all this points. In future work, we will compare the performance to computed one big ellipse or many ellipse to enclose the object.

In the following sub-section, it will be presented the efficient method to compute the ellipse parameters from range data [26].

A. Heuristic approach

The proposed heuristic approach uses the distance between the points to obtain one of the axes.

This method computes the distance between all the points $d_{ij} = \|p_i - p_j\|$ with $i, j = 1, \ldots, n$; and select the maximum

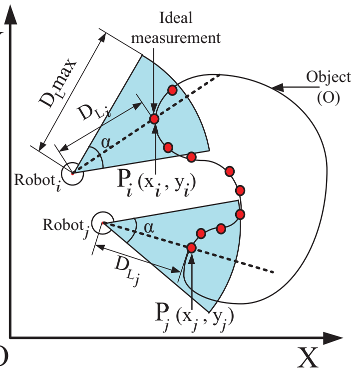

Fig. 5. Range sensor model and data set of n points.

distance d_{max}. We have thus, $d_{ij} \leq d_{max}$. With this manner, this maximum distance is not decreasing. The line connecting the corresponding two points (the points with the maximum distance) is one of the ellipses axes, where the ellipse center C_O is the middle point between the points with maximum distances and the first semi-axes $a_1 = d_{max}/2$ (cf. Fig 6).

Now, we work in the new coordinates system $X'Y'$ to obtain the second ellipse semi-axes a_2. We transform the n points to new coordinates system using (21).

$$\mathbf{P}'_i = \begin{bmatrix} cos(\Omega) & sin(\Omega) \\ -sin(\Omega) & cos(\Omega) \end{bmatrix} (\mathbf{P}_i - \mathbf{C}_O) \tag{21}$$

Where Ω is the orientation of the line between the two points that have the maximum distance. $\mathbf{P}'_i(x'_i, y'_i)$ is the coordinate in the new system, $\mathbf{P}_i(x_i, y_i)$ is the coordinate in the initial system and $\mathbf{C}_O$ is the coordinate of the ellipse center in the initial system.

If the coordinate y'_i of the points is greater than a threshold $\epsilon > 0$, the distance of $\mathbf{P}'_i$ to the origin O' is computed, i.e., $|y'_i| > \epsilon \Rightarrow d'_i = \|\mathbf{P}'_i\|$. The threshold is used to eliminate the points that are collinear with the two points that have the maximum distance.

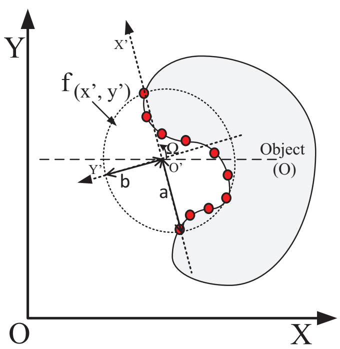

Fig. 6. Obtained ellipse using heuristic approach.

We know that all points inside the ellipse have the distance $d'_i < max\,\{a_1, a_2\}$. As we do not know the spatial distribution of the set of points and to ensure that all the points are inside the ellipse, we choose that $a_2 = max\{b_i\}$, where b_i is the computed semi-axes using $\mathbf{P}'_i$ in (20). In other words, $b_i \leq a_2 \leq max\{a_1, a_2\} \Rightarrow \mathbf{P}_i \in Ellipse$. Therefore, the ellipse will enclose all points without regard of the object shape.

Finally, we obtain the semi-axes of the ellipse (20), cf. Fig. 6, such as:

$$\begin{aligned} a &= max\{a_1, a_2\} \\ b &= min\{a_1, a_2\} \end{aligned} \tag{22}$$

The heuristic approach is an efficient method to enclose data with an ellipse, however, this method does not consider the uncertainties in the data which characterize the real experiments.

V. SIMULATIONS RESULTS

To demonstrate the efficiency of the proposed multi-robot navigation using the cooperative object detection, a survey was made. In this survey, we consider a dynamic object as the main target (leader) i.e., the formation will be defined according to the leader configuration. The leader has a square shape with a side of $l = 0.13\ m$. We consider a group of $N = 2$ mobile robots with a radius of $R_R = 0.065\ m$ and each one has six infrared range sensors with the maximum detected range equal to $D_Lmax = 0.30\ m$ (cf. Fig. 5). The virtual structure is defined by $D_i = 5R_R$ and $\Phi_1 = -120°$ and $\Phi_2 = 120°$ (cf. Fig. 1). The maximum velocity of the robots is $0.4\ m/s$ and the sample time is $0.01\ s$. For each simulation the robots start at the same configuration and try to reach the same final configuration. We do not start to use any object detection method until we have enough data range ($n_{data} \geq 3$).

This survey is used to make a focus around navigation of the multi-robot formation. Furthermore, the performance of the navigation of MRF using range data of each robot separately or of all group of robots to detect the leader is compared.

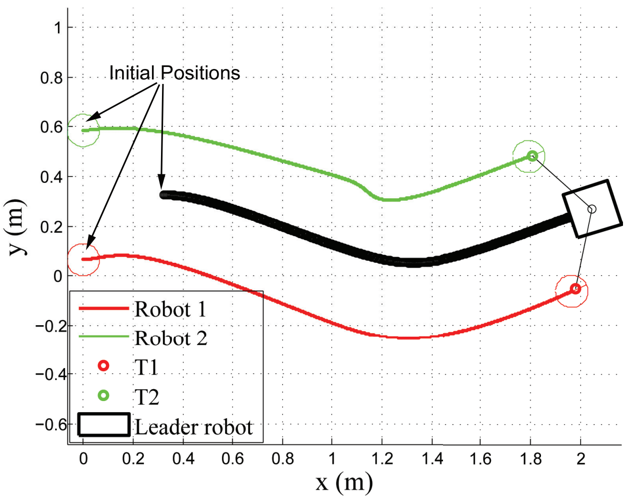

Fig. 7. Navigation of the multi-robot formation.

Fig. 7 shows the trajectory of the multi-robot formation using accurate information of the position an velocity of the object (leader). We observe that the robots converge toward the desired formation (secondary target ST$_i$) while tracking a smooth trajectories. Fig. 8 shows the distance and orientation error of the mobile robots of the formation. The orientation error shows an overshoot that it was generated when the robots were tracking the curve.

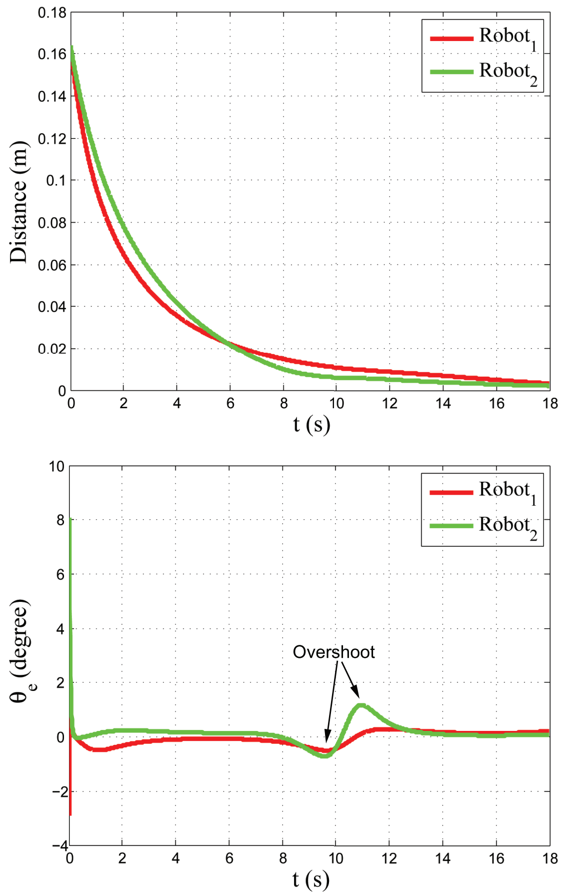

Fig. 8. Distance and orientation error of the multi-robot formation.

The heuristic method gives satisfactory results enclosing the leader by an appropriate circle (cf. Fig 9 and 11).

Fig. 9 shows the trajectory of the multi-robot formation using the estimated position of the object computed from the range data of each robot separately. Also, one of the sample of the evolution of the obtained ellipse is shown. We observe that the robots do not converge toward the desired formation (secondary targets). Fig. 10 shows the distance and orientation error of the mobile robots of the formation.

Fig. 11 shows the trajectory of the multi-robot formation using the estimated position of the object computed from the range data of all group of robots. Also, one of the sample of the evolution of the obtained ellipse is shown. We observe that the robots converge to the desired formation (secondary targets) tracking a smooth trajectory. Fig. 12 shows the distance and orientation error of the mobile robots of the formation. These figures show the moment when the evolution of the obtained ellipse has an abrupt change ($t_c \approx 10$ s). After t_c, the error decrease rapidly because the center of the obtained ellipse is close to the center of the effective leader position.

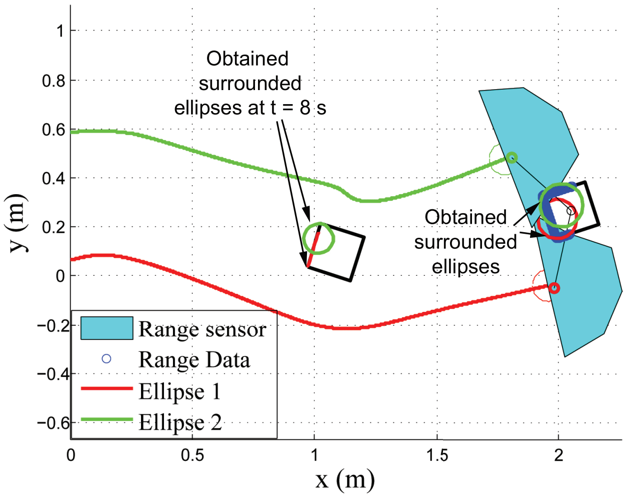

Fig. 9. Navigation of the multi-robot formation using object detection of each robot separately.

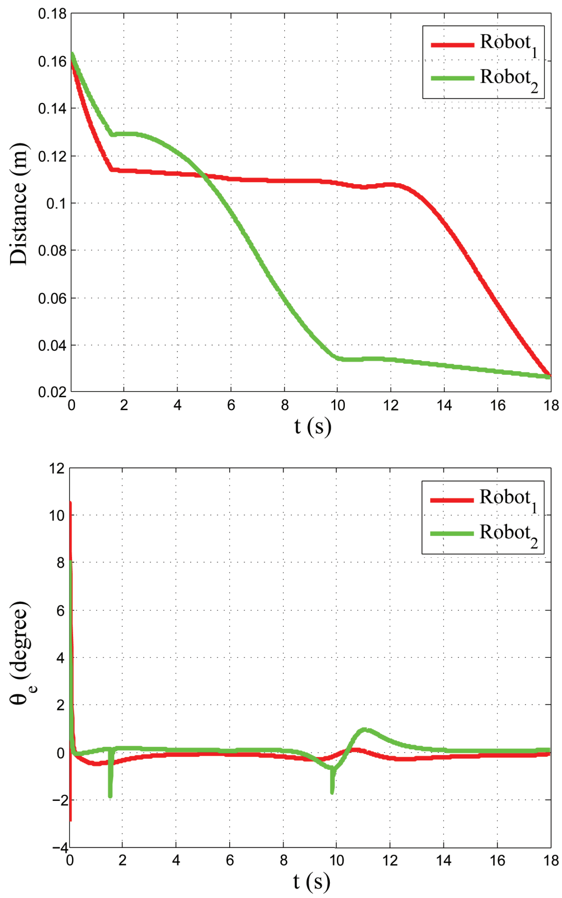

Fig. 10. Distance and orientation error of the multi-robot formation.

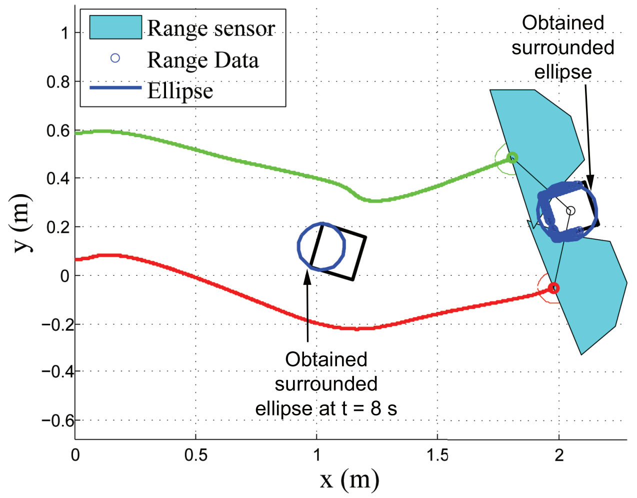

Fig. 11. Navigation of the multi-robot formation using object detection of all group of robot.

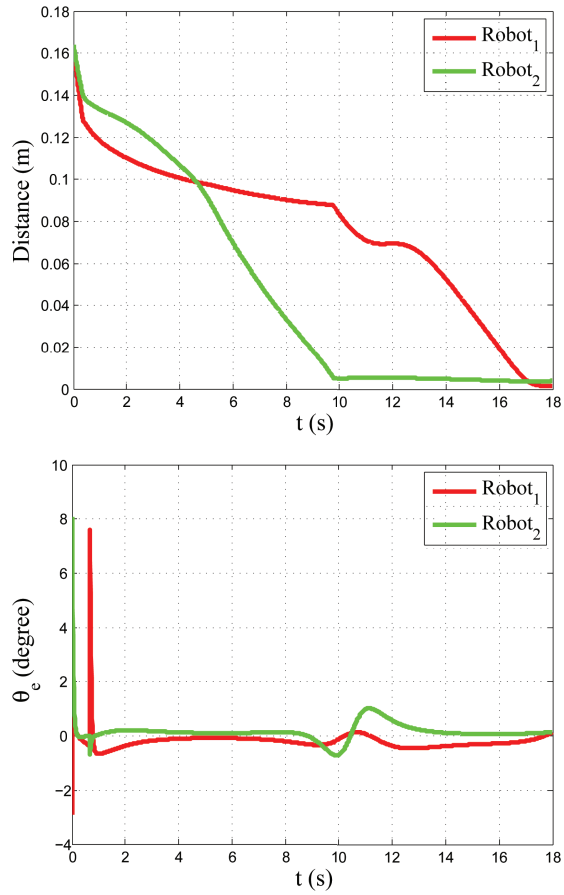

Fig. 12. Distance and orientation error of the multi-robot formation.

VI. CONCLUSION

This paper proposes to address multi-robot formation control problem using the combination between: behavior based, dynamical virtual structure (already presented in [1]) and the leader-follower approach. In addition, to obtain reactive and distributed control architecture, only robot's local frame were used. Moreover, an on-line object detection, performed by the multi-robot system is presented. The objective is to localize the position of the leader in the formation. This leader detection is obtained while using a heuristic method that exploits the range data from the group of cooperative robots to obtain the parameters of an ellipse [25]. This ellipse surround completely the leader to follow. Collision with objects was not addressed in this work, it will be subject of further works.

In future works, the problem of outlier detection and uncertainty of the range data will be considered. Also, the segmentation method will be used to categorize between the presence of big and many small objects.

ACKNOWLEDGMENT

This work is supported by the National Research Agency of France (ANR).

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