Decentralized Control Strategy for Cooperative Mobile Robots

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Abstract

The main goal of this paper is to define, study and analyse a remote control architecture for a set of non-holonomic robotic vehicles. This project (ACCORD) gathers three laboratories and the French Army Research Office. Each of these laboratories deals with a part of this multidisciplinary project which includes coordinated control, control architecture, control with time delay and monitoring of the wireless network. In this paper, we propose to present the whole goal of this project including the basis experimental setup developed to validate our control algorithm. Secondly, we focus on a new decentralized control strategy that uses the Leader-Follower principle. The originality of this paper stems from the use of the signal level of the wireless connection as a control vector. Indeed, each vehicle is fitted with two wireless devices. One of them is equipped of a sector antenna fitted on DC-motor to track the direction of better receiving level. Thus, it allows us to know the relative angular position of the Follower pointing out the Leader. By using the wireless technology as sensor instead of vision for instance, allows a longer distance of coordinated control loop between each vehicle (approx. 100m) even if the GPS information is not available.

1 Introduction

The control of multiple cooperative robotic vehicules is becoming an important robotics research field. A set of robotic vehicles can perform some tasks more efficiently than a single vehicle. Some missions such as exploration, rescue or search need to cover a large area. Sharing sensors information about their current and previous locations, the vehicles can also interact with the remote operator to concentrate the search around the local area. Other types of cooperative tasks have been adressed such as cooperative transport [1] or soccer playing [2]. To perform these tasks, research workers studied different cooperative techniques from decentralized control to animal-like cooperative behavior. These techniques are based on differents kind of sensors such as vision, position, velocity. The sharing of this information is often performed with wireless communications in the case of decentralized control.

Our research works have focused on new control strategies of multiple vehicles based on GPS position and wireless communications. The wireless communications based on Wifi technology between each vehicle allow a geometric formation to be spread over a large spatial terrain (10 to 200m between each vehicle). The vehicles or the formation will be teleoperated by a remote operator within the Wifi communication area. The objective is to analyse and perform a new control algorithm to coordinate robotic vehicles. This algorithm is based on centralized or decentralized control laws. The control variables are the position vector obtained by a GPS sensor fitted on each vehicle and the signal level of wireless communications (see figure 1).

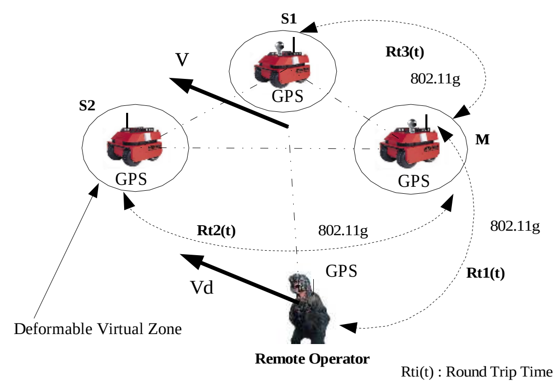

Figure 1: Cooperative robotic vehicles

The wireless communications are used to share informations except if the GPS sensor information is not available. In that case, the communication device also becomes a sensor and the signal level stemming from the neighbor vehicle allows the vehicle to stay in a communication zone. To reach this objective we have to consider and solve some technical and theoretical points :

- Control hybrid Position/Signal level strategies including obstacle avoidance
- Stable controller of multiple vehicles under time delay
- Monitoring the Quality of Service of the wireless network and measurement of the Round Trip Time

To deal with these different scientific points, we created in September 2003, a multi-laboratories research national project (CNRS) with the support of the french army research office (DGA). This project is funded for 2 years. We are designing an experimental setup which is expected to run to early September 2004.

2 Control strategies

We propose two control strategies (a decentralized one and a centralized one) dedicated for two different status of the formation:

- Decentralized control strategy will be based on a Leader-Followers structure as [3] and [4]. This control strategy will be chosen firstly when one robot is not in the communication area of the Operator at least. Secondly, when the GPS sensors information is partially available. Partially available means that the nearest vehicle to the vehicle without position information must have its GPS position information available.

- Centralized control strategy will be performed when all the vehicles will be in the communication area of the Operator and the GPS sensors information will be available.

In both cases, an obstacle avoidance algorithm, based on the Deformable Virtual Zone method (DVZ) and using ultrasound information [9], will be implemented on each vehicle and will be used as a reactive behavior control algorithm when unpredictable obstacles appear.

2.1 Decentralized control law

The decentralized control law is based on a Leader-Followers model (cf. figure 2). One of them is chosen as the Leader by the operator at the beginning of the experimentation. Any robots could be a Leader or Follower. Thus, if the position information given by the GPS is not available then the Leader assignement is automatically swapped to a vehicle which has a valid position.

The desired position of the Leader is defined by the current position of the operator and a distance d_{ol} which could be constant or variable. The Follower desired positions are defined by the position of its neighbor (Follower or Leader) rose by a distance $d_{f_i f_j}$ (distance between Followers i and j) or $d_{l_{fi}}$ (distance between the Leader and Follower i). Thus, the movement of the operator is automatically followed by the formation. In that strategy case, each Follower is also a Leader for its lower neighbor. Meanwhile, the operator could receive some information from the Leader about the sensors fitted on each vehicle (ex.: video).

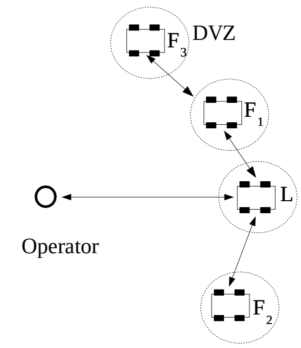

Figure 2: Decentralized control strategy

2.2 Centralized control law

The centralized control law is located in the near operator environment and broadcasts the displacement vector (velocity and steering angle) to the vehicles.

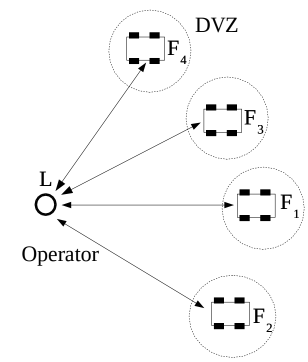

Figure 3: Centralized control strategy

In this case the Operator becomes the Leader and the motion of each vehicle depends on the Operator position and a constant or variable distance d_{ofi} between the Operator and the i^{th} Follower. The desired position of the formation is defined by the current position of the Operator and some geometric constraints to hold the formation.

2.3 Position/Signal Level hybrid control strategy

Position/Signal Level hybrid control law is defined as a complementary control. Indeed, the signal level control loop is an external loop which provides an additional relative desired position ΔP_d to the absolute desired position P. Position and Signal Level vectors can be expressed as $P = [x \ \ y \ \ \theta]^t$ and $S_l = [\lambda \ \ l]^t$, with x and y the cartesian position, θ the steering angle, λ the angle between the directive antenna and vehicle and l the level of the signal. To track the trajectory of its neighbor by using reception signal level and meanwhile, transmit its position to the second neigbhor (cf. figure 4); each vehicle must have two Wifi cards.

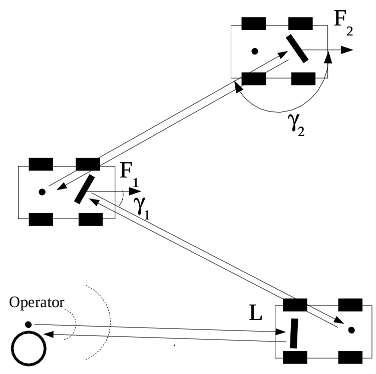

Figure 4: Decentralized hybrid control strategy

One wireless unit using an omnidirectional antenna and the second one a sector antenna fitted on a DC-motor in order to follow the movement of its nearest neighbor. Thus, the angle λ between two vehicles is given by the position sensor of the sector antenna DC-motor. The sector antenna is useful to emit data on the upload link in either case (decentralized or centralized control strategies). The download transmission will be performed via the card equipped with the omnidirectionnal antenna. Figures 2 and 3 illustrate these transmission links between the vehicles and Operator.

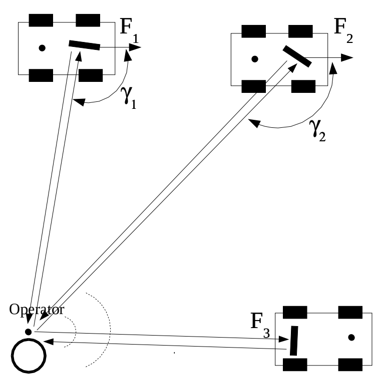

Figure 5: Centralized hybrid control strategy

The reception signal level control strategy holds the communication network available within the formation.

3 Decentralized Control Algorithm

Under decentralized control strategy, the set of coordinated mobile robots follows a Leader-Follower model (cf. figure 6). Each Follower deduces his position vector by using both GPS sensor and the angular position ψ of the Wifi sector antenna.

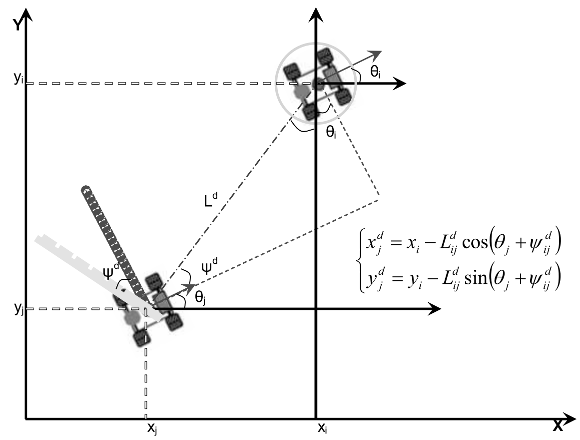

Figure 6: Decentralized

The Wifi motorized sector antenna gives the steering angle of the best receiving level from the Leader. Using this information and the absolute position given by the GPS sensor, we can define the expression of the desired position vector of the vehicle j as :

$$\begin{aligned} x_j^d &= x_i - L_{ij}^d cos(\theta_j + \psi_{ij}) \\ y_j^d &= y_i - L_{ij}^d sin(\theta_j + \psi_{ij}) \\ \theta_j^d &= atan\left(\frac{y_j^d - y_j}{x_i^d - x_i}\right) \end{aligned} \tag{1}$$

where L_{ij}^d is the desired length between the vehicles i and j, ψ the angular position between the two vehicles and θ the relative orientation of the vehicle. The desired position of the First Leader is defined by the position of the Operator. The non-holonomy constraint can be written as :

$$\begin{aligned} \dot{x}_j &= v_j \cos(\theta_j) \\ \dot{y}_j &= v_j \sin(\theta_j) \\ \dot{\theta}_j &= \omega_j \end{aligned} \tag{2}$$

where ω_i is the steering angular velocity of the vehicle i and v_i its cartesian velocity. We can therefore write the direct kinematic equation as :

$$\begin{pmatrix} \dot{x}_j \\ \dot{y}_j \\ \dot{\theta}_j \end{pmatrix} = \begin{bmatrix} \cos(\theta_j) & 0 \\ \sin(\theta_j) & 0 \\ 0 & 1 \end{bmatrix} \begin{pmatrix} v_j \\ \omega_j \end{pmatrix} = J \begin{pmatrix} v_j \\ \omega_j \end{pmatrix} \tag{3}$$

3.1 Decentralized control algorithm

At this step, we do not include the time delay constraint. We provide a mathematical task description in the decentralized control strategy. The control vector can be defined as :

$$\begin{pmatrix} U_{\dot{x}_j} \\ U_{\dot{y}_j} \\ U_{\dot{\theta}_j} \end{pmatrix} = K_p \begin{pmatrix} x_j^d - x_j \\ y_j^d - y_j \\ \theta_j^d - \theta_j \end{pmatrix} \quad (4)$$

The velocity control vector applied to the actuators can be defined as :

$$\mathbf{U}_{p_j} = \begin{pmatrix} U_{v_j} \\ U_{\omega_j} \end{pmatrix} = J^+ \begin{pmatrix} U_{\dot{x}_j} \\ U_{\dot{y}_j} \\ U_{\dot{\theta}_j} \end{pmatrix} \quad (5)$$

J^+ is the pseudo-inverse of the jacobian defined by the direct kinematic equation 3.

3.2 Leader-Follower Positioning without GPS information

Since, the GPS information for each vehicle is not always available, for instance within an Urban area, the decentralized control strategy could lost some vehicles. Each vehicle being a data communication relay between two other robots, the loss of one vehicle breaks down the chain of the coordinated control. To face up to this problem, we propose a new definition of the control vector **U** whose the components use the Received Signal Level (RSL). We propose:

$$\mathbf{U}_{r_j} = \begin{pmatrix} K_{pj}(R_{ij}^d - R_{ij}) + K_{vj}(\dot{R}_{ij}^d - \dot{R}_{ij}) \\ K_{p\omega j}(\theta_j^d - \psi_j) \end{pmatrix} \quad (6)$$

where R_{ij}^d the Received Signal Level of the vehicle j from vehicle i.

3.3 Decentralized control algorithm without the GPS information

The decentralized control algorithm without GPS information is based on the tracking of the transmission signal of the Leader. We assume that the angle ψ of the motorized antenna measuring the best receiving level points out the nearest Leader. At this step of the study, we do not include the spatial propagation model of the signal. To switch the control law strategy from the position loop to the RSL loop, we insert a switching matrix **S** as :

$$\mathbf{U} = \mathbf{S}\mathbf{U_{pj}} + (\mathbf{1} - \mathbf{S})\mathbf{U_{rj}} \quad (7)$$

The control vector $\mathbf{U} = \left[U_{v_j} U_{\omega_j}\right]$ enables to connect either the position control loop or RSL control loop. The RSL control strategy allows to hold the vehicles gathered around the First Leader.

The switching between the Position and the Signal Level loops can be made automatically via the switching matrix **S** as soon as the GPS information disappears. Nevertheless, the Operator can also opt for this control mode to ensure a high quality of the transmission channel between the vehicles.

4 Control with time delay

The remote control of multiple robotic vehicles via a wireless connection needs a stabilizing controller under time delay. Indeed, wireless transmissions with the fading effect or paquet loss might destabilized the control loop. We propose also to study the stability of the decentralized and centralized control laws with time-varying delay.

4.1 Stability

Many existing results concern systems with unknown but constant delay. However, in some applications, such as networked control or teleoperated systems, the assumption of a constant delay is too restrictive; this can lead to bad performances or, even worse, to unstable behaviors. This research work, leaded by J.P. Richard, proposes some results on an efficient sliding mode controller for uncertains systems with time-varying delays and norm-bounded uncertainties [6]. Some research results on the observers based on the sliding modes will be use to estimate the unknown time delay [5]. We expect to use and adapt these results to stabilise the decentralised and centralised control strategies under time delay. We plan to start the validation of these theoretical results on the experimental setup to early September 2004.

4.2 Monitoring of the Wireless Network

To stabilize the formation control loop with time-varying delays between vehicles and Operator, we have developed a tool to monitor the network quality of service and transmit to the controller all information about the round trip time and packet loss. This tool has been developed by the research team of Nancy headed by T. Divoux [7]. This monitoring tool deals with two-way active network measurements. Measured parameters are the one-way delay, the round-trip time, the jitter, the loss rate and the available bandwidth. The tool is also planned to work on IP network using TCP or UDP transport protocols. Frequency of the measurement process is configurable. The time information stems from the GPS sensors fitted on the vehicles and Operator in order to reach a high accuracy.

5 Experimental setup

The experimental setup is located at the Lirmm laboratory which develops a formation of five vehicles.

5.1 Vehicle

The mobile robot is based on 4X4 electrical vehicles (cf. figure 7) with a microcontroller which deals with controlling the velocity and steering angle of the vehicle and the sector antenna angle. Three ultrasound sensors are connecteed to the microcontroller in order to avoid obstacle.

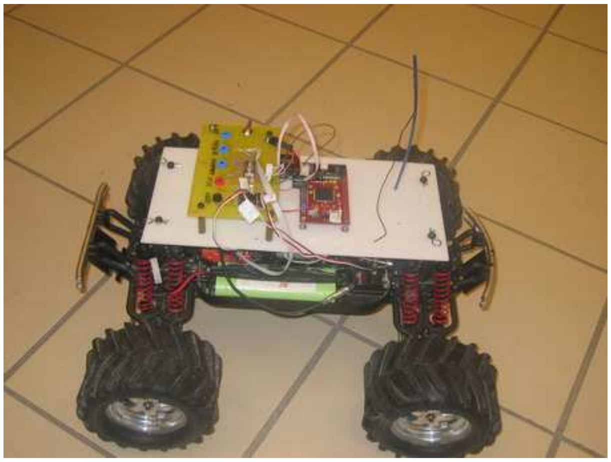

Figure 7: Mobile robot

A PC embedded card running under a Real Time Linux Operating System (RTAI), is connected to the microcontroller via a serial link. This card deals with wireless communication cards and sensors such as GPS or Webcam. Two wireless devices are embedded on the vehicle. One with a omnidirectionnal antenna and the second one with a motorized sector antenna. To supply peripherals, a set of batteries NiMH is added.

5.2 Human Man Interface

We are developing a Human Man Interface (Java) for the remote Operator (cf. figure 8). This interface is to handle and supervise the multirobot formation.

It allows to define and init the geometric formation and the control strategy. The operator can also define which sensor information is needed and visualize it on the graphic interface (cf. figure **??**).

5.3 Communications

The communication cards are based on 802.11b and 802.11g [11] technologies which allow to obtain a theoretical rate respectively of 11Mbps and 54 Mbps in either direction up to 400m. The useful rate by using UDP/IP protocol is actually lower (ex 802.11b: 8Mbps). The Decentralized control communications between the mobile units are based on the ad-hoc mode. While the Centralized control communications (cf. figure 5) will be in the infrastructure mode with an Access Point in the Operator area.

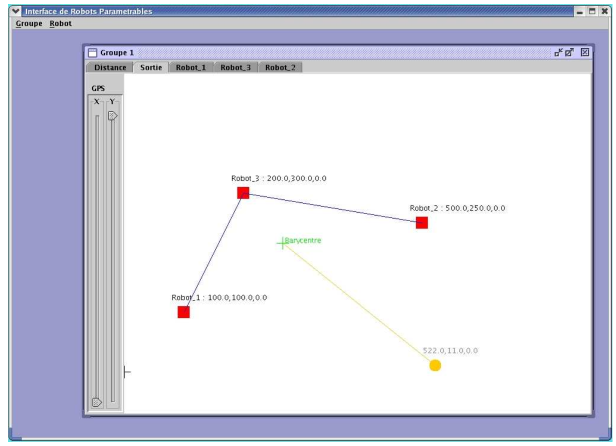

Figure 8: Human Man Interface

6 Simulation results

We have developed a simulator with the Graphical User Interface Tool of $MATLAB^{13}$ which includes up to five non-holomic mobile robots with ultrasound sensors. The dynamic behavior of the vehicles is modelled and implemented within the software.

6.1 Position/RSL control law with three vehicles

The movement of the formation starts with the two followers controlled by the position of the Leader (see figure 9). At the time $t = 36s$ the matrix $\mathbf{S}_2$ of the Follower 2 switches to the RSL loop with a desired Received Signal Level as : $R_2^d = -5dBm$.

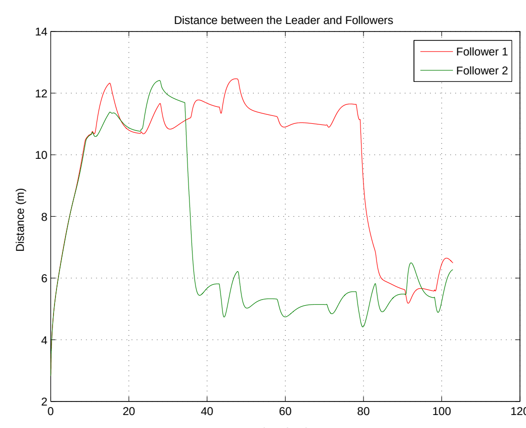

Figure 9: Distances between the Leader and Followers

At the time $t = 80s$, the Follower 1 switchs also to the RSL loop with $R_2^d = -5dBm$. The distances between the Leader and Followers are presented figure 9. The important tracking error between the desired and current distance for a couple of Leader-Follower is produced by the use of proportionnal gain. This compliance enables to avoid the blocking of the Followers when the Leader carries out a U-turn, for instance. Indeed, in that case the velocity needed to maintain a small tracking error is over the maximum velocity of the vehicle. The whole trajectory of the three robots is presented figure 10.

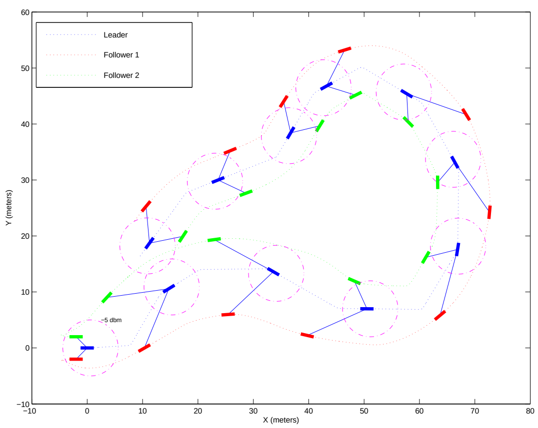

Figure 10: Cooperative Motion with three vehicles

7 Conclusion

This multidisciplinary research collaboration proposes a new strategy to control a set of coordinated vehicle based on GPS and receiving signal level sensors. The sensor of a reception signal level is a wireless communication device based on Wifi standard [11]. This strategy allow to avoid the breaking of the communication link between robots. Thus, the mobile robots are reachable even if the GPS sensors do not work. However, the geometric formation will not match with the initial one. That the condition to keep the vehicle in a communication area. We hope to test and validate our developements on the experimental setup as soon as possible in order to highlight the advantages and drawback of this method. This method will allow to spread over a large urban area, a set of mobile vehicles as a mobile communication network.

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