Motion Control of a heterogeneous fleet of mobile robots: Formation control for achieving agriculture task

P. Cartade, R. Lenain, Benoît Thuilot, B. Benet, M. Berducat

Motion Control of a heterogeneous fleet of mobile robots: Formation control for achieving agriculture task

Pierre Cartade[1]*, Roland Lenain[1], Benoit Thuilot[2,3], Bernard Benet[1], Michel Berducat[1]
[1]*Irstea, 24 avenue des Landais, Aubière, 63172 Aubière, France*
[2]*Clermont université, Université Blaise Pascal, Institut Pascal, BP 10448, 63000 Clermont-Ferrand, France*
[3] *CNRS, UMR 6602, Institut Pascal, 63171 Aubière, France*
**Corresponding author. E-mail:* pierre.cartade@irstea.fr

Abstract

The necessity of decreasing the environmental impact of agricultural activities, while preserving the level of production to satisfy growing population demands requires investigation of new production tools. Mobile robots may constitute a promising solution, since autonomous devices may allow increasing production levels, while preserving the environment thanks to their high accuracy. In this paper, the use of several autonomous mobile robots to perform field operation is investigated. In particular, predictive techniques are also proposed to account for delays induced by low-level actuators. Capabilities of the proposed approach are investigated through full scale experiments.

Key words: off-road mobile robots, automatic path tracking, formation control, multi-robot management.

1 Introduction

The continuous advances in autonomous mobile robot control (concerning both a single robot (de Wit et al., 1996), as well as multi-robots (Balch and Arkin, 1998), (Desai et al., 1998)) offer new possibilities in terms of applications for every-day life improvement. For instance, the development of automated multi-robot fleets can benefit to many applications requiring to cover large areas (Cao et al., 1997), such as surveillance, cleaning, exploration, etc. It is particularly interesting in environmental applications such as farming, where the use of several light robots in the field may permit to reduce environmental impact while preserving the level of production. This constitutes a challenging problem as stated in (Blackmore et al., 2005). Rather than considering numerous small robots, as in swarm robotics (Şahin, 2005), a cooperation framework with a limited number of light machines seems preferable when field treatment is addressed: on one hand, some farming operations such as harvesting require quite large machines to achieve tasks properly, and on the other hand, it appears more tractable from a practical point of view (maintenance, monitoring, acceptability, etc). As a consequence, this paper is focused on formation control of several light robots executing operations in field (as illustrated in figure **Erreur ! Source du renvoi introuvable.**), allowing the use of several autonomous entities instead of driving a sole huge vehicle.

In the considered applications, a reference path is defined by a leader vehicle, controlled either manually or autonomously. The shape of the formation is not considered as fixed, since the area covering may require a varying formation (tank unload, maneuvers, etc). Several approaches have been proposed for mobile robot formation control (Fax and Murray, 2004), (Yamaguchi et al., 2001), but they are mainly dedicated to structured environments. In contrast, the context of the considered tasks requires a high accurate relative positioning of the robots despite the numerous perturbations encountered in natural environment (skidding,


Figure 1: Illustration of the application

terrain irregularities, etc). This is not addressed by classical approaches.

In this paper, an adaptive algorithm for formation control is proposed, relying on a reference trajectory defining a local relative frame. It decouples longitudinal and lateral dynamics with respect to the desired path: the advance of each robot along the reference path can be addressed independently from the regulation of its lateral deviation with respect to this path. Longitudinal control is based on the regulation of curvilinear inter-vehicle distances, while lateral regulation relies on an observer-based adaptive control approach as has been proposed in (Lenain et al., 2011). The control of the possibly varying formation gathers both control laws, enabling an accurate formation regulation for field operations, independently from the reference path shape and environment properties. In this paper an adaptive and predictive approach is proposed to reduce lateral overshoots occurring along curves and due to delay introduced.

The paper is presented as following. First the model of a robot including bad grip condition is proposed. As soon as sideslip angles are available by observation, this model can be used for control purpose. The adaptive control of each robot is then investigated in section 3. It permits an accurate servoing in steady state but overshoots occur when transient curvature phase due to neglected actuator setting time. The efficiency of the proposed control law is finally investigated through full scale experiments.

2 Mobile Robot Modeling

The autonomous control of a fleet of mobile robots is considered with respect to a desired path, used as a reference frame for both longitudinal and lateral positioning of each robot. The objective is to ensure an accurate overall motion of the robots in a desired, but potentially varying, configuration along this chosen trajectory.

2.1 Model of a robot formation

The overall control strategy for the robot formation is based on the modeling proposed in Figure 2 (two robots among n are shown). In this representation, each robot is viewed as a bicycle, as in the celebrated Ackermann model, see (Samson, 1995). The classical rolling without sliding assumption is not satisfied in a natural environment. As they affect robot dynamics significantly, low grip conditions reduce the path tracking accuracy. In order to account for this specific problem, two sideslip angles are added: β^F and β^R, respectively for front and rear axles. These variables are representative of the difference between the tire orientation and the actual tire speed vector direction. Longitudinal sliding is not here accounted, since in the considered applications, longitudinal guidance accuracy is not as critical as the lateral one.

Based on these assumptions, the notations used in the sequel are depicted in Figure 2 for the i^{th} robot are:

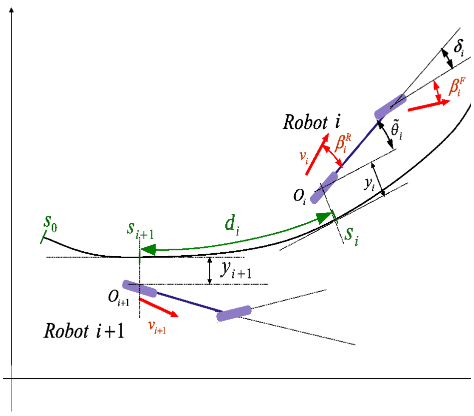

Figure 2: Longitudinal model of a robot fleet

- Γ is the common reference path for each robot defined in an absolute frame (computed or recorded beforehand).
- O_i is the center of the i^{th} mobile robot rear axle. It is the point to be controlled for each robot.
- s_i is the curvilinear co-ordinate of the closest point from O_i belonging to Γ. It corresponds to the distance covered Γ by robot *i*.
- $c(s_i)$ denotes the curvature of path Γ at s_i .
- y_i is the lateral deviation of robot *i* w.r.t. Γ.
- δ_i is the i^{th} robot front wheel steering angle.
- *l* is the robot wheelbase.
- v_i is the i^{th} robot linear velocity at point O_i.

- β_i^F and β_i^R denote the sideslip angles (front and rear) of the ith robot.

2.2 Sideslip angle estimation

As sideslip angles integrated into robot model are hardly measurable directly, their indirect estimation has to be addressed. The observer-based approach detailed in (Cariou et al., 2009) is here implemented. It follows the algorithm described in Figure 3, taking benefit of the duality principle between observation and control.

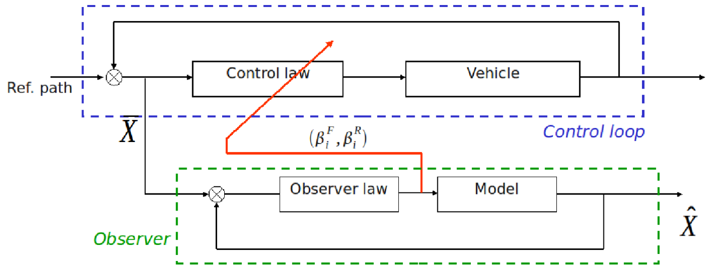

Figure 3: Observer principle scheme

2.3 Model exact linearization for control

Kinematic model has been extended to account for low grip conditions. Nevertheless, it is still consistent with classical kinematic models, such as considered in (Samson, 1995) and (Lenain et al., 2011). It can consequently be turned into a chained form, enabling then an exact linearization. Both longitudinal and lateral control can then be addressed independently.

3 Mobile Robot Formation Control

To address the control of a fleet of mobile robots in a path tracking context, the relative positioning of each robot with respect to the reference trajectory is achieved and then shared within the fleet via wireless communication. The control of each robot aims then at ensuring convergence to desired set points in terms of curvilinear offset (longitudinal control) and lateral deviation offset (lateral control).

3.1 Longitudinal control law

The objective of longitudinal control is to maintain a desired distance (denoted d) between curvilinear abscissas of successive vehicles. Each robot is controlled with respect to the curvilinear abscissa s_1 of the leader. This enables avoidance of an oscillating behavior due to error propagation along the fleet. However, for obvious safety reasons, the distance to the previous vehicle has also to be considered. Therefore, as proposed in (Bom et al., 2005), a composite error x_i equal to the distance to the leader vehicle e_i^1 in the nominal case, and smoothly commuting to the distance to the preceding vehicle e_i^{i-1} when the security distance is approached, is here regulated, see Figure 4. The ith robot linear velocity v_i ensuring that x_i converges to 0, so that each vehicle can be controlled longitudinally, whatever the velocity of the leader.

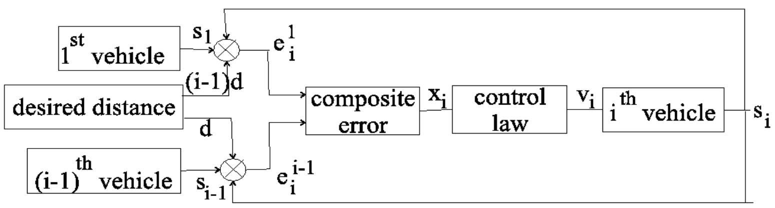

Figure 4: Longitudinal control scheme

3.2 Lateral control law

Once longitudinal control has been achieved, the one of the lateral positions can be addressed. In contrast to the classical path tracking problem, where the error is expected to be null, the lateral deviation of each robot in a formation has to converge to a non-null desired set point.

The steering control law of robot *i*, can be determined using a new variable $y_i^d(s_i)$, representative of its desired lateral deviation. The variable y_i^d permits definition of their lateral positions with respect to the global formation motion. Longitudinal and lateral relative positions of each robot can then be specified in the reference trajectory frame independently. The set point y_i^d has to be constructed to regulate a desired formation, in order to achieve a multi-robot task.
A first mode consists in taking $y_i^d(s_i) = d_i^y$, with d_i^y a constant chosen w.r.t. implement widths. It is completely satisfactory as long as vehicles are never side-by-side.
In contrast, when robots have to work side-by-side we propose the following definition of $y_i^d(s_i)$

$$y_i^d(s_i) = d_i^y + \sigma(y_{i-1} - d_{i-1}^y)[y_{i-1} - d_{i-1}^y]$$

where σ is the smooth commutation function shown. Thus Robot *i* reproduces robot $i-1$ deviation, if the latter exceeds a pre-specified threshold. Such a behavior permit to keep the formation when an important deviation is recorded while preserving the global formation free oscillating behavior.
Moreover when a vehicle enters a curve we observe transient overshoots in lateral deviations. They are mainly due to delays induced by low-level actuators, the delays depending of intrinsic properties of the actuators. To reduce such overshoots, we use predictive techniques.
More precisely, assuming that the overshoots are only generated by delays of the actuators in response to fast variations of the curvature, a predictive algorithm is designed, focused on the part of the control law linked to the curvature of the path.

4 Experimental results

4.1 Experimental setup

The electric off-road vehicles depicted in figure 5 are used as an experimental platform. On this picture the leader is RobuFAST and the follower is named Arocco, they are designed for mobility and they can climb slopes up to 45^o.

Robots	RobuFAST	Arocco
Total mass	*m*=350 kg	*m*=620 kg
Wheelbase	*L*=1.2 m	*L*=1.2 m
maximum speed	8 m s^{-1}	4 m s^{-1}

Table 1: Main parameters of experimental robots

The main exteroceptive sensor on-board on the two robots is a RTK-GPS receiver, which supplies absolute position measurement with an accuracy of 2 cm at a 10 Hz sampling frequency. The communications between vehicles are made by WiFi communication.

Figure 5: Experimental platform

4.2 Path tracking results

The experiments for the algorithm's validation consist in following the path depicted on figure 6. This path has been recorded beforehand, when the robot was steered manually at 1 m s^{-1}. It is composed of two straight lines and a turn; half the trajectory is on a sloping ground and the other on a level ground. On figure 7 and 8 one iteration corresponds to 0.1 s.

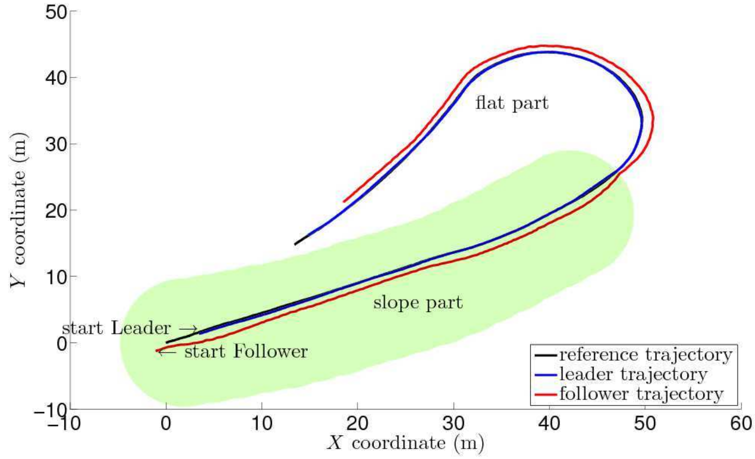

Figure 6: Robots trajectories

The leader moves at 2 m s^{-1}, and has to follow the reference trajectory. The follower has to maintain a lateral distance of 1m and a longitudinal distance of 10 m with the leader. As regards the lateral error on figure 7 we can consider the objective is achieved, as it can be seen that after an initializing phase (after iteration 250) the lateral error does not exceed 20 cm with respect to desired deviations: 0m for the leader and 1m for the follower. An overshoot can be observed at iterations 400 and 450 (resp. for the leader and the follower) corresponding to a motion through a bump (slope to flat ground part). This indeed generates a roll motion explaining the variation in lateral error (GPS antennas are placed in the top of robots, see figure 5), which does not correspond to an actual robot motion. Despite this perturbation, the control algorithm stays stable, and provides a level accuracy compatible with actual field operations.

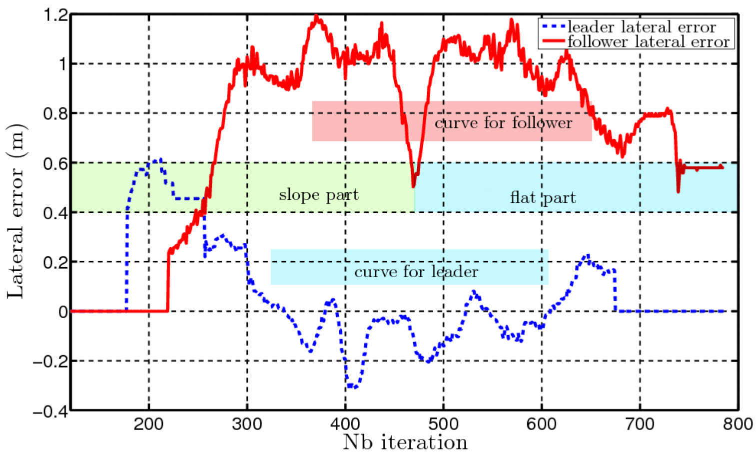

Figure 7 Robots lateral errors

Figure 8 shows a comparison plot of velocity of robots and longitudinal distance. It can be seen at the start a 2m longitudinal error and at the end another one of more than 3 m. It can be explained by the long time the follower requires to accelerate at the beginning and decelerate at the end. Moreover we note that the longitudinal distance oscillates when robots take the turn and when they reach the flat ground. These inaccuracies occur when fast speed variations are required. Nevertheless, during steady state period, the curvilinear distance between robots is well regulated on the desired value of 10m.

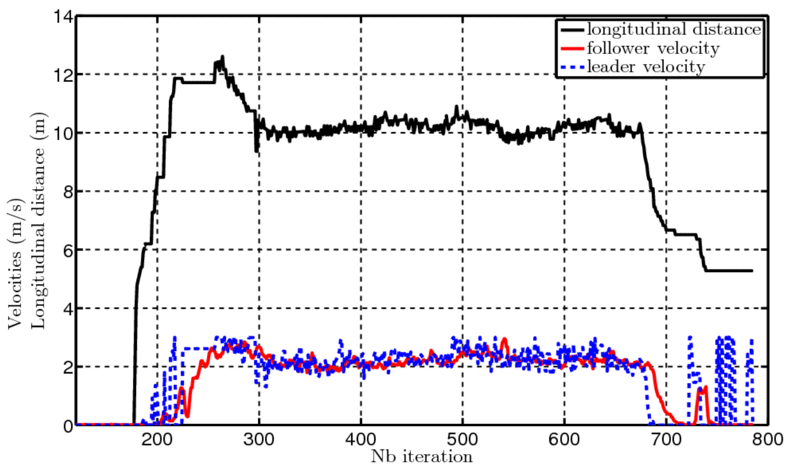

Figure 8: Longitudinal distance and velocity of robots

5 Conclusion and future works

This paper proposes an algorithm for the accurate control of a mobile robot formation moving off-road. This approach considers the formation control as the combination of (i) a platooning control and (ii) an extension of the path tracking problem to a non-null lateral deviation regulation. As a result, the control of each vehicle is decomposed into longitudinal and lateral control with respect to a reference path. An adaptive control strategy is designed. It allows to take into account for low grip conditions, as well as other phenomena encountered off-road and depreciating the accuracy when using classical algorithms. In addition, a predictive curvature servoing has been designed in order to anticipate for overshoots, due to steering actuator settling time. The relative positioning of each robot with respect to a possibly varying formation can then be regulated, with a few centimeter accuracy, whatever the shape of the reference trajectory and the grip conditions. The efficiency of the approach has been tested through actual experiments with two off-road mobile robots.

In addition, the proposed strategy is focused on the regulation of a formation with respect to a reference trajectory supplied beforehand. Such an algorithm has now to be extended in order to manage automatically the formation (modification of the formation at the end of the field in order to operate an U-turn, mobile robot entering/leaving the fleet, leader manually controlled, obstacle avoidance, etc). In order to improve longitudinal regulation with respect to follower acceleration performances, a predictive step is under development to anticipate for leader fast speed variation.

Reference list

Balch, T., Arkin, R.C., 1998. Behavior-based formation control for multirobot teams. Robotics and Automation, IEEE Transactions on 14, 926 –939.

Blackmore, B.S., Stout, W., Wang, M., Runov, B., 2005. Robotic agriculture – the future of agricultural mechanisation? Presented at the 5th European Conference on Precision Agriculture, Upsala, Sweden, pp. 621–628.

Bom, J., Thuilot, B., Marmoiton, F., Martinet, P., 2005. A global control strategy for urban vehicles platooning relying on nonlinear decoupling laws. Edmonton, Canada, pp. 2875 – 2880.

Cao, Y.U., Fukunaga, A.S., Kahng, A., 1997. Cooperative Mobile Robotics: Antecedents and Directions. Autonomous Robots 4, 7–27.

Cariou, C., Lenain, R., Thuilot, B., Berducat, M., 2009. Automatic guidance of a four-wheel-steering mobile robot for accurate field operations. Journal of Field Robotics 26, 504–518.

Desai, J.P., Ostrowski, J., Kumar, V., 1998. Controlling formations of multiple mobile robots. pp. 2864 –2869 vol.4.

Fax, J.A., Murray, R.M., 2004. Information flow and cooperative control of vehicle formations. Automatic Control, IEEE Transactions on 49, 1465 – 1476.

Lenain, R., Berducat, M., Cartade, P., Thuilot, B., 2011. Co-ordination of Multiple robots in outdoor environments. Presented at the 8th European Conference on Precision Agriculture, Prague, Czech Republic.

Şahin, E., 2005. Swarm Robotics: From Sources of Inspiration to Domains of Application, in: Sahin, E., Spears, W. (Eds.), Swarm Robotics, Lecture Notes in Computer Science. Springer Berlin / Heidelberg, pp. 10–20.

Samson, C., 1995. Control of chained systems application to path following and time-varying point-stabilization of mobile robots. Automatic Control, IEEE Transactions on 40, 64 – 77.

de Wit, C.C., Bastin, G., Siciliano, B. (Eds.), 1996. Theory of Robot Control, 1st ed. Springer-Verlag New York, Inc., Secaucus, NJ, USA.

Yamaguchi, H., Arai, T., Beni, G., 2001. A distributed control scheme for multiple robotic vehicles to make group formations. Robotics and Autonomous Systems 36, 125–147.