

Robocoop: tools for cooperative mobile robots autonomous navigation

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Abstract. This paper outlines some of the key characteristics of the navigation of a swarm of autonomous mobile robots. The results in localisation problem using only one landmark are given. A decentralized path planning algorithm for the swarm which takes into account the physical limitations of the robot and its kinematic model is presented. Moreover, a tracking algorithm is developed to guarantee that each robot follows the desired trajectory. We also discuss the strategies designed in order to increase the swarm efficiency. Simulation on Player/Stage and experimental results on three nonholonomic robots are provided to show the effectiveness of the proposed algorithms.

Keywords: mono landmark localisation, decentralized path planning, tracking, cooperative robot swarm strategy.

1 Introduction

Multirobot systems have the possibility to solve problems more efficiently than a single one, but also problems that cannot be handle by a single one. Cooperative robotics concerns a network of robots exchanging informations in order to tackle a common problem. It can provide solutions to several applicative fields including manufacturing, supervision (forest fire, military applications, . . .), space or underwater exploration, medical applications, Such deployment of large scale networks of cooperative robots can also provide complex behaviors by using simple agent based behaviors.

The Robocoop project (see website <http://syner.ec-lille.fr/robocoop/>), started in 2003, deals with cooperative mobile robots. Within a multidisciplinary research framework, it focused on the two following main problems (2003-2008):

- collaborative path planning,
- collaborative control design for mobile robots including path tracking control even in the presence of delays due to communications.

This project is now addressing additional aspects such as localization and strategy design.

This paper focuses on the problem of autonomous navigation of a swarm of mobile robots which navigate in a partially known or unknown environment with obstacles. The swarm must navigate between known initial and final points without collision. In order to be able to move autonomously, the robot needs to know at each moment its localization on the map and information about the obstacles in its neighborhood. The software architecture of each robot of the swarm proposed in this paper is depicted in figure 1.

The blocks “Perception” and “Localisation” receive information from the proprioceptive and exteroceptive sensors of the robot. In the “Localisation” block, the information is processed in order to obtain the robot position and orientation. This paper proposes a new localisation algorithm by using a mono-landmark. In the “Perception” block, the measurements obtained from the sensors are used in order to obtain information about the position and the shape of the obstacles in the robot neighbourhood. The block “Strategy” receives

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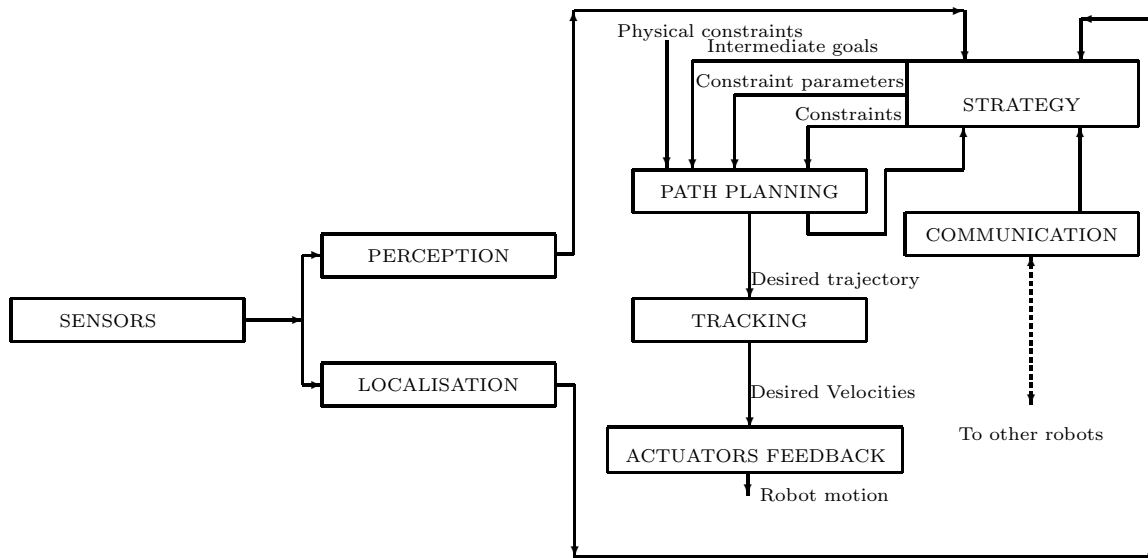


Fig. 1. Software architecture for an autonomous mobile robot

information about the robot localisation and the environment and about the internal state of the robot. With this information, it must evaluate the robot situation, and if necessary, it can ask the complementary information to the robots in its neighbourhood in order to make a decision about the direction of the robot movement. This paper introduces a new cooperative strategy which takes the robot neighbours into account. It is based on the use of two functions. The first one defines the satisfaction of the robot neighbours with regard to the degree of congestion of the space around them. The second one estimates the fulfilment of the mission of every robot. The “Path Planning” and “Tracking” blocks are intended to calculate and to apply an optimal trajectory for the robot, according to the information coming from the block “Strategy”, the kinematic constraints of the robot and the constraints related to the environment. The block “Actuators feedback” guarantees that the desired calculated speeds will be equal to the speeds of robot wheels. The block “Communication” ensures information exchanges between each blocks of the robot and with the other robots of the swarm.

2 Path Planning

The aim of path planning is to compute admissible trajectories for a swarm of mobile robots such that they can evolve in an unknown environment from an initial configuration to a final configuration without collision and, eventually, in minimal time respecting an acceptable geometrical shape during the movement. Some constraints must be taken into account:

- constraints due to physics (energy limitation, maximal velocity and acceleration of the robots)
- obstacle avoidance,
- collision avoidance with the robots and other mobile objects,
- distances between robots (communication constraints),
- geometry of the formation,
- time constraints (in the case of rescue missions), energy constraints (batteries duration, ...)

The path planning problem is expressed as an optimal problem under constraints: find the optimal control and the optimal trajectory of each robot which minimizes a cost function (i.e. minimal time or minimal energy or a mix between minimal time and minimal energy) and which satisfies the constraints enumerated above. In order to solve this problem in real time, we proposed an approach based on dynamical optimization over a sliding horizon and based on the flatness property.

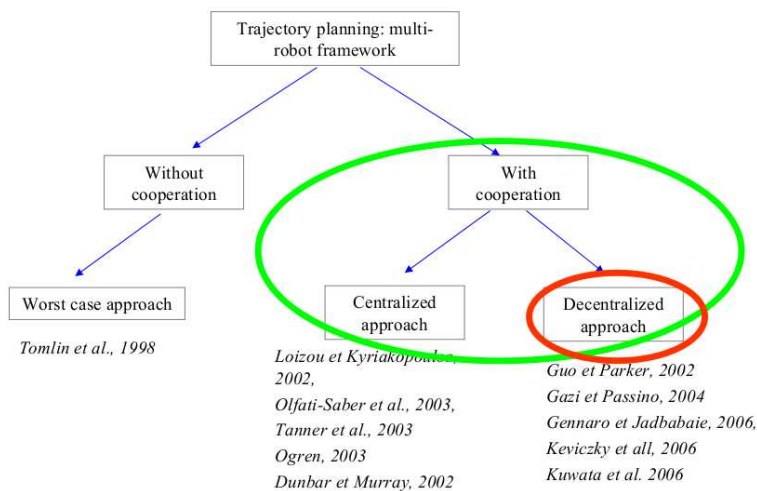
Flatness means that all the state variables and the inputs of a dynamical system can be parameterized in terms of so-called flat outputs (or linearizing outputs) and a finite number of their successive time derivatives (see [1]). This is the case of most of mobile robots, for which the flat outputs are the coordinates of the center of gravity up to a translation. For example, for the unicycle type mobile robot which model is described by the following equations

$$\begin{aligned}\dot{x} &= v \cos \theta \\ \dot{y} &= v \sin \theta \\ \dot{\theta} &= w\end{aligned}\tag{1}$$

the flat outputs are (x, y) . Indeed, one has: $\theta = \arctan\left(\frac{\dot{y}}{\dot{x}}\right)$, $v = \pm\sqrt{\dot{x}^2 + \dot{y}^2}$ and $w = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{\dot{x}^2 + \dot{y}^2}$. Using this property, all the dynamics of the vehicles, as well as the constraints, can be expressed as functions of the flat outputs and their time derivatives. Then, the problem is to minimize a criteria that only depends on the flat outputs and their time derivatives. This optimal problem can be easily transformed into a nonlinear programming problem, using B-spline functions in order to approximate the trajectory of the flat outputs, and also, to deduce the optimal control $u(t) = [v(t), w(t)]^T$ and the optimal trajectory $q(t) = [x(t) \ y(t) \ \theta(t)]^T$.

Within a swarm of mobile robots, some of them may play a particular role: the leaders. One has to distinguish between swarms:

1. with leader: the leader drive the whole swarm or a part of it.
2. without leader: need of a local/global coordination. Decision rules must use local information (most of the time neighbors) or global information.



First a scheme of coordination according to the method described above was designed *via* a global supervisor, which can be seen as a the leader of the swarm (centralized approach). In that case, the supervisor generates trajectories for all the vehicles by solving an optimization problem of large dimension. However, the lack of autonomy of robots with regard to the supervisor, the centralization of the information and the costs in terms of calculation time make difficult the on-line implementation of this strategy.

In order to get rid of these drawbacks, and to strongly decentralize the path planning algorithm, we proposed an on-line decentralized algorithm on a sliding horizon, based only on the available local information for each robot [2], [3]. It consists in decomposing the problem of path planning of each robot into two steps. In the first one, every robot builds an intuitive trajectory using local information and taking only the obstacles

into account. In the same time, each robot analyzes, by using its sensors, the potential problems which may appear (loss of communication or collision with another robot). In the second one, the robots which can be in collision or lose the communication with the other robots of the swarm adjust their intuitive trajectories by taking constraints of communication and of collision avoidance with the robots into account. This new trajectory is called **planned trajectory** and it is the trajectory that the robot must track in the time interval $[\tau_k, \tau_{k+1}]$, where $\tau_k = t_0 + kT_c$ with t_0 the initial time and T_c the update period.

This distributed implementation increases not only the autonomy of robots, but also reduces the complexity in term of calculations with regard to a centralized implementation. These two algorithms were tested and compared with other existing methods (the detail of these results can be find in [4]) and advantages of the approach were highlighted in terms of low computation time, communication resources, easiness of implementation (such as the number of parameters), high performances and the fact that there is no supervisor. Experiments were performed on a team of three nonholonomic mobile robots to demonstrate the validity of the proposed approach (see [4]).

3 Tracking

Once the desired trajectories have been computed, robust control algorithms must be designed so that the robots accurately track the reference trajectories in spite of model uncertainties and external perturbations.

To this end, so-called sliding mode control laws have been chosen, not only for their properties of robustness, but also for their intermittent character. Indeed, mobile robots belong to the class of the nonholonomic systems, which do not satisfied the Brockett condition for the existence of a continuous and independent of time state feedback controller. It is then necessary to solve this problem to develop control laws which depend on time or which are discontinuous, such as in our case the sliding modes.

Various types of sliding mode control laws have been designed and experimentally tested for unicycle robots ([5], [6]), as well as for vehicle like robot, in particular by taking into account the skidding and sliding phenomena ([7], [8]).

Some results have been obtained within the framework of the trajectory tracking of a swarm of mobile robots using a decentralized scheme of type “leader / follower” where a hierarchical relations exist between robots. For every robot, the decision rule is to follow the closest robot (local leader). Then, one can designed control laws using relative positions between robots and capable to ensure collision avoidance in spite of measurement errors and external perturbations (see [9] for details).

In the experimental results reported in Fig. 2) and 3), the objective is to maintain a triangular formation between the robots. The leader R_1 plans its own trajectory and the followers R_2 and R_3 have to maintain fixed orientation and distance with respect to R_1 .

4 Localisation

Some of the originalities of the localisation algorithm described herein are the use of only one landmark tracking during the navigation, no hypothesis on the nature of the signal, the possibility to implement in real time and no initialisation step required. This work is innovative, because, to our knowledge, there is no other result which uses only one landmark in the localisation process. This idea is very interesting because it is possible to think about a fusion process which then could improve the final result. Moreover it is possible to work in an environment where it is difficult to track a lot of landmarks (not a lot of landmarks or very poor computational capacities).

The state model of a nonholonomic mobile robot can be described by the following equations:

$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} u \cos \theta \\ u \sin \theta \\ \omega \end{bmatrix} \\ \alpha = \arctan \left(\frac{y_r}{x_r} \right) - \theta + \xi_\alpha \end{cases} \quad (2)$$

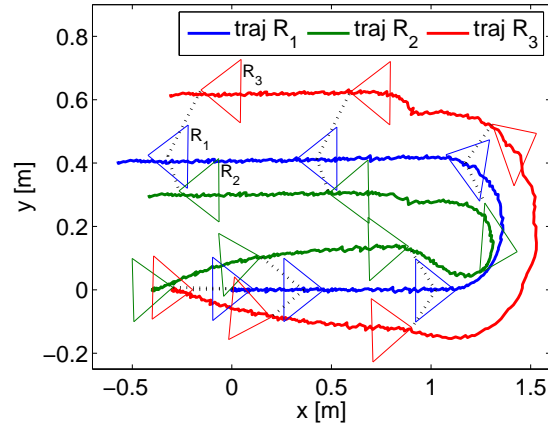


Fig. 2. Leader R_1 and followers R_2 et R_3 trajectories

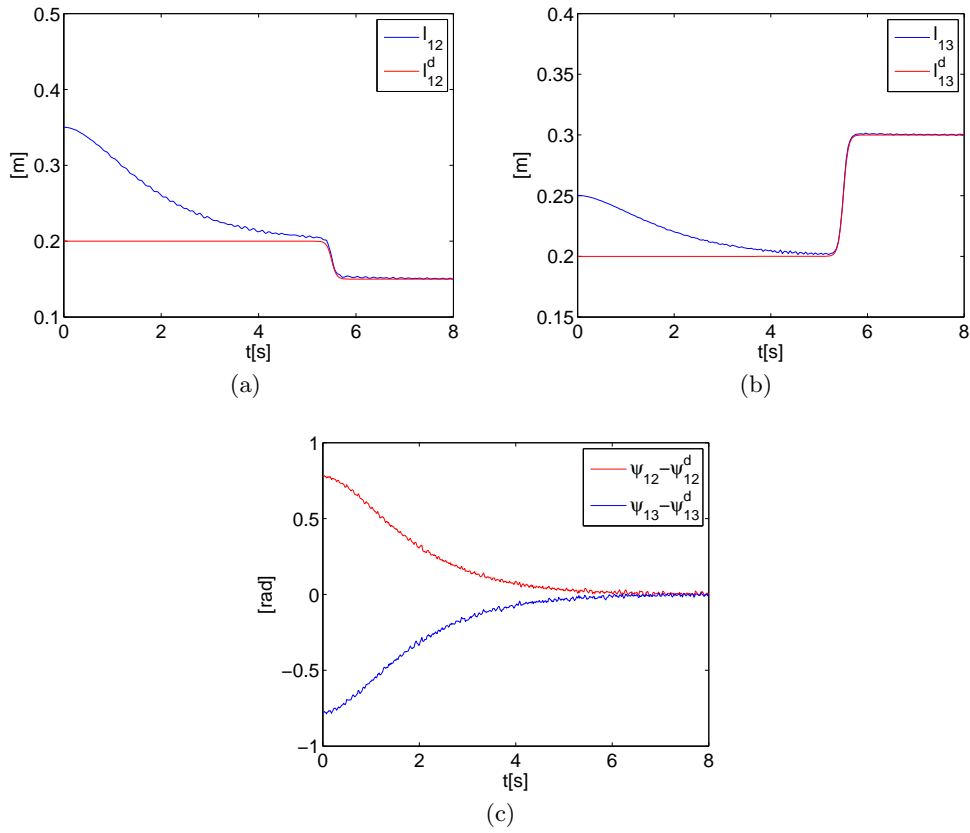


Fig. 3. Tracking errors

with (x, y, θ) the position of the robot, u its linear speed and ω its angular speed. x_r and y_r are the relative position between a given landmark and the robot, α is the angle of the robot with respect to the landmark

and ξ_α is an additive noise (there are no more hypothesis on the nature of the noise).

The goal is to calculate the robot position $[x \ y]^T$ in function of the measurement α and its successive time derivatives.

Theorem 1. [10] Consider a nonholonomic mobile robot with state model described by equation (2), and assume that the following data are measured or known:

- Known : (x_A, y_A, z_A) , the coordinate of the landmark,
- Measurement (possibly noisy): u, ω, α and θ (measured with a compass for example).

Then, the position of the robot can be calculated using the following equation :

$$\begin{bmatrix} x_r \\ y_r \end{bmatrix} = \begin{bmatrix} x_A - x \\ y_A - y \end{bmatrix} = \begin{bmatrix} \frac{u \sin(\alpha) \cos(\alpha + \theta)}{(\dot{\alpha} + \dot{\omega})} \\ \frac{u \sin(\alpha) \sin(\alpha + \theta)}{(\dot{\alpha} + \dot{\omega})} \end{bmatrix} \quad (3)$$

where u, ω, θ and α are filtered by using a zero order differentiator and $\dot{\alpha}$ is calculated by using a first order differentiator.

We use for the zero and first order differentiators an algebraic numerical differentiator of noisy signals which was introduced in [11] and analysed in [12, 13] (see also [14] for interesting discussions and comparisons). The reader may find additional theoretical foundations in [15, 16].

5 Strategy

In [4] and [17], decentralized path planning algorithms for a swarm of mobile robots were introduced. However, these works suffer from some limitations. First of all, only the case of circular shape obstacles could be addressed. So a new formulation was given in [17] that allows to have obstacles of more general shape but only in the mono-robot case. In [18], these approaches were generalized to the navigation problem of a cooperative swarm. In fact, it is interesting to consider the case where robots of the swarm communicate in order to help their neighbours or to get help from them. We think that it is impossible to solve this problem at the same level of abstraction than the path planning block because at this level the information are too local. We developed a strategy block which can communicate with the path planning block and sends it an intermediate objective, new constraints or new parameters. Under the assumption that the planning is done on an horizon time of length T_c , it is possible to update the information at the input of the strategy block at a T_c sampling rate and the strategy can be modified at each T_c . For example, the cost function can be change in function of the internal state of the robot. If, for example, the cost function is the time minimization and if a power problem appears, it is possible to change the cost function in order to minimize the energy consumption. It is also possible to change the parameters of some constraints in function of the environment, to add or to remove constraints in function of neighbours or obstacles. This interaction between the strategy block which has high level information (discrete optimization) and the path planning block which has low level information (continuous optimization) gives the guarantee of a good appliance of the mission. The strategy block is elaborated in the framework of a multi-agents system based on a decision process established with the IODA methodology (for more details see [19]).

In this paper, cooperation means that a robot cooperates with its neighbours, if this cooperation allows it to get closer to its objective or to avoid a strongly congestion zone. The swarm keeps its decentralized character because every robot is responsible for its reasoning and processes the data of its neighbours as it wishes it.

Two functions are defined, allowing to express the degree of satisfaction of the robot towards its environment and towards the task to be done:

- A function of satisfaction, $f_{i_S}(t)$, which describes the degree of congestion of the space around the robot,
- A function of fulfilment of the task, $f_{i_A}(t)$ which estimates the fulfilment of the mission of every robot.

All the values of these functions must be in the interval $[0, 1]$ in order to be comparable.

A functional expressing the satisfaction of each robot is then defined according to the values of functions $f_{i_S}(t)$ and $f_{i_A}(t)$ with regard to functions $f_{j_S}(t)$ and $f_{j_A}(t)$ for a neighbour R_j of the robot R_i . So :

$$f_{ij}(t) = \begin{cases} 0 & \text{if } R_i \text{ decides to not cooperate with } R_j \\ 1 & \text{if } R_i \text{ decides to cooperate with } R_j \end{cases} \quad (4)$$

So that, each robot decides to cooperate with its neighbours, if the values of the satisfaction and fulfilment functions of these neighbours are better than its own values.

$S_{i/j} = f_{j_S}(t) - f_{i_S}(t)$		
$A_{i/j} = f_{i_{A_{i/j}}}(t) - f_{i_{A_{i/i}}}(t)$		
	$f_{i_{A_{i/j}}}(t) > f_{i_{A_{i/i}}}(t)$	$f_{i_{A_{i/j}}}(t) \leq f_{i_{A_{i/i}}}(t)$
$f_{j_S}(t) > f_{i_S}(t)$	$f_{ij}(t) = 1$	$S_{i/j} > Threshold_S \ f_{ij}(t) = 1$ Otherwise $f_{ij}(t) = 0$
$f_{j_S}(t) \leq f_{i_S}(t)$	$A_{i/j} > Threshold_A \ f_{ij}(t) = 1$ Otherwise $f_{ij}(t) = 0$	$f_{ij}(t) = 0$

$Threshold_S$ and $Threshold_A$ are two thresholds of cooperation and $f_{i_{A_{i/j}}}$ is the fulfilment function of R_i in the referential of R_j .

When a robot decides to cooperate with another robot, it decides to take the last position known for this one as an intermediate objective.

Simulation results could be found in [18].

6 Conclusion

During the Robocoop project, several tools have been proposed in order to perform the autonomous navigation of a swarm of mobile robots. It is well known that one of the most important challenges for the autonomous navigation is the robot perception and its localisation. In fact, the robot must know at every moment its localisation in the environment and the distance between it and the obstacles which are in its range of sensors. We proposed a new algorithm of localisation based on the use of only one landmark. The proposed localisation algorithm calculates the robot position using only the knowledge of the landmark coordinates. The robot control input is known and the robot orientation and the angle between the robot and the landmark are measured by using, for example, a compass and a vision system respectively. Another important challenge is the decentralized path planning. It is important to plan in real time a trajectory for each robot that takes into account the obstacles in the robot neighbourhood, the physical robot limitations (maximal acceleration, maximal velocities), the robot model (kinematic or dynamic), the broadcasting range. The proposed path planning algorithm was described like a constrained optimal problem. The use of the flatness property of the robot allows the utilization of this algorithm for a large class of robots. Some strategies have been proposed in order to increase the efficiency of the swarm. Each robot can help its neighbours if they are in a critical situation. A tracking algorithm was also proposed to guarantee that each robot tracks accurately and in a robust way the desired optimal trajectory. All the proposed algorithms were implemented on Player/Stage or on three mobile robots Peking manufactured by Wany Robotics. The videos of the experiments can be visualized on the web site http://oban.isen.fr/~sst_lille/.

References

1. Fliess, M., Levine, J., Martin, P., Rouchon, P.: Flatness and defect of non-linear systems: introductory theory and examples. *International journal of control* **61**(6) (1995) 1327–1361
2. Defoort, M., Palos, J., Kokosy, A., Floquet, T., Perruquetti, W., Boulinguez, D.: Experimental motion planning and control for an autonomous nonholonomic mobile robot. In: *IEEE International Conference on Robotics and Automation*, Roma, Italy. (2007)
3. Defoort, M., Palos, J., Kokosy, A., Floquet, T., Perruquetti, W.: Performance-based reactive navigation for non-holonomic mobile robots. *Robotica* **27**(02) (2008) 281–290

4. Defoort, M., Kokosy, A., Floquet, T., Perruquetti, W., Palos, J.: Motion planning for cooperative unicycle-type mobile robots with limited sensing ranges: A distributed receding horizon approach. *Robotics and Autonomous Systems* **57** (2009) 1094–1106
5. Defoort, M., Floquet, T., Kokosy, A., Perruquetti, W.: Integral sliding mode control for trajectory tracking of a unicycle type mobile robot. *Integrated Computer Aided Engineering* **13** (2006) 277–288
6. Defoort, M., Floquet, T., Perruquetti, W., Drakunov, S.: Integral sliding mode control of an extended Heisenberg system. *IET Control Theory & Applications* (2009)
7. Hamerlain, F., Achour, K., Floquet, T., Perruquetti, W.: Higher Order Sliding Mode Control of wheeled mobile robots in the presence of sliding effects. In: *IEEE Conf. on Decision and Control, Seville, Spain.* (2005)
8. Hamerlain, F., Achour, K., Floquet, T., Perruquetti, W.: Higher order sliding mode stabilization of a car-like mobile robot. In: *ICINCO, Angers, France.* (2007)
9. Defoort, M., Floquet, T., Kokosy, A., Perruquetti, W.: Sliding mode formation control for cooperative autonomous mobile robots. *IEEE Transactions on Industrial Electronics* **55** (2008) 3944–3953
10. Sert, H., Kökösy, A., Palos, J., Perruquetti, W.: Mono landmark localization for an autonomous navigation of a cooperative mobile robot formation. In: *International Conference on Intelligent Robotics and Applications, Singapore (December 2009)*
11. Fliess, M., Join, C., Mboup, M., Sira-Ramírez, H.: Compression différentielle de transitoires bruités. *C.R. Acad. Sci.* **I(339)** (2004) 821–826 Paris.
12. Mboup, M., Join, C., Fliess, M.: A revised look at numerical differentiation with an application to nonlinear feedback control. In: *The 15th Mediterrean Conference on Control and Automation - MED'2007, Athènes Grèce (June 2007)*
13. Mboup, M., Join, C., Fliess, M.: Numerical differentiation with annihilators in noisy environment. *Numerical Algorithms* **50** (2009) 439–467
14. Nöthen, C.: Beiträge zur rekonstruktion nicht direkt gemessener größen bei der silizium-einkristallzüchtung nach dem czochralski-verfahren. *Diplomarbeit, Technische Universität Dresden* (2007)
15. Fliess, M.: Analyse non standard du bruit. *C.R. Acad. Sci.* **I(342)** (2006) 797–802 Paris.
16. Fliess, M., Sira-Ramírez, H.: An algebraic framework for linear identification. *ESAIM Control Optim. Calc. Variat.* **9** (2003) 151–168
17. Kokosy, A., Defaux, F., Perruquetti, W.: Autonomous navigation of a nonholonomic mobile robot in a complex environment. In: *IEEE International Workshop on Safety, Security and Rescue Robotics, 2008. SSRR 2008, Sendai, Japan (October 2008)*
18. Sert, H.: Résolution de conflits pour la collaboration des entités mobiles. *Master's thesis, Université des Sciences et Technologies de Lille* (2009)
19. Kubera, Y., Mathieu, P., Picault, S.: Interaction-oriented agent simulations : From theory to implementation, *Patras Greece (July 2008)*