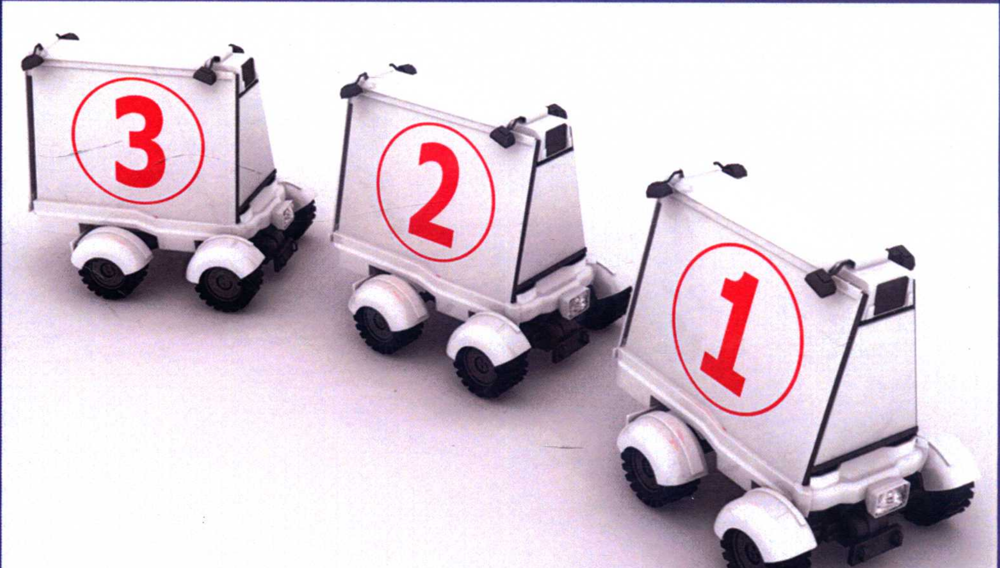
Autonomous Vehicle Navigation

From Behavioral to Hybrid Multi-Controller Architectures

Lounis Adouane



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Institut Pascal - Polytech
Clermont-Ferrand, France

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To my parents (Hayat and Larbi)
To my family
To my wife and our two angels (Tanirt and Yani)

Foreword

This manuscript will emphasize the investigated scientific research themes addressed throughout our developments since my incorporation in September 2006 at Polytech Clermont-Ferrand – Institut Pascal UMR CNRS 6602 (France) as an associate professor. Obviously, it will not detail exhaustively all the developments undertaken since 2006, but will only focus on the most important achievements/results while highlighting the innovative scientific methodology leading to the different outcomes.[1] The presented researches are focused on the way to **increase the autonomy** of mobile **mono robot** as well as **Multi-Robot Systems** (MRS) to **achieve complex tasks**. More precisely, the main objective is to emphasize the developed **generic control architectures** in order to enhance the **safety**, **flexibility** and the **reliability** of **autonomous navigations in complex environments** (e.g., cluttered, uncertain and/or dynamic). The proposed control architectures (**decision/action**) have been addressed through three closely related elements: **task modeling**; **planning** and finally the **control** aspect. Among the main ideas developed in this manuscript are those related to the potentiality of using **multi-controller architectures**.[2] Indeed, using this kind of control permits us to break the complexity of the overall tasks to be carried out and therefore allows a **bottom-up** development. This will imply the development of appropriate reliable elementary controllers (**obstacle avoidance**, **target reaching/tracking**, **formation maintaining**, etc.), but also the proposition of appropriate mechanisms to manage the interaction of these multi-controller architectures while ensuring the respect of different constraints and enhancing metrics/criteria linked to the safety, flexibility and reliability of the overall control.

Although the developed concepts/methods/architectures could be applied for different domains (such as service robotics or agriculture), the **transportation domain** remains the privileged target. Applications include the transportation of persons (private car or public transport) as well as merchandise transportation (in warehouses or ports for instance). The different proposals will be applied for simple robotic entities (like Khepera® robots modeled as unicycles) as much as for larger ones (like VIPALAB® vehicles modeled as tricycles). The theoretical aspect will take a part of the manuscript, but several simulations and experiments will be given to demonstrate the efficiency of the adopted approaches.

[1] The details could be shown in the referenced papers, supervised PhD thesis, project manuscripts, etc.

[2] Well-known initially in the literature as behavioral control architectures (cf. section 1.4, page 15).

Acknowledgments

This book would not have been possible without the help and support of my family members, many friends, students, and colleagues in the field. It would be impossible to list all of them here.

First of all, it is a great pleasure to acknowledge the people who have closely collaborated with me in the research contained in this book. A special acknowledgment goes to all the current and past PhD students who worked intensively with me during these last years; in alphabetical order, let me cite: Ahmed Benzerrouk, Suhyeon Gim, Bassem Hichri, Guillaume Lozenguez, Mehdi Mouad and José Miguel Vilca Ventura.

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Author Biography

Lounis Adouane is an associate professor since 2006 at the Institut Pascal–Polytech Clermont-Ferrand in France. He received an MS in 2001 from IRCCyN–ECN Nantes, where he worked on the control of legged mobile robotics. In 2005, he obtained a PhD in automatic control from FEMTO-ST laboratory–UFC Besançon. During his PhD studies he deeply investigated the field of multi-robot systems, especially those related to bottom-up and reactive control architectures. After that, he joined in 2005 Ampère laboratory–INSA Lyon and studied hybrid (continuous/discrete) control architectures applied to cooperative mobile robot arms. In 2014, he spent 6 months as a visiting professor in two robotics laboratories at Cranfield and Kingston universities (United Kingdom). Dr. Adouane's main research and teaching activities are linked to robotics, automatic control and computer science. His current research topics are related to both *autonomous navigation of mobile robots in complex environments* and *cooperative control architectures for multi-robot systems*. Since 2006, he has authored/coauthored more than 60 international references dealing mainly with the following keywords: autonomous mobile robots/vehicles; control of complex systems; multi-controller architectures; hybrid (continuous/discrete) and hybrid (reactive/cognitive) control architectures; Lyapunov-based synthesis and stability; obstacle avoidance (static and dynamic); limit-cycle approach; target reaching/tracking; cooperative multi-robot systems; navigation in formation (virtual structure, leader-follower); cooperative exploration task; cooperative transportation task; task allocation; auction coordination; kinematic constraints; constrained control; optimal planning; continuous curvature path; clothoids composition; velocity planning; waypoints generation; multi-criteria optimization; artificial intelligence (such as Markov decision process, multi-agent system, fuzzy logic, etc.); multi-robot/agent simulation.

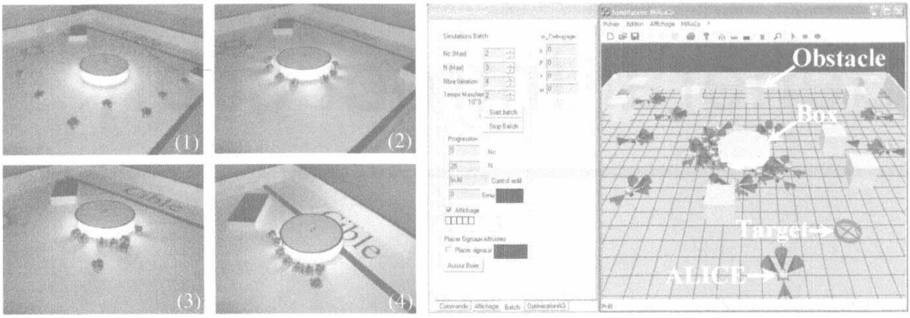
General Introduction

Everything should be made as simple
as possible, but not simpler.
Albert Einstein

GENESIS OF THE RESEARCH WORKS

During my PhD thesis [Adouane, 2005], achieved in the micro-robotics team at LAB (Labortaoire d'Automatique de Besançon, France), the research objective was to control a group of minimalist mobile robots, called ALICE [Caprari, 2003] (with a dimension of 2cm × 2cm × 2cm) to perform, among others, the CBPT[3] (Cooperative Box-Pushing Task, cf. Figure1(a)). The constraints imposed by the use of these minimalist structures as well as the nature of the achieved cooperative task, which aims to control the navigation and the interaction of a swarm of mobile mini-robots, led us to develop several mechanisms/ideas to deal with this highly dynamic system. Indeed, the interaction of a swarm of mini-robots in the immediate vicinity of the box to push is very high and needs to be addressed without neither high cognition/planning (cf. section 1.3.2, page 11) aspects nor centralized control (cf. section 1.3.3, page 13) [Adouane, 2005]. Therefore, fully reactive and decentralized behavioral control architectures have been proposed to take into account the different constraints linked to the control of this highly dynamic swarm of robots. More precisely, a Hierarchical Action Selection Process (HASP) was proposed which allows us to coordinate with stimuli-response mechanism, the activity of the elementary behaviors/controllers composing the proposed architectures. The HASP has been, thereafter, improved by integrating mechanisms of fusion of actions and a mechanism of dynamical gains adaptation [Adouane and Le Fort-Piat, 2005], to obtain the Hybrid-HASP [Adouane and Le-Fort-Piat, 2004]. This last process of coordination is more flexible, intuitive and scalable than the basic HASP, and it has been proved to be strongly adapted to control highly dynamic multi-robot systems. This process allows us, at the level of the robot, to coordinate in a hierarchical and flexible manner the activity of a set of elementary controllers (behaviors), and at the level of the

[3] In the field of swarm robotics, the CBPT is among the privileged complex task, in order to study the relevance of reactive and decentralized control architectures [Parker, 1999], [Yamada and Saito, 2001], [Ahmadabadi and Nakano, 2001], [Baldassarre et al., 2003], [Muñoz, 2003].



(a) (b)

FIGURE 1 (See color insert) (a) Experimentation of the proposed control architecture with 8 mini-robots ALICE pushing a cylindrical object to a final assigned area; (b) *MiRoCo* simulator.

group of robots, the coordination of the robot's interactions for reaching global objectives and desired mass effects. Otherwise, specific low-level communication, called altruistic behaviors, reproducing the simple interaction (attraction/repulsion) of individuals constituting societies of insects [Bonabeau et al., 1999] were integrated into the proposed control architectures in order to improve the efficiency of robots' coordination [Adouane, 2005].

The validation of the proposed mechanisms of control was made through actual experiments (cf. Figure 1(a)) but more intensively according to statistical studies done on a large number of data obtained thanks to MiRoCo[4] simulator (cf. Figure 1(b)). The performed statistical studies show, among others, the existence of an optimal number of robots to achieve the CBPT and underline the importance of implicit communications induced by the altruistic behaviors [Adouane and Le-Fort-Piat, 2004]. It is important to emphasize that with this kind of approach, followed during the PhD thesis [Adouane, 2005], there is no other analytic technique to prove the actual reliability of the proposed control/strategy. The step consisting of using statistical study in order to prove the efficiency of the proposals is in general mandatory in these kinds of approaches [Bonabeau et al., 1999].

Although if the obtained results during the PhD are efficient to control a highly dynamic multi-robot system, the lack of accurate analytic analysis reduces drastically the scope of possible use of the already proposed control architectures, especially if the targeted tasks imply close interaction between the robots and humans (e.g., transportation or service robotics tasks) or industrial applications (e.g., automatic warehouse management/manipulation/transportation by a group of mobile robots). It has been decided thereafter to improve the features of these multi-controller architec-

[4] *MiRoCo* (for Mini Robotique Collective, cf. ref [Adouane, 2005, chapter 7]) is a reliable and 3D simulator dedicated in general to cooperative mobile robotics. *MiRoCo* gives a very good approximation of the different physical constraints linked to the interaction of the robots between them and with their environment.

tures, which still have large potentialities (cf. section 1.4, page 15), while permitting analytic and accurate stability/reliability analysis. This could be reached while introducing more automatic control theory and while better mastering the elementary developed controllers and their interactions, in order to actually attest to the reliability of the overall control architecture.

IMPORTANT INVESTIGATED DOMAINS AND MANUSCRIPT STRUCTURE

The main ideas developed in this book are related to the potentialities of using multi-controller architectures[5] to tend ineluctably toward fully autonomous robot navigation even in highly dynamic and cluttered environments. Indeed, using this kind of control permits us to break up the complexity of the overall tasks to be carried out and therefore allows a bottom-up development. It will be shown in this manuscript how the proposed techniques, concepts and methodologies can address different complex mobile robot tasks. This will imply the development of appropriate reliable elementary controllers (obstacle avoidance, target reaching, formation maintaining, etc.), but also the proposition of appropriate mechanisms to manage the interaction of these multi-controller architectures while ensuring the respect of different constraints and enhancing metrics/criteria linked to the safety, flexibility and reliability of the overall proposed control architectures.

Furthermore, in order to enhance the autonomy of mobile robots, several investigated works will be presented in this book, dealing with: modeling of sub-tasks; reliable obstacle avoidance; appropriate stable control laws for target reaching/tracking; short-term and long-term trajectories/waypoints planning; navigation through sequential waypoints; cooperative control and interaction of a group of mobile robots. More precisely, this manuscript is organized into 6 chapters:

- **Chapter 1** introduces briefly the domain of autonomous mobile robotics while highlighting its main achievements/challenges. It will also emphasize also the main concepts/paradigms/motivations/definitions used throughout the text. The objective is to clarify them in order to simplify the different explanations and developments used in the rest of the book. Among them let us cite: the boundary limit between planning and control; interest and most challenging aspects linked to multi-controller architectures; the notion of reactive/cognitive, centralized/decentralized,[6] flexibility, stability and reliability of the developed control architectures.

- **Chapter 2** is devoted to an important navigation function corresponding to obstacle avoidance controller. Thereby, a safe and flexible obstacle avoidance controller, based on Limit-Cycles, for autonomous navigation in cluttered environments will be presented. This chapter will also introduce important ele-

[5] Well-known initially in the literature as behavioral control architectures (cf. section 1.4, page 15).

[6] It is to be noted that in literature, cognitive and decentralized are, respectively, also called deliberative and distributed control architectures.

mentary building blocks characterizing the different multi-controller architectures developed throughout this manuscript. A brief description of the methodology to detect and to characterize obstacles in the environment will also be presented.

- **Chapter 3** focuses on the proposed Hybrid$_{CD}$ (Continuous/Discrete) multi-controller architectures for online mobile robot navigation in cluttered environments. The developed stable control laws for target reaching/tracking will be presented. An important part of this chapter emphasizes how to obtain stable and smooth switching between the different elementary controllers composing the proposed architectures.

- **Chapter 4** focuses on the proposed Hybrid$_{RC}$ (Reactive/Cognitive) control architecture permitting us to simply manage the activation of reactive and cognitive navigation according to the environment context (uncertain or not, dynamic or not, etc.). This architecture is based among others on the use of the homogeneous set-points definition coupled with appropriate control law shared by all the controllers. This chapter will pay attention to the proposed planning methods, mainly the one based on PELC for car-like robots.

- **Chapter 5** emphasizes the fact that it is not absolutely mandatory (as commonly admitted and broadly used in the literature) to have a predetermined trajectory to be followed by a robot to perform reliable and safe navigation in an urban and/or cluttered environment. In this chapter, a new definition of the navigation task, using only discrete waypoints in the environment, will be presented and applied for an urban electric vehicle. This approach permits us to reduce the computational costs and leads to even more flexible navigation with respect to traditional approaches (mainly if the environment is cluttered and/or dynamic).

- **Chapter 6** is dedicated to the control of multi-robot systems. The focus will be on dynamic multi-robot navigation in formation and on the cooperative strategies to perform safe, reliable and flexible navigation. An overview of other addressed multi-robot tasks (such as "co-manipulation and transportation" and "exploration under uncertainty") will also be briefly presented.

A general conclusion and prospects are given at the end of the book.

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