An Adaptive Multi-Controller Architecture for Mobile Robot Navigation

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Abstract. This paper proposes a hybrid control architecture dedicated to the navigation of autonomous mobile robots in presence of obstacles. The proposed control structure is flexible, adaptive and takes into account the different possible interactions between the multitude of controllers composing the architecture of control. This is enabled by the use of stable elementary controllers and to specific mechanisms of coordination and adaptation which guaranties the stability of the overall architecture.

Keywords. Mobile robot navigation, Hybrid architecture of control, Adaptive systems, Lyapunov controller synthesis.

Introduction

The navigation of autonomous mobile robots in a cluttered and open environment is a fundamental problem that has received a large amount of attention. A part of literature in this domain considers that the robot is fully actuated with no control bounds and focuses their contribution on path planning. Voronoï diagrams and visibility graphs [1] or navigation functions [2] are among these roadmap based methods. However, the other part of the literature considers that to control a robot with safety, flexibility and reliability, it is essential to accurately take into account: robot's structural constraints (e.g., nonholonomy); avoiding command discontinuities and jerking set points, etc. Nevertheless, even in this method, there are two schools of thoughts, the one which uses the notion of planning and re-planning to reach the target e.g., [3] and [4] and those which are more reactive (without planning) like in [5] or [6]. Our proposed architecture of control/management is linked to this last approach.

The architecture that will be able to guaranties multi-objective criteria can be elaborated with modular and bottom-up manner as introduced in [7] and so called behavioral architectures [8]. They are based on the concept that a robot can achieve a global complex task while using only the coordination of several elementary behaviors. It is considered in a lot of studies (the proposed paper is among them), the investigation of the potentialities of the hybrid systems controllers [9] which provide a formal framework to demonstrate the robustness and the stability of such architecture. Thus, this formalism permits a rigorous automatic's control analysis on the performances of the architecture of control [10].

The rest of the paper is organized as follows. Section 1 gives the specificities of the proposed control architecture. In section 2, the architecture of control is applied to the task of navigation in presence of obstacles. Details of the proposed and implemented elementary controllers are given also in this last section. Section 3 is devoted to the description and analysis of the simulation results. This paper ends with some conclusions and further works.

1. Control architecture

The proposed structure of control (cf. figure. 1) has an objective to manage the interactions between different elementary controllers while guaranteing the stability of the overall control. It will also obtain a suppleness of the control command when the switch between controllers occurs. It will permit for example to an autonomous applications of travelers transportation [11] to have more comfortable displacements of the passengers. The specific blocks composing this control are detailed below.

1.1. Hierarchical action selection

The activation of one controller in favor of another is achieved here completely with a hierarchical manner like the principle of the subsumption proposed by Brooks in [7].

1.2. Controllers

Every controller is characterized by a stable nominal law which is represented by the function: $F_i(P_i, t) = \eta_i(P_i, t)$ with: P_i perceptions useful to the controller "i". Otherwise, in order to avoid among others, the important jump of commands at the time of the switch between controllers (for example here from the controller "j" toward the controller "i" at the instant t_0), an adaptation of the nominal law is proposed:

$$F_i(P_i, t) = \eta_i(P_i, t) + G_i(t) \tag{1}$$

with: $G_i(t)$ a monotonous function that tends to zero at the end of a certain time"T" and

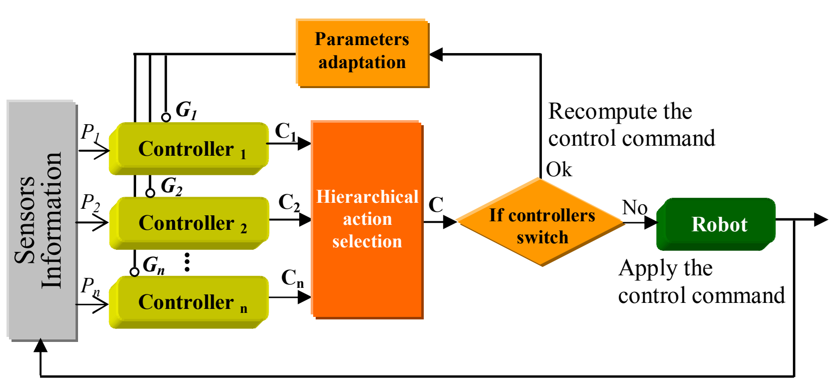


Figure 1. Hybrid control architecture for mobiles robots navigation

$$G_i(t_0) = F_j(P_j, t_0 - \Delta t) - \eta_i(P_i, t_0) \quad (2)$$

where: Δt represents the sampling time between two control commands.

The definition of $G_i(t)$ allows us to guarantee that the law of control (cf. equation. 1) tends toward the nominal control law after a certain time "T", i.e., $F_i(P_i,\ t_0 + T) = \eta_i(P_i,\ t_0 + T)$.

The function of adaptation $G_i(t)$ is updated by "the parameters adaptation block (see section below)" every time the switch of control toward the "i" controller occurs. The main constraint emanating from this structure of control is to guarantee the stability of the updated control law (cf. equation. 1) during the period where $G_i(t)$ is not zero.

1.3. Parameters adaptation

This block has as input the "conditional block" (cf. figure. 1) that verifies if the controller which should be active in the current instant "t" is different than the one active at the instant "t-Δt". If it is the case then it must update its function of adaptation (cf. equation. 2).

2. Navigation in presence of obstacles

The investigated task that is used to illustrate the application of the proposed control structure corresponds to the navigation of an unicycle robot in presence of obstacles (cf. figure. 2). The controlled position of the unicycle can be off-center as it is given in figure 2 by (l_x, l_y).

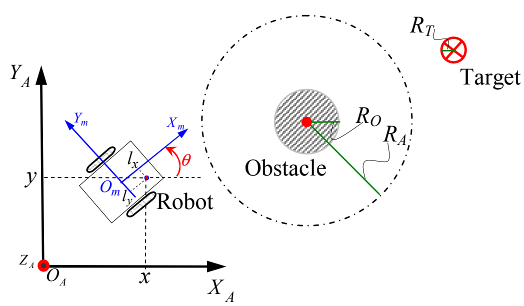


Figure 2. Mobile robot and the task parameters for the navigation in presence of obstacles

One presents below the proposed elementary controllers to achieve the desired navigation task.

2.1. Attraction to the objective controller

This controller guides the robot toward the target to reach. Classical techniques of linear systems stabilization can be used here to asymptotically stabilize the error $e_x = x - x_T$ and $e_y = y - y_T$ to zero, where: (x, y) corresponds to the position of the robot and (x_T, y_T) corresponds to the position of the target (cf. figure. 2). We use a simple proportional command which is given by:

$$\begin{pmatrix} v \\ w \end{pmatrix} = -K \begin{pmatrix} \cos\theta & -l_x \sin\theta \\ \sin\theta & l_x \cos\theta \end{pmatrix}^{-1} e = -K \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta/l_x & \cos\theta/l_x \end{pmatrix} \begin{pmatrix} e_x \\ e_y \end{pmatrix} \tag{3}$$

With: v and w are respectively linear and angular speed controls; $K > 0$; $l_x \neq 0$ (cf. figure. 2). To guaranty the right transition between controllers as described in sections (1.2) and (1.3), the modification to the above command becomes:

$$\begin{pmatrix} v \\ w \end{pmatrix} = -K \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta/l_x & \cos\theta/l_x \end{pmatrix} \begin{pmatrix} e_x \\ e_y \end{pmatrix} + \begin{pmatrix} G_{A\_v}(t) \\ G_{A\_w}(t) \end{pmatrix} \tag{4}$$

While using the following Lyapunov function $V_1 = \frac{1}{2}d^2$ (with $d = \sqrt{e_x^2 + e_y^2}$), we therefore obtain $\dot{V}_1 = d\dot{d}$.

To guaranty that the proposed controller is asymptotically stable we must have $\dot{V}_1 < 0$. Therefore, after some simplification we can deduce that:

$$K > \frac{-(G_{A\_v}(t)e_x + G_{A\_w}(t)e_y)}{e_x^2 + e_y^2} \tag{5}$$

Where $G_{A\_v}(t)$ and $G_{A\_w}(t)$ functions must be chosen with respect to the constraints given in sections (1.2) and (1.3) and to the fact that they decrease more quickly to zero than d^2 (to have bounded K).

2.2. Obstacle avoiding controller

To implement this controller, the method of the limit-cycle was used [12]. The control law proposed to follow these trajectories (which tends toward a circle of R_A radius (cf. figure. 2)) is a control of orientation. The robot is controlled in relation to the center of its axle. The desired robot orientation θ_d is given by $\theta_d = \arctan(\frac{\dot{y}}{\dot{x}})$ where ($\dot{x}$ and $\dot{y}$) are given by a differential equation describing the limit-cycle [12], and the error by $\theta_e = \theta_d - \theta$.

One can control the robot to move to the desired orientation by using the following control law: $w = \dot{\theta}_d + K_p\theta_e + G_O(t)$, where $K_p > 0$ and $G_O(t)$ the function which guaranties the right transition between controllers (cf. sections (1.2) and (1.3)). It is noted that the nominal linear speed of the robot v for this controller is considered as a constant.

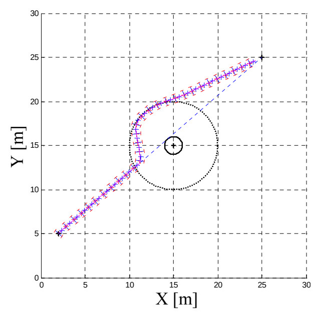
The derivative of θ_e is given by $\dot{\theta}_e = -K_p\theta_e - G_O(t)$. One takes the following Lyapunov function $V_2 = \frac{1}{2}\theta_e^2$. Therefore, $\dot{V}_2 = \theta_e\dot{\theta}_e = -K_p\theta_e^2 - G_O(t)\theta_e$. To guaranty that the proposed controller is asymptotically stable we must have $\dot{V}_2 < 0$, so:

$$K_p > -\frac{G_O(t)}{\theta_e} \tag{6}$$

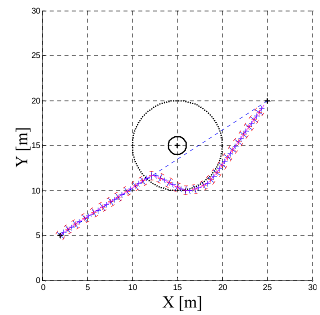
Where $G_O(t)$ function is chosen with respect to the constraints given in section 1.3 and the fact that it decreases more quickly to zero than θ_e.

3. Simulation results

Before giving comments on the achieved simulation, it must be noted that $G_{A\_v}(t)$, $G_{A\_w}(t)$ and $G_O(t)$ were implemented using decreasing linear functions. Figures 3(a) and 3(b) show respectively the clockwise and counter-clockwise obstacle avoiding when the proposed control architecture is used.



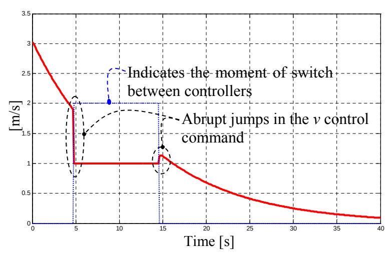
(a) Clockwise skirting



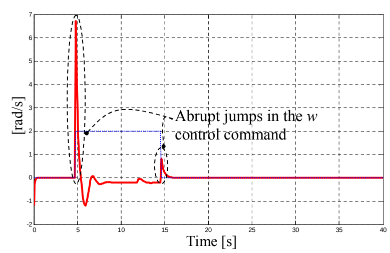
(b) Counter-clockwise skirting

Figure 3. Application of the proposed control architecture for different target position

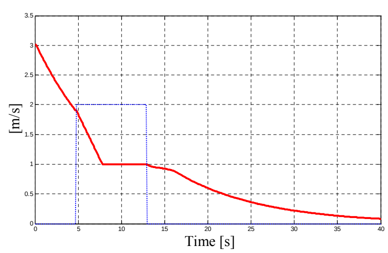
Figure 4 shows the effect of the use of adaptive parameters mechanism on v and w control commands (here the obstacle is clockwise skirting). v and w control becomes thus less abrupt and smoother when the switch between controllers occurs.



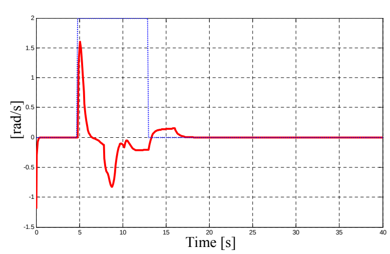
(a) v control without adaptive control



(b) w control without adaptive control



(c) v control with adaptive control



(d) w control with adaptive control

Figure 4. Effect of the adaptive parameters mechanism on v and w control commands

Figure 5 shows that the overall proposed structure of control is stable, and here the Lyapunov function attributed to each controller $V_i|_{i=1..2}$ decreases always asymptotically to the equilibrium point.

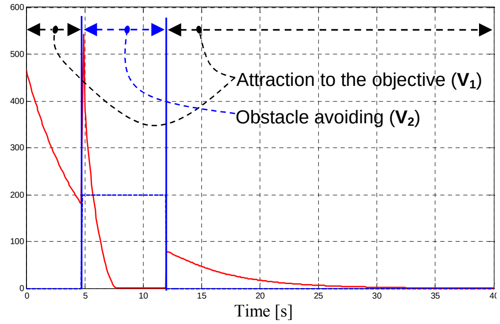


Figure 5. Evolution of V_1 and V_2 Lyapunov functions

4. Conclusion and future works

In this paper, an adaptive multi-controller architecture of control is proposed and applied on the task of mobile robot navigation in presence of obstacles. The proposed adaptive mechanism permits to achieve the switch between controllers while guaranteeing the smoothness of the control commands and the stability of the overall system. Future works will test first the proposed architecture of control on the CyCab vehicle [11]. The second step is to apply the proposed structure of control on more complex tasks like navigation in highly dynamical environment.

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