Eduardo Freire

On the Control of a Mobile Robot: A Comparative Study Regarding a New Approach and Two Well-Known Approaches
A Mobile Robot Prototype with Multiple Sensing Levels Included in an Agent-Based Control System

On the Control of a Mobile Robot: A Comparative Study Regarding a New Approach and Two Well-Known Approaches

Eduardo O. Freire [1,2], Ricardo Carelli [3], Vicente Mut [3], Humberto Secchi [3], Teodiano F. Bastos-Filho [2], Mário Sarcinelli-Filho [2]

[1] Tiradentes University/CCFT
Av. Murilo Dantas, 300 49030-270 Aracaju/SE Brazil
Fax: +55 79 218 2200
E-mail: freire@ele.ufes.br

[2] Department of Electrical Engineering
Federal University of Espirito Santo
Av. Fernando Ferrari, s/n 29060-900 Vitória/ES Brazil
Voice: +55 27 335 2684 Fax: +55 27 335 2737
E-mail: mario.sarcinelli@ele.ufes.br

[3] Institute of Automatics
National University of San Juan
Av. San Martin Oeste 1109 5400 San Juan, Argentina
Voice: +54 64 213303 Fax: +54 64 213672
E-mail: rcarelli@inaut.unsj.edu.ar

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ABSTRACT

This paper deals with three distinct control approaches used to guide a mobile robot during the execution of a certain task. They are the fusion of control signals approach, proposed by the same authors of this paper, and the well-known behavior-based and impedance-based approaches. The corresponding three control systems are implemented, and the results obtained when they are used to guide the robot from an initial position to a final position are reported and analyzed. These points are in two parallel corridors that are connected one to another through a transversal smaller corridor. Fixed or mobile obstacles can appear in the robot path, and the robot should avoid them. As a conclusion of this comparative study, the fusion of control signals approach is pointed out as the control approach showing the better performance.

1 Introduction

Nowadays there are three main approaches to solve the problem of controlling the navigation of a mobile robot. They are the classical approach, the behavior-based approach and the hybrid approach [1] [2] [3] [4] [5] [6].

The classical (or traditional) approach decomposes the control system in an ordinate sequence of functional components [1]. In these control architectures, the sensorial data are initially collected from all sensors available in the robot. Problems with noise and conflicting data are solved in such a way that it becomes possible to build a consistent model of the "real world" that surrounds the robot. Such model must include information about the dimensions, shape, position and orientation of all objects in the robot workspace [1]. Most times, part of the model or map of the world is programmed in the memory of the robot before it starts operating, thus making its operation limited to the environment the robot "knows". In this case, the sensors are used only to locate the point in the map in which the robot is [2] [3] [4]. Once the model of the "world" where the robot navigates is available, it starts using this model to plan sequences of actions with the final goal of executing a specific task. Finally, this plan is executed by sending the suitable commands to the actuators.

By their turn, the behavior-based control architectures follow a quite different procedure. The behaviors are layers of a control system that work in parallel whenever they are fired by the suitable sensors [1] [4] [5] [6]. The problem of conflicting sensorial data of the classical control architectures is now replaced by a problem of conflicting behaviors. Thus, the integration is now executed in the output of the behaviors, instead of in the output of the sensors (behavior integration). An arbitration scheme based on priorities is used to determine which behavior is dominant in each situation. In these architectures the idea of a behavior calling another behavior, like a subroutine, disappears. In opposition to this idea, all behaviors are executed in parallel, with higher-level behaviors having the power of temporarily suppressing the output of the lower-level behaviors. When the higher-level behaviors are not active anymore, for a given sensorial condition, they stop suppressing the lower-level behaviors, which resume the control of the robot. This way, such control architectures are inherently parallel, and the sensors interact directly with all control layers or behaviors. By their turn, each behavior interacts directly with the actuators. In the behavior-based control architectures, in addition, there are no unified data structures or models of the "geometric world".

The hybrid control architectures, finally, were developed to solve the inherent limitations of both control architectures previously mentioned, by adopting a combination of models coherent and well-defined [4]. The hybrid architectures integrate low-level and high-level considerations in a coherent structure: a reactive system (memoryless behaviors) executes the low-level tasks, and a planning system defines the higher-level tasks. Such control architectures separate the whole control system in two or more independent parts that communicate among themselves. The low-level procedures are responsible for the robot integrity in each instant, while the planning system is in charge of selecting the actions to be executed in the future.

In this paper, it is presented a comparative study of the classical control architectures and the behavior-based control architectures. Both are compared to a new control approach presented in [7], which is called *fusion of control signals*, which is briefly described in the sequence.

In order to check how the three control approaches here addressed perform, an experiment consisting in guiding a wheeled mobile robot from an origin point to a destination point avoiding any obstacle in its path is run. The complexity of this task is associated to the position of the origin and destination points. They are located in two parallel corridors that are interconnected by a smaller transversal corridor, in a geometric array that resembles the capital letter H when laid down. The results of using the three distinct control approaches are here reported and the performances of them are compared.

To cover the topics above mentioned, the paper is organized as follows: Section 2 describes the fusion of control signals approach, recently proposed by the same authors. Sections 3 and 4, by their turn, describe the behavior-based control architecture implemented and the classical impedance control algorithm, respectively, which are compared to the fusion of control signals approach in the sequence of the paper. Section 5 describes an experiment implemented in order to compare the performance of the different control systems adopted, and finally, Section 6 presents the conclusions obtained from the comparative study regarding the three control approaches.

2 The Fusion of Control Signals

In many applications, the sensorial data refer to distinct aspects of the robot workspace. This makes inconvenient to apply sensor fusion, because it is difficult to translate all the data to a unique data structure, as the use of such technique requires [11].

On the other hand, classical control algorithms, which can have the advantage of guaranteed stability, can result in too complex control equations, depending on the complexity of the task to be executed. This would demand too powerful hardware resources, which could become prohibitive.

When using a behavior-based control approach one can have various distinct behaviors, each one corresponding to a distinct controller, which deals with different environmental conditions. For example, if there is a corridor navigate along it, if there is an obstacle avoid it, and if none of the previous conditions takes place go to the destination point. This way, one can solve complex problems using a group of simple controllers. However, a new problem arises when using behavior-based control algorithms: it is normally used to switch from one to other controller, thus generating undesired abrupt variations in the acceleration of the motors driving the robot.

Some authors tried to minimize this problem introducing a progressive variation from the instantaneous speed to the new desired setup value [8]. However, this empirical method is deficient for not considering the possibility of a second abrupt variation after starting the progressive variation.

The fusion of control signals approach, by its turn, allows to get the advantages of the behavior-based control architectures, besides allowing to get a softly robot navigation, as it will be shown below. For now, consider Figure 1, where it is shown the general control system structure adopted for implementing the fusion of control signals approach.

As it can be seen from the figure, each one of the three controllers used generates its own output control signal based on the sensorial information available. The figure also shows that some sensorial data are fused before being delivered to the respective controller, what is done in order to get information that is more precise. In the sequence, a decentralized information filter is used to fuse the output signals of the distinct controllers and to generate a final control signal that gets the effective control of the robot [7].

Each controller of Figure 1 has a covariance value associated to it, which varies according to some criteria based on the information coming from the sensorial system. As an example, if an obstacle is close to the robot the minimal distance obtained through the ultrasonic sensing system is small, which results in a covariance value associated to the controller responsible for avoiding obstacles that is also small. Thus, the output signal of this controller is more important in the composition of the control signal resulting from the fusion. This way, the navigation system is able to select, in each instant, which controller is more meaningful, based on the environment surrounding the robot in that instant, while considering all the other controllers. Thus, softer transitions in the linear and angular speeds of the robot are obtained, which results in a safer navigation.

A detailed description of the three controllers included in Figure 1 is out of the scope of this work. For a further discussion of this topic, the reader should refer to [9] and [10], for example.

3 The Behavior-Based Controller

When implementing the behavior-based control system used in this work, the same controllers included in Figure 1 were used. This means that each of those controllers became a behavior, and instead of fusing the controller outputs it was used an arbitration scheme based on a priority associated to each control output. This way, in each

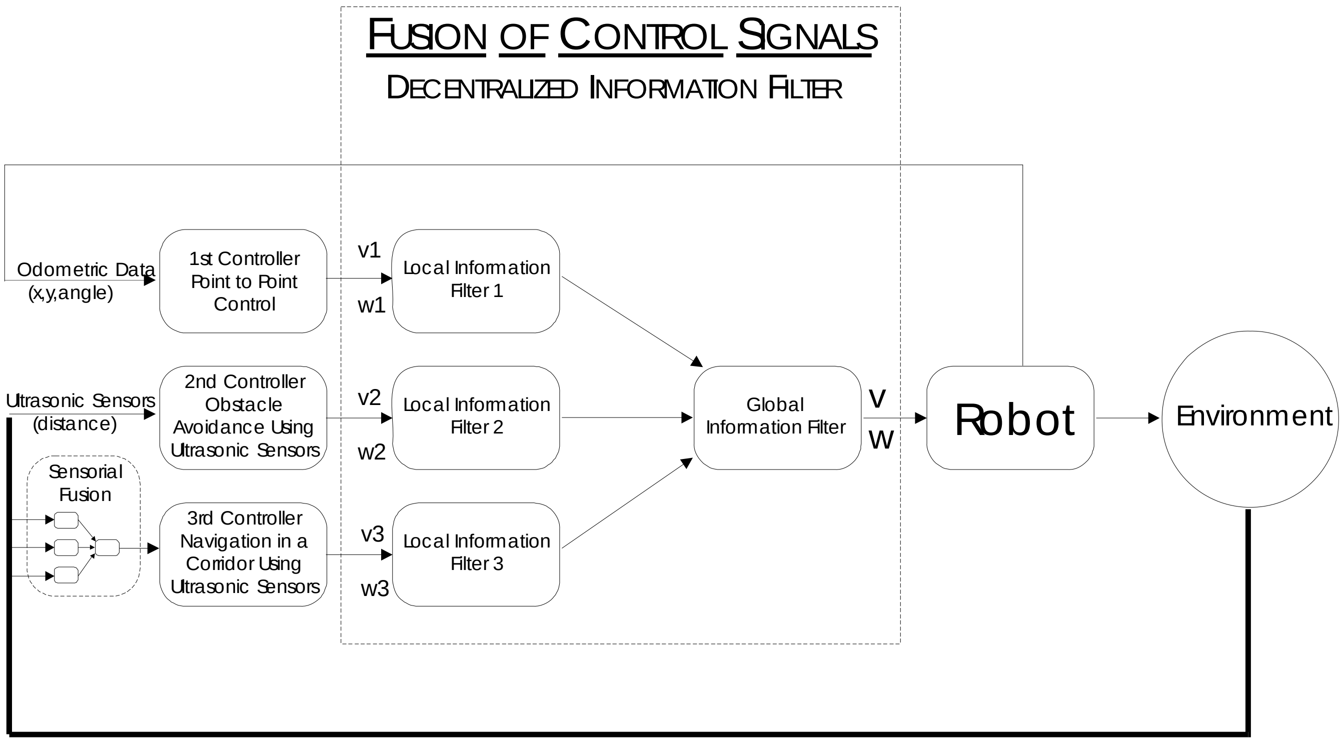

Figure 1: The structure used in the fusion of control signals.

moment the control of the robot actuators is assumed by one of the controllers, what means one of the behaviors. Then, the behavior-based control system implemented is composed by the following behaviors: point to point navigation, obstacle avoidance and navigation in corridors.

In order to arbitrate which behavior should have the control of the actuators in each instant, it is used the covariance value associated to each one. These values are the same used in the fusion procedure described in Section 2. In this sense, the covariance values are here used as an estimate of the degree of priority of the controller to which it is associated. This evaluation is dynamically determined with basis in the measurements provided by the sensing system of the robot. The idea is that in each instant the controller of greatest priority is the one that possesses the lowest covariance value associated to it. This way, it is natural to use the covariance values to arbitrate which behavior should get the control of the actuators in each instant. Then, the behavior (or controller) with the lowest covariance value will control the robot until another controller whose covariance value has lowered enough to give it the control of the robot.

The control system thus implemented was used to control the robot in order to perform the same task performed when using the fusion of control signals approach, in order to compare the performance of both systems.

4 Impedance-Based Controller

As a classical control approach, it is used a point to point controller slightly modified in order to incorporate the ability to avoid obstacles. It was used an algorithm based on fictitious repulsive forces, in which objects detected close to the robot generate repulsive forces inversely proportional to the distance from the robot to the obstacle. It was defined a circular area surrounding the robot, called repulsion zone, which corresponds to distances between the ultrasonic sensors and the obstacles below 0,5 m. Any obstacle detected inside this region generates a repulsive force. Obstacles detected outside this region do not generate repulsive forces. To define the best path to allow the robot to avoid an obstacle, the resultant of all repulsive forces is calculated. Based on the resulting repulsive force, it is calculated a modified position of the destination point, thus allowing the point to point controller to drive the robot such that it avoids the obstacle. As soon as the repulsive forces disappear, the robot resumes the original destination point. A detailed analysis of this algorithm is out of the scope of this work, and can be addressed in [9].

5 The Experiment Realized

In order to allow comparing the three control approaches briefly discussed in Sections 2, 3 and 4, it was used a wheeled mobile robot Pioneer II DX, from ActivMedia. Its sensing apparatus includes sixteen ultrasound transducers, six in the front part, six in the rear part and four in the side parts (two in each side), besides a CCD camera (see Figure 2). The robot is controlled via a radio link from an external workstation, for not having onboard computer. It also includes a radio frequency link for image transmission, for the image processing is also performed outside the robot. In this work, however, only ten ultrasonic transducers are used, concerning the three controllers included in Figure 1. They are the six frontal transducers and the four side transducers (two in each side). The reason for not using the rear ultrasonic transducers is that the robot only moves ahead, so that the rear ultrasonic transducers are less important for detecting obstacles. In addition, the four side ultrasonic transducers are meaningful for detecting the walls in both sides of a corridor.

Figure 2: The mobile robot Pioneer 2 DX.

The standard experiment for comparing the performance of the three control approaches here addressed consists on guiding the robot from an origin point defined as (0 m, 0 m) to a destination point defined as (15 m, 5 m). During its navigation in a corridor of 1,40 m wide (in the Institute of Automatics, National University of San Juan, in San Juan, Argentina) the robot deviates from a fixed obstacle in the middle of the corridor (see Figure 3). Some time after it turns ninety degrees to the left and some time after it turns ninety degrees to the right. After this maneuver, it continues navigating through a corridor towards the destination point. The entire path is then composed by three corridors with obstacles included.

5.1 The Results Obtained Using the Fusion of Control Signals

Figure 3 shows the entire path the robot went through when the fusion of control signals is adopted as the control approach. Figure 4 shows the linear and angular speeds along the trajectory. It is important to mention that in addition to the results reported in Figures 3 and 4, the experiment was run about ten times, and the robot always accomplished the task assigned to it, in spite of its high complexity.

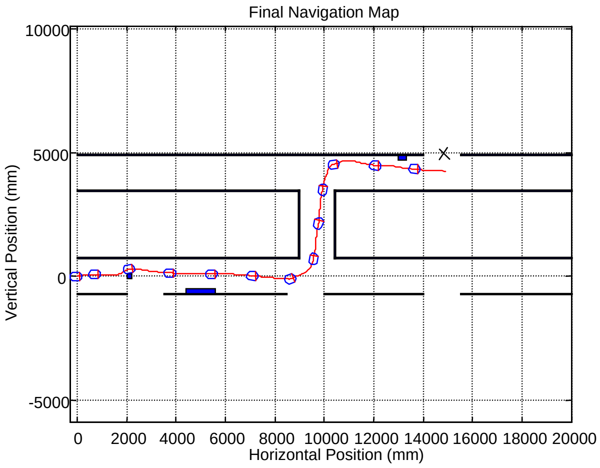

Figure 3: The trajectory followed by the robot (fusion of control signals). X defines the destination point.

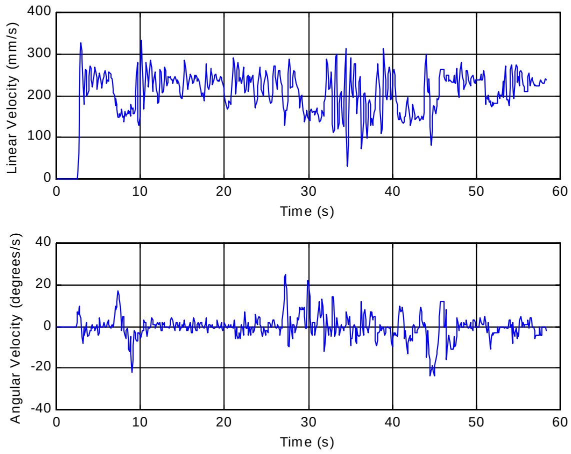

Figure 4: Instantaneous linear and angular speeds (fusion of control signals).

As one can check in Figure 3, the robot was able to go from the initial position to the final position, located in a distinct corridor. During its navigation, it was also demanded to turn to the left and to the right in corners and to avoid fixed or mobile obstacles (like persons walking in the corridors). Notice that mobile obstacles could not be represented in Figure 3, but various situations like that occurred during the various runs of the experiment. In all those situations, the robot was able to avoid colliding with the obstacles. Figure 3 includes a fixed obstacle represented by the small black square in the middle of the first corridor right after the origin. During all runs of the experiment, the robot was able to avoid it, although having a very small area for maneuvering. In the case of absence of obstacles, the robot remains approximately in the middle of the corridor, at a linear speed of 25 cm/s, which is relatively high for the robot used. Regarding the final position the robot reaches, one can observe from Figure 3 that it is not exactly the desired position, which is due to odometric errors.

5.2 The Results Obtained Using the Behavior-Based Control System

Figure 5 shows the path followed by the robot when using the behavior-based control approach implemented, while Figure 6 shows the instantaneous linear and angular speeds along the robot trajectory.

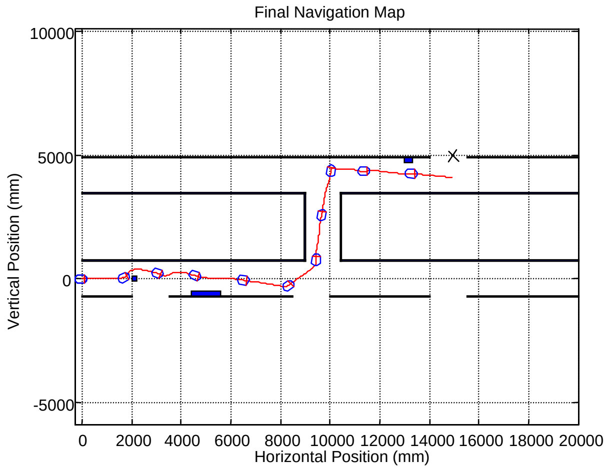

Figure 5: The trajectory followed by the robot (behavior-based control). X defines the destination point.

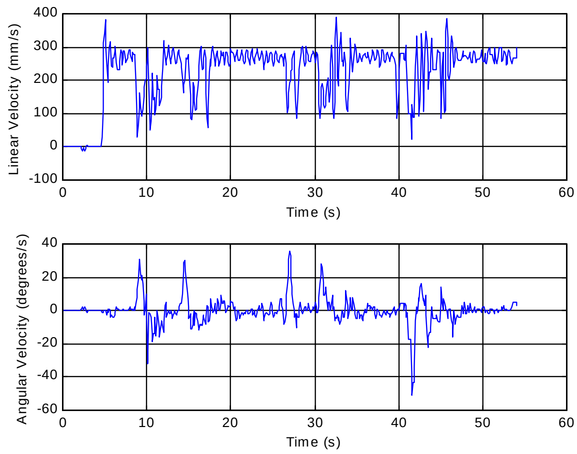

Figure 6: Instantaneous linear and angular speeds (behavior-based control).

As it is shown in Figure 5, the behavior-based control approach is also able to guide the robot to execute the same task. However, it is possible to check that in some points along the trajectory the motors driving the robot suffer abrupt variations in the acceleration. This can be checked by observing Figure 6, and is because the switching from one to other behavior is abrupt. It is also important to stress that once more the experiment was run many times, with the robot reaching the final position all times, although Figures 5 and 6 report just one of them.

The abrupt variations in the motors acceleration may cause not only their breakdown (if too frequent) after long time, but also to increase the odometric errors. In addition, it is also possible that the robot become unstable in some way. Indeed, during some runs of the experiment, when the robot turned right in the last corner, the wall at its right side was detected as an obstacle. This made it to turn to the left in order to avoid the obstacle. At this moment, it detected the wall at its left side as an obstacle, and then turned to the right again. These turning movements were repeated many times, keeping the robot much time in this cycle up to take the right decision. In the experiment run reported in Figures 5 and 6, however, this problem did not occur, but it is possible to notice that the robot executed abrupt turns and presented abrupt variations in the linear speed.

5.3 The Results Obtained Using the Impedance-Based Controller

This algorithm was not able to guide the robot during the experiment, even after many attempts. The main problem was the small space available for executing evasive maneuvering when the robot detected the obstacle in the middle of the first corridor. In this case, the robot detected the obstacle and the wall inside the repulsion zone established, which generated a resultant repulsive force that did not allow him to take the right direction. The solution, in this case, would be to diminish the radius of the repulsion zone, but when this was done the robot became unable to detect obstacles before colliding to them.

6 Conclusion

According to the experiment reported in this paper, it is verified that the fusion-of-control-signals control approach allows a safer and softer navigation of the mobile robot, compared to the behavior-based control approach or the impedance-based control approach. This last one, including, was unable to guide the robot in the execution of the task proposed.

The behavior-based control system, in spite of guiding the robot to the destination point as proposed, exhibited abrupt variations in the acceleration of the motors during the navigation of the robot. By its turn, the classical control algorithm based on impedance was not able to assure the execution of the whole task.

It can also be checked that when using the behavior-based control approach the whole task was executed in about 10% less time (see Figure 6), when compared to the fusion of control signals approach (Figure 4). This occurs because the controller responsible for navigating in a corridor is active most time, and it has the higher linear speed associated to it. In opposition, the final linear speed resulting from the fusion of the linear speeds associated to each controller in Figure 1 is always lower than the linear speed corresponding to the navigation in a corridor. This way, for the fusion of control signals approach the average linear speed is lower, thus resulting in a greater time to execute the same task.

It is also possible to verify that the fusion of control signals is able to guide the robot to a final point that is closer to the desired one (Figure 3), when compared to the behavior-based control approach (Figure 5). This happened because when using the fusion of control signals approach the variations in the motor acceleration are not abrupt, for the absence of controller switching. As aforementioned, these abrupt variations in the acceleration cause bigger odometric errors, what can be checked comparing Figures 3 and 5.

Finally, considering all the aspects here mentioned, one can conclude that for this task the control approach exhibiting better performance is the recently proposed fusion of control signals approach.

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