Robôs Móveis e Veículos Autônomos: Pesquisa, Desenvolvimento e Desafios na área da Inteligência Artificial

Mobile Robots and Autonomous Vehicles: Development of Intelligent Robots and the Challenges for Artificial Intelligence Research

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Abstract. This tutorial intends to introduce concepts, techniques and applications of intelligent autonomous mobile robots. Firstly, concepts related to mobile robots and autonomous vehicles are presented: sensors, actuators and different types of robots. Important questions about autonomy and intelligent robot control are posed, discussing how to define and execute robot behaviors in order to accomplish different tasks autonomously, from the simple ones to a set of complex tasks. Some recent proposed AI problems, applications and competitions, as for example, the DARPA Grand Challenge, the DARPA Urban Challenge, the TORCS AI Competition (CEC, CIG) and the RoboCup will be discussed. These competitions are known as AI research grand challenges, where it is interesting to us to study the possible approaches used to solve these problems. From this initial discussion will emerge several current research topics related to intelligent robots and vehicles, as for example: using incomplete and approximate information; classifying and recognizing input patterns; sensor fusion; robot pose estimation and maintenance; path planning; robust robot control and navigation avoiding obstacles; multi-robotic systems interaction. Therefore, a special attention will be provided to Machine Learning methods, especially to Artificial Neural Networks and Genetic Algorithms, used to implement robust intelligent robot behaviors. Besides that, machine vision techniques will be also discussed since these techniques are also very important in the context of mobile robots. Then, the last part of this tutorial is reserved to the presentation of the INCT-SEC (National Science and Technology Institute on Embedded Critical Systems) research developments: indoor service robots, unmanned terrestrial vehicles and unmanned aerial vehicles. Finally, the new challenges and perspectives in the intelligent mobile robots and vehicles research field will be discussed.

Keywords: Intelligent Robots, Mobile Autonomous Robots, Autonomous Vehicles, UGVs and UAVs, Simulation, Artificial Intelligence, Machine Learning

1 Introduction

Nowadays, mobile robots and autonomous vehicles are becoming more and more usual in our domestic, professional and urban environments [8,28,32,37]. Starting from small robots like autonomous vacuum cleaners (e.g. iRobot Roomba) and lawn mowers (e.g. Husqvarna Auto-mower), up to more sophisticated autonomous vehicles, security and service robots[1]. According to a new market research report, “Global Service Robotics Market (2009-2014)”, published by MarketsandMarkets[2], the total global service robotics market is expected to be worth US$21 billion by 2014. On the other hand, although the demand for autonomous robot applications and solutions keeps growing, the development of such systems still requires a long product development time. It is also considered a very complex task, due to the several requirements of hardware and software integration and even due to safety aspects (since mobile robots usually have direct contact with humans). Even a tele-operated mobile robot should guarantee safety for the people and also other elements present in their operational environment [12].

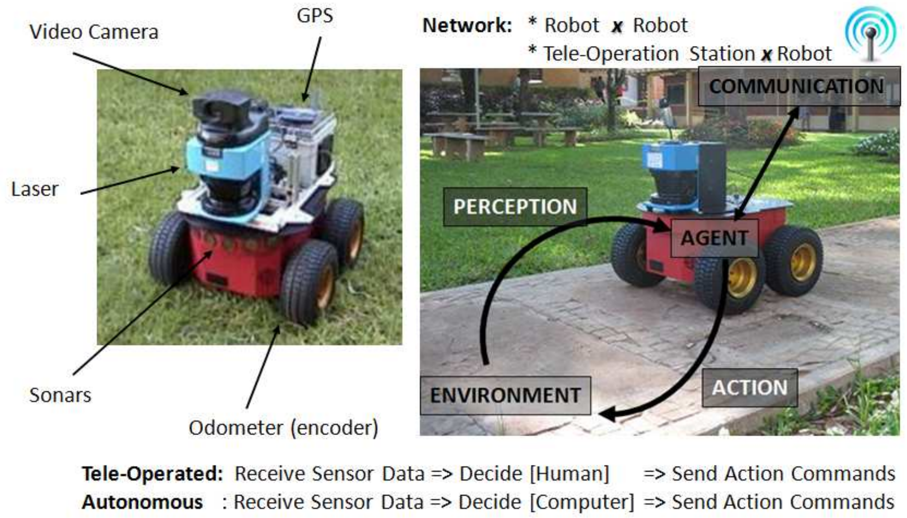

Fig. 1. Intelligent Mobile Robots – Agents with Sensors, Actuators, Communication and Decision Making/Reasoning for Control (Tele-Operated and/or Autonomous) [LRM Lab].

Mobile robotics is a multidisciplinary research area that aims to develop machines capable to use sensors to perceive the environment, make decisions, and move autonomously to complete assigned tasks [2,28]. Research work in this field deals with autonomous systems which are Intelligent Mobile Agents (see Fig. 1), but also work with semi-autonomous systems which are able to assist and interact with humans.

[1] Technical Committee for Service Robots of the IEEE Robotics and Automation Society. http://www.service-robots.org/applications.htm
[2] MarkestandMarkets: Global market research and consulting - http://marketsandmarkets.com

One important research domain of mobile robotics, which also attracted the attention of the general public in the last years, is the field of Autonomous/Unmanned Ground Vehicles (UGVs) development. It has been receiving considerable attention by robotics community in the last five years. Initiatives like DARPA Grand Challenge [40,41,42,48,49], DARPA Urban Challenge [42,50] and ELROB [43] have been concentrating efforts of several universities and research institutes to push the state of the art in ***outdoor*** navigation algorithms, assisted car driving, and autonomous car transportation systems [2,4,5,8,19,20]. Although autonomous cars are not yet available commercially, several techniques developed by robotics and Artificial Intelligence (A.I.) researchers can already be applied in day by day problems. These systems can help us to reduce significantly the number of victims of car accidents that is one of the major causes of death in the world [2,29,30].

On the other hand, a big effort of research is being done in the development of ***indoor*** service robots, with several applications in security, people and goods transportation, health care, housekeeping, and others very important tasks [28,31,37]. This research includes also Robot Soccer (RoboCup) competitions and Search and Rescue competitions (e.g. rescue robot league and rescue in urban disaster scenarios) [51,52]. Another important research field in autonomous robots are the Autonomous/Unmanned Aerial Vehicles (UAVs) [21,22,28], which also have attracted the general public attention to the performance of "war drones" (even if these last ones are tele-operated, a new generation of totally autonomous UAVs are on the way).

Fig. 2. Some sensors used in mobile robotics applications available at LRM-ICMC-USP

1.1 Design and Implementation of Mobile Robots

In order to design, build and test mobile robot systems, we should be able to select, integrate and configure the hardware, and then develop the software (the "Robot Intelligence" – A.I. modules) to interpret and operate signals obtained from different types of sensors, that range from sonars, infrared, lidars (laser range finders), cameras, GPS, electronic compass, accelerometers, and other devices (see Fig. 2). It is also necessary to consider the different types of locomotion systems, based on wheels, tracks, and even on legged walking systems, where the software modules are responsible for controlling these actuators based on the sensors readings [28,32,37]. Mobile robots are usually equipped with contact, distance and visual sensors that enable them to perceive the environment and to avoid collisions, allowing for safe autonomous navigation.

Some more complex applications may require some advanced capabilities, other than simple obstacle avoidance, like for example: map building, auto-localization, path-planning and coordinated robot control and navigation [28,34,37,39]. Robots can be tele-operated and/or have an autonomous control (Fig.1), but even tele-operated robots are expected to avoid collisions and do not cause damages to objects or people that are around them [12]. These different tasks and robot modules are usually implemented using different Artificial Intelligence techniques, based on pattern recognition, classification of sensors data and environment elements, machine learning techniques, probabilistic reasoning, advanced computer vision algorithms, planning algorithms and other A.I. advanced techniques. In order to put these components and modules all together, usually we need to chose a ***Robot Control Architecture*** [8,28,35]. The Robot Control Architecture defines the main components and the interconnection of these different modules resulting into a complete ***Intelligent Control System***. Some well known robot control architectures are based on techniques of: reactive control, deliberative control, hierarchical or modular control, and hybrid control [28].

The implementation of an Intelligent Autonomous Mobile Robot Control System is a very complex and challenging task. We need to deal with different sensors, integrating them, and creating an internal representation of the environment, and then we need, using these "environmental knowledge", to plan a sequence of actions that approaches the robot to its goal/destination. Sometimes we need a map of the environment, and the robot's current and destination positions referenced according to this map; and in other situations, we could need to locally react to obstacles, identifying landmarks to use as references for the navigation. The robot control system must do all this, and also ensure safety (for the own robot, people, elements present in the environment), react as quick as possible to unexpected changes in the environment and goals, and also be fault tolerant since sensors and actuators can be imprecise and also fail (e.g. a GPS can lose the satellite signal). We can also add to this list problems that require multi-robot group interaction and group coordination. All those tasks are extremely complex, but are executed by human beings naturally when they accomplish simple tasks like "walk to the library", "play soccer" or "drive the car to the supermarket". This is the main reason that nowadays the A.I. big challenges are focused in autonomous mobile robots, because the perception, mobility, reasoning and action are key elements in the quest for realistic Artificial Intelligence Behaviors.

In the next section we will discuss about how complex mobile robot control systems can be designed, implemented and tested, based on virtual simulations tools. The section 3 presents some of the most important and usual robotic tasks, used to implement intelligent control systems. Section 4 concludes this tutorial presenting conclusions and perspectives in the intelligent mobile robots research field.

2 Virtual Simulation Tools

As robotics is invariably becoming part of our everyday life, real situations demand mobile systems capable of acquiring information of their own state and of the surroundings, interpret the data obtained, and make decisions to accomplish tasks. The more realistic are these tasks, the more complex are the designing and building of these machines. Although there are several mechanical challenges in creating robots that are capable of moving around and climbing stairs inside our house, most of the difficulty in the development of robots is related its intelligence and decision making capabilities. In this context, computer scientists have a major role in developing techniques that enable robots to think. Obviously, this is a major challenge in the field that is not going to be completely solved in the next decades. On the other hand, several solid advances have been obtained by the scientists in the last 20 years.

In the mobile robotics design particular case, the modeling and simulation of the system can be successfully done using Interactive Virtual Reality Simulation Tools. Adopting 3D Realistic Virtual Environments to model and simulate mobile robots, testing and evaluating the different aspects of the system before implementing it physically is an efficient manner to decrease the development time. This type of approach is becoming more and more common not only in the robotics design but also in other industrial products design.

Differently from most computer science areas, robotics deals with physical environments and real situations. This certainly makes its development hard and slow as it is necessary to consider several aspects such as: battery charge, adequate connection of sensors, actuators, and computers, network accessibility, and even the weather conditions in outdoor experiments. Nowadays, the time to market is absolutely essential for a success of a commercial product. A single bug in the control software can lead to a robot colliding to an obstacle or falling from the stairs, which can result in hundreds or thousands of dollars in expenses due to a broken laser sensor in the experimental tests. In order to make the development process faster and easier, and to avoid such cases, simulation has a major role in mobile robots development. Of course, the simulation has to be as realistic as possible and its integration with real systems is essential to fulfill the requirements for its use in the robot development process.

Over the years, robot simulators have become more and more accurate in representing real environments, sensors and actuators. Nowadays there are several simulators available for virtual experiments with a large number of robotic platforms and sensors (e.g. Microsoft Robotics Studio, Cyberbotics Webots, Player-Stage, MSF Nasa) [28,11]. Some of them are proprietary software and have to be purchased. Others are open source code, freely available for download in the internet. Probably the most used platform used by scientists and robotics developers is the open source tool Player/Stage/Gazebo[3] [56,57,58,59].

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[3] Stage and Player are freely available under the GNU General Public License from http://playerstage.sourceforge.net.

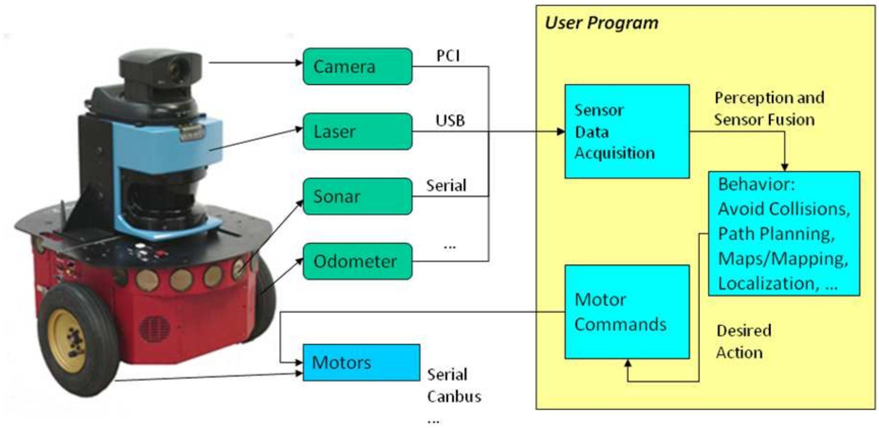

Fig. 3. Mobile Robot based on a complete user control system development

2.1 Player-Stage-Gazebo: Software Architecture

In the earlier stages of mobile robots development, all the systems should be implemented by the user, including device drivers for different sensors and motors, as showed in Figure 3. As the development of mobile robot platforms become more complex, the reuse of software modules became indispensable, and software packages like Player appeared [56,57], allowing the user to reuse device driver components, and simplifying the task of creating a mobile robot control system (see Figure 4). The user has access to an API interface, with an easy configuration and use of different types of hardware devices. Using systems like Player, the user/programmer can focus his attention on the high-level control systems tasks development: environment mapping, planning trajectories using maps, auto-localize the robot in the environment, avoid collisions and obstacles, etc.

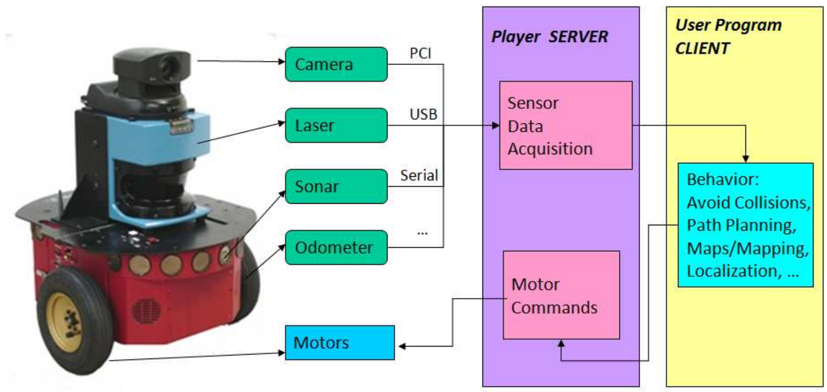

Fig. 4. Mobile Robot based on the use of player device drivers and specific user control system development

Player is a server for robots and sensors control developed for Unix-like systems. It provides simple and efficient interfaces to robots and sensors over the network. Application programs (clients) can obtain data and send commands to robots and sensors using well defined and high level functions without to worry with hardware connection issues. All the hardware access is done by the server, which have specific drivers for each sensor or robot supported. Different devices of the same type have the same client interface, making the replacement of hardware parts a transparent task.

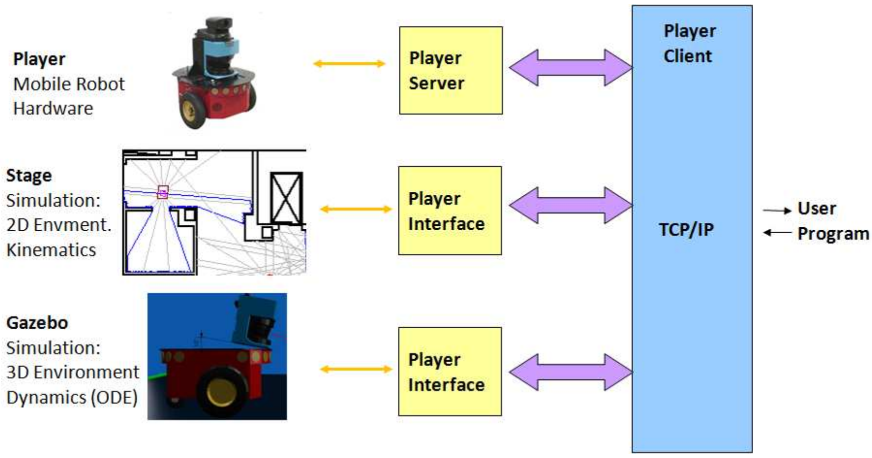

Fig. 5. Player-Stage-Gazebo Architecture:
Controlling real and virtual (simulated) mobile robots

Player was primary designed to interface to real hardware but it is also fully compatible to virtual robots and sensors through the use of the Stage and Gazebo simulators. As the client/server communication is performed over the network, it is completely transparent to the client (high level control software) whether it is connected to real or simulated devices (see Figure 5).

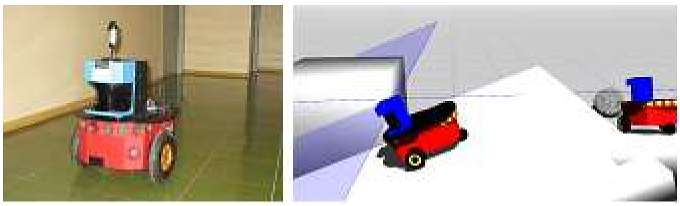

Fig. 6. Pioneer DX robots: real and simulated

While Stage simulates robots in two-dimensional spaces, Gazebo is capable of recreating complex 3D environments. Through the use of the ODE library (Open Dynamics Engine – Open Source Tool), Gazebo can simulate the physical interaction of several robots and sensors in realistic environments and situations. Its seamless integration to Player makes it a very interesting platform for robotics control software development. Figure 6 show real and simulated Pioneer DX robots using Gazebo. Figure 7 shows a robotic vehicle. It is possible to notice that fine details of the environment and represented in the virtual (simulated) world.

Fig. 7. Robotic vehicle in an urban environment: real and simulated

The mobile robotic platforms presented in Figures 6,7 and 8, represent the research efforts of two working groups (WG) of the INCT-SEC[4](Brazilian National Institute of Science and Technology in Critical Embedded Systems). The Working Group WG1 aims to develop indoors tactical robots (monitoring and security robots – Fig.6), tele-operated and/or autonomous, based on platforms similar to those presented in Fig. 6. The WG2 intend to develop computer assisted driving systems and autonomous terrestrial vehicles, based on platforms like those presented in Figures 7 and 8 which is being developed at USP (Univ. of Sao Paulo) in collaboration with SENA Project[5]. The INCT-SEC and LRM Lab. are also working in projects of UAVs (aerial robots).

The electrical vehicle presented in Figure 8 can be remotely controlled using the player-stage, where we are able to read sensor data from the lidars and send commands to the motor controller (Roboteq) that controls the steering of the vehicle. The images from camera are treated separately by an OpenCV application and can communicate with the player-stage tool.

Fig. 8. Electrical Autonomous Vehicle under development at LRM Lab:
Club Car equipped with Roboteq Motor Controller (Steering), Laser Sick and Camera

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[4] INCT-SEC: http://www.inct-sec.org/actrep/
[5] SENA Project: http://www.eesc.usp.br/sena/url/en/index.php

3 Intelligent Control: Robotic Modules and Tasks

Some of the main modules/tasks that can be implemented into an intelligent mobile robot control system are the following:

1. Sensor Acquisition, Processing and Fusion
2. Auto-Localization
3. Environment Mapping
4. Path-Planning
5. Control and Navigation (Obstacle Avoidance)
6. Multi-robots System Coordination

3.1 Sensor Acquisition, Processing and Fusion

The first stage of the design of a mobile robot is the sensors fusion. The sensors are responsible for acquiring information from the environment, allowing the robot to know: (i) how are configured the elements present in the environment, usually sensing the elements that are nearby/around the robot [3,4,5]; (ii) where is the robot, and where are the obstacles present in the environment, so this is can help us to build maps and localize the robot [24,28,37,39]; (iii) what are the changes in the environment, allowing to detect unexpected events and situations (e.g. dynamically changing environments with moving obstacles)[25,39,55]; (iv) how are the conditions of navigability, classifying the terrain as navigable and non-navigable, free and with obstacle, road and off-road [3,18,19,20,44,45,46,48,53]; (v) where are the land-marks identifying specific positions of the environment or locations of destination, or even where are the reference points defining a way-point path(GPS way-point) [2,48, 49,50].

As the sensors have different distance measurement ranges (e.g. Lidar, infrared and ultrasound) and also different types of information (e.g. GPS, video camera and Lidar), almost all the time is very important to proceed with a sensor fusion, integrating the sensorial information in order to obtain a high level environment representation or to exploit different types of information [2,47,48,50]. The sensor information can be also processed in order to extract structured information, as for example, classifying the terrain as a flat or rough surface, or identifying a free or blocked portion of the estimated path. In order to process data from laser sensors and cameras, it is very common to adopt A.I. tools as machine learning methods [36,38], as for example, in [3,6,19,20,44,45,46] where Artificial Neural Networks [33] were used to process the sensor data.

3.2 Auto-Localization

In order to accomplish one task of moving from a specific location to a destination location, the mobile robot usually should know: the map of the environment, the initial position of the robot, and the destination position. Using these information, it is possible to define a trajectory from the initial position to the destination, avoiding the known obstacles [8,54,28,34,55]. We can use algorithms, as for example, those based on A* or path planning based on Djikstra using graphs.

There are some well known algorithms for auto-localization presented in the mobile robotics literature: Markov Localization, Extended Kalman Filter Localization (EKF), and Particle Filter based Localization (Monte-Carlo – MCL) [28,37,39]. These methods have been exhaustively studied by roboticists and A.I. researchers.

3.3 Environment Mapping

Since robots need to use a map in order to self-localize in it and to do path planning, one important mobile robot task is the environment mapping. There are some well known techniques for environment mapping [4,24,28,39], but usually we have a mutual dependence between localization and mapping, since: (i) to build a map we need to know the pose (position and orientation) of the observer, in that case, the robot pose and the pose of each sensor; (ii) to determine the robot localization we need to know the map of the environment where the robot is placed, or, we need to know precisely each movement accomplished by the robot (registering the trajectory into a map). So, this mutual dependence motivated the development of SLAM methods – Simultaneous Localization and Mapping Algorithms [25,28,39].

3.4 Path-Planning

Once we have the map, initial position, and destination, it is possible to determine the path from the initial position to the destination. As cited above, it is possible to use algorithms inspired on the A* (A Star), or to use path planning based on some graph optimization algorithm, like Djikstra Algorithm [8,34,54]. Various path planning techniques are classical A.I. studied methods.

Sometimes the path is not defined over a pre-defined map, but only a sequence of pre-defined positions defining a path is passed to the robot, and the robot should follow the pre-specified trajectory just following the points: the way-point following. Competitions like the Darpa Grand Challenge, the Urban Challenge, and ELROB are mainly based in the definition of a GPS way-point sequence provided to the competitors that should follow the pre-specified path [42,43,49,53].

3.5 Control and Navigation (Obstacle Avoidance)

One of the most important robot modules is the robot control and navigation, which performs the motor commands in order to move the robot following the pre-specified path or directing the robot towards a specified goal. It is well known that the pre-specified path is used just as a reference, since the robot should respect the kinematics restrictions of the adopted robot model [8,11,28,32] and also it should avoid obstacles (static or dynamic) [28,31,37,55]. The control and navigation is strongly related to the robot control architecture, and can be implemented in different ways, using a reactive, deliberative, modular, hierarchical or hybrid architecture [28,32,35].

When there is an available map, the control and navigation system try to keep with a certain precision the estimated robot position related to the map, allowing to control the robot in order to move towards its next destination, and being prepared to detect and detour from any obstacle present in the robot path.

When there is no previous map available, it is possible to apply techniques based mainly in reactive behaviors, as for example, Potential Fields navigation methods [32,37]. On the other hand, if the robot has to follow a road, the navigation method should detect the road and the regions that are off-road [3,18,19,20] and keep the robot following the road.

It is also possible to follow a way-point, where there is no explicit and complete environment map [2,48,49]. In this case, as the GPS is very imprecise, such a technique of way-point following should be combined with other techniques, using some method of sensor fusion, for example, combining GPS with data obtained from a Lidar or Video Camera [2,48,49]. The UAVs (Unmanned Aerial Vehicles) used for non-military applications usually implement a GPS way-point following algorithm, as implemented in the ARARA Project [21,22,28] (See Fig. 9).

Fig. 9. ARARA Project under development at LRM Lab: Autonomous UAV capable of following a pre-defined GPS way-point

3.6 6. Multi-robots System Coordination

The implementation of an autonomous multi-robots control system is one of the most challenging areas in robotics. As described in the previous sections, the implementation of one single intelligent robot control system is a very complex and hard task, and the combination of multiple robots, acting together in order to achieve a common goal, is something with a considerably superior degree of complexity.

Some techniques for multi-robot coordination are being investigated using Genetic Algorithms to optimize the robot group execution of an specific task, as demonstrated in the Robombeiros (Fire-Fighting Robot Squad) work described in [13,14,15]. This is just only one example of this kind of problem; however it demonstrates several components and problems that should be investigated when working with a robotic squad.

Other example of multiple mobile systems interacting with an autonomous vehicle was presented in the DARPA Urban Challenge [42,50], where the autonomous vehicles should respect the traffic laws in order to exhibit a coordinated behavior “respecting” the other vehicles. Finally, the integration of Aerial and Ground vehicles is also a very challenging research field [7] in this domain of applications.

4 Conclusion

This tutorial presented a discussion about the design and implementation of mobile autonomous robots and intelligent control system, starting from the concept of virtual design and simulation, up to the description of the main modules and architectural components of these systems. Several examples were presented together with complementary bibliographical references, which aim to introduce to the reader the main A.I. research challenges related to this domain of application.

Although many important achievements have been done in recent years in this field, there are still several open research questions to be studied and developed. For instance, the aspects related to robot communications, cooperation, safety, security and fault tolerance, certainty should be more investigated. Also the multi-robotics systems, from squads to swarms, are also a very promising field for academic research and development of applications.

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