AUTONOMOUS AND TELEOPERATED CONTROL OF THE AURORA MOBILE ROBOT

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Abstract: This paper presents the main components of a control architecture that allows both autonomous and teleoperated navigation in agricultural and industrial environments with high obstacle density. They support user interaction, task execution, navigation, and feedback control. The architecture combines parallel behavior control concepts with hierarchical organization. Moreover, the architecture allows multilevel remote operator intervention for monitoring and control. The paper emphasizes the components (sensors and controllers) to implement motion and feedback control, as well as the teleoperation station integration. The control architecture has been implemented to control the AURORA mobile robot. The efficiency and robustness of the components have been tested in the experiments with this mobile robot. The paper includes a description of an autonomous navigation experiment.

Keywords: mobile robots, autonomous vehicles, telerobotics, architectures, ultrasonic transducers.

1. INTRODUCTION

AURORA† is an autonomous wheeled mobile robot designed for automatic greenhouse operations, without the physical presence of a human operator or supervisor. Its aim is to perform purposeful operations in its particular working environment, which means it must integrate a variety of components for autonomous navigation and operation, and to support remote human supervision and teleoperation. Although typical operation for this system is chemical spraying, its flexibility allows its adaptation to other operations and applications, such as greenhouse monitoring, transportation or production inspection.

The control architecture presented here has been concurrently designed and implemented in a progressive refinement basis, trying to cope with the most of real-life situations. A main feature of the implementation of this control system is the low computational software and hardware requirements, that makes possible a reliable and low-cost product. The architecture integrates sensors, controllers and actuators as well as software and communication components.

This implementation has been based on previous works on the development of RAM-1 (Ollero et al, 1993), and also considering other research works on teleoperated mobile robots in different issues: autonomous navigation (Muñoz et al, 1994), teleautonomous navigation (Borenstein and Koren, 1990), (Connel and Viola, 1990), telepresence
(Clement et al., 1988), and mobile manipulators (Fukuda et al., 1992).

Next sections include an overview of the AURORA robot, the sensors for navigation and operation, the architecture description through its different levels, the tele-operator station implementation, and the results of a navigation experiment. The last two sections are for conclusions and references.

2. THE AURORA ROBOT

AURORA is an autonomous wheeled mobile robot for greenhouse operations built at the Málaga University (see Fig. 1.). The original aim of AURORA is to perform operations in greenhouses. In order to be competitive, AURORA must be capable of operating in a variety of different greenhouses without imposing any alterations on them at all.

The mechatronic system consists of an octagonal mobile platform that accommodates a spraying device, the power system, standard electronic and computer enclosures, and a variety of sensors. Its dimensions, constrained for the ability to navigate in narrow greenhouse corridors, are 80 cm in width and 140 cm in length.

The locomotion system is a modification of the RAM-1 dual configuration (Ollero et al., 1993) that renders high maneuverability (zero turning radius), which is essential in constrained environments. It has four wheels located in the vertices of a rhomb. A description of AURORA can be found in Ollero et al. (1995).

3. SENSORS FOR NAVIGATION AND OPERATION.

Ultrasonic sensed information is frequently updated and requires little processing, properties that are especially useful for reactive control. Instead of a classical homogeneous sonar ring, AURORA’s configuration of ultrasonic sensors has been chosen considering the characteristics of constrained environments. Thus, a combination of three different types of ultrasonic sensors has been placed in the front half of the robot, covering the ranges shown in Fig. 2. The number and types of sonars that have been used are the following: 4 Short-Range Digital sensors (SRD), 2 Mid-Range Digital sensors (MRD), and 4 Mid-Range Analog sensors (MRA) with adjustable orientation.

These sensors can also be used to estimate the growing density in order to control the spraying operation, that can be done by simply adapting the vehicle speed depending on the estimated growing density.

Additional proprioceptive digital sensors are included in order to obtain the vehicle’s power status, the spraying device status, and the detection of malfunction conditions.

A video camera has been added for remote human supervision purposes. An on-board video transmitter sends analog TV images to the teleoperator station. Video cameras will also support autonomous navigation and intelligent spraying by means of real-time image processing. However, these facilities are not currently implemented.

4. THE AURORA CONTROL ARCHITECTURE

The system supports autonomous task execution and navigation. The teleoperator can supervise, cooperate, or take integral control of the system. The control architecture has been designed by using traded and shared control concepts.

This autonomous control system allows interactions with the environment, the user and the operator. The user is the human that interacts with the robot through its on-board console for performing the start-up and shutdown, as well as
task related operations. Furthermore, the user can also take direct motion control, for robot transportation or maintenance. However, the operator is located remotely from the robot, and can survey one or more robots simultaneously. Moreover, the operator communicates with different levels of the control system, which allows remote emulation of the user operations, performing collaborative guidance or taking control for resolving special situations, when required by the autonomous system or when desired by the operator (see Fig. 3). The architecture follows a hierarchical decomposition composed by five levels: User, Supervisor, Reference generation, Executive and Servo. Upper levels are characterized by soft real time constraints whereas the lower levels are hard real time constrained.

4.1. The User level

This level handles local user communication for start-up, shutdown, task programming, transporting and maintenance. Three accessible emergence push-buttons allow the local user to stop and lock the motion of the robot. The user interface consists of an embedded 2x40 characters LCD display and a 16 keys key-pad. The display shows the current robot and task status. The key-pad has special editing and control keys with iconic representation for the different behaviors, as can be seen in Fig. 4. The remote user connection with the communication controller allows the remote operator emulate the key-pad and display on the teleoperator station console.

4.2. The Supervisor level

The core of this level is the Supervisor Sequential Controller (SSC). Its sequential event-driven task description coordinates the behaviors of the reference generation subsystems. These subsystems issue events to the SSC in order to report the current status and to notify the normal termination of an activity or an unexpected condition. They must also give timely response to such incoming events as an activity start, activity stop, or synchronization point acknowledgment. The SSC coordinates the overall behavior by sending the activity start events and waiting for the incoming events and clock events. For this reason, the navigation subsystems are built as “behavior based” processes. The set of active (executing processes) activities, and consequently their emergent behavior (Brooks, 1986) is controlled by the incoming events.

Fig. 3. The AURORA implementation of the control architecture.

Fig. 4. The user’s keypad layout.
4.3. The Reference Generation level

This level is composed of a set of basic behaviors. Each of these behaviors generates a specific robot motion schema. The activation of the right behavior is controlled by the SSC, and its output supplies motion commands to the lower level, based on the current sensorial information. The activation of these processes can admit associated parameters for improving its performance. The normal or abnormal process termination is notified to the SSC, which selects the next step in the task sequence.

Some implemented behaviors (Madow et al., 1995) are “Wall following”, “Corridor following”, “Turning”, “Collision detection”, “Operator mode”. Outputs of more than one active behaviors are combined to obtain a single motion reference.

4.4. The executive level

Aurora’s low level control is the interface with the vehicle’s internal sensors and actuators. Thus, the vehicle’s hardware details are encapsulated.

The vehicle control module achieves the vehicle dependent functions and brings vehicle independent services (SetSpeed(), SetCurvature(), GetStatus(), etc.). Internal functions of this module include the inverse kinematic model for supporting vehicle independency, considering actuation limits (maximum driving speed).

This module supervises the activation of the low level control loops, establishing different vehicle states and their related transitions (See Fig. 5). The “starting” state represents the control initialization, “Normal” represents regular operation state, “Fail” for control malfunctioning, and “Off” for detected external motor deactivation (Emergence button pressure).

Another important task implemented in the vehicle control module is the responsible for wheels coordination in this locomotion redundant system, because of the difference between the driving motors acceleration, and the steering motor speed. Bad coordination causes wheel’s slippage that increases the vehicle position uncertainty. This coordination tasks periodically establishes the speed of the driving motors (fast response) as a function of the steering motor actual position (slower response).

The module responsible for sensor management and interfacing is also included in this level. Furthermore, calibrated sensor reading services are included.

This level also includes a module for direct user guidance. By means of a joystick, the user can drive the vehicle to its operation site by ordering changes of speed or curvature.

4.5. The servo level

This level provides a set of hardware independent services for controlling the vehicle mechatronic. Common services of this hardware control module are the wheel speed and steering reference settings. It is composed of the service high level interface libraries and the low level feedback control hardware and software.

A dedicated processor board is devoted to the feedback control task. Besides, this board provides electrical connection for sensors and actuators. The main tasks performed by this board are: Speed control for the left and right driving motors, position control for steering motor, reading of the state of the emergency buttons, the user joystick, and motoramplifiers, reading of the digital and analog ultrasonic sensors measurements and sprayer activation/deactivation.

The control period is 1 millisecond. The velocity, the controller parameters, the acceleration, braking, and the reference position and velocity can be changed, even while executing a motion.

5. THE TELEOPERATOR STATION

The operator is located away from the robot working environment. The operator communicates with the robot through the Teleoperator station (TOS), which is a real-time computer system, with man/machine interfaces attached, and a video monitor.

This station allows the operator the performance of several tasks such as monitoring, task programming, task intervention, and shared or traded vehicle control.

Communication between TOS and AURORA features multi-level access, which means communication at different levels of control: User, supervision, reference generation and executive. This makes possible the achievement of many different operations from the operator station, allowing complete robot control.
The TOS scheme is shown in Fig. 6. This is a PC based workstation, with a radio modem, a genlock module (for computer on video overlay), a TV receiver, and a video monitor. Several man/machine interfaces have been experimented during development: SpaceBall (6 dof force/torque sensor), mouse, digital (incremental) joystick, analog (absolute) joystick and keyboard in various operating modes.

The computer screen layout gives graphical representation of the remote vehicle’s status and sensor’s readings (see Fig. 7.). This representation can be overlapped (switchable, wireframe and numerical) onto real video images in order to have actual information of the commanded speed (needed with incremental interfaces) and obstacle proximity (not in the field of view) while visually driving the vehicle.

Communications are implemented by means of an RS-232 serial link, and a 1200 bauds, half-duplex radio modem for wireless data transmission. There is also another communication channel for analog video and audio transmission for visual feedback only. The TOS is the responsible of initiating the message transfer, and AURORA of returning the appropriate response. The TOS sends commands, and AURORA returns status messages. Every message consist of a single command or status message.

The Semiduplex communication channel imposes the convenience of a transmission control protocol. Two different transmission control protocols have been tried: synchronous message transmission, and asynchronous message transmission. A comparison of these schemes can be shown in Fig. 8. The synchronous model offer deterministic control period, desirable for operation with incremental man/machine interfaces. The asynchronous approach gives better performance, and flexibility, allowing variable size messages to be exchanged, but poor real-time response.

6. EXPERIMENT

A number of successful experiments have been performed with AURORA both in greenhouse and indoor environments. Fig. 9, presents an image showing the layout of the actual experiment, in which AURORA navigates autonomously through a recreated storage environment. The walls are of an uneven nature, since they are composed using cardboard boxes of different sizes and leaving empty spaces between them.

Superimposed over Fig. 9. is the path the robot must follow during the task, and how it can be easily decomposed in basic behaviours. Thus, the program introduced through AURORA’s keypad is composed of the following steps: 1) Follow wall at the right. 2) Turn right up to 90°. 3) Follow corridor. 4) Turn right up to 90°. 5) Follow corridor. 6) Turn left up to 90°. 7) Follow wall at the left. 8) Turn left up to 90°. 9) Follow wall at the left.

Each of these steps is programmed by pressing a single key of the onboard keypad, and they provide implicitly information about the environment, since no explicit map is stored or registered for operation. These instructions can also be organized in loops in order to simplify the specification of long tasks in which a particular navigation pattern is repeated a number of times, such as spraying all corridors in a greenhouse.
This experiment shows how AURORA follows a high level path by using only the information provided by the ultrasonic sensors. Each of the navigation behaviors that implement the different steps in the sequence makes use of the particular set of sensed data required to accomplish its aim. They provide a speed and curvature reference based on the latest readings of the ultrasonic sensors.

The turning behaviors are activated when a mid-range free space is sensed at the side of the turn and it approximates and turns to the left, respectively. The speed and turning curvature for each behavior are specified beforehand (speed was 0.4 m/s in this particular task). For turning, it uses a combination of local odometry (the “approximate” angle to be turned is specified, since only a small error accumulation is possible for such a small distance) and sensed information (if an object is detected at the immediate left, then the turn has been completed).

This experiment also shows the safety behavior for obstacle detection, since the task is paused, and eventually finished, when a wall is detected by the front sensors of the robot at the end of the last wall following in the sequence.

7. CONCLUSIONS

The control architecture has a significant impact on the performance of autonomous vehicles and mobile robots when executing practical tasks. Navigation and operation in real applications always requires some class of intervention of human operators. The architecture presented in this paper supports autonomous navigation and task execution but the human operator can also take the control when necessary. The architecture is the result of a dual design approach: the global control is hierarchical but the internal implementation of the modules is layered.

The architecture has been implemented and tested successfully for real applications. Furthermore, its operating flexibility has been shown through different modes of control: Teleoperator guidance, teleprogramming, user programming and autonomous operation. The high level of flexibility conveyed by this system offers a highly reliable solution for a wide fan-out of industrial applications.

The AURORA robot has demonstrated its capabilities in greenhouse spraying tasks. A successful public demonstration has been recently carried out in a greenhouse of FIAPA (Almeria, Spain, February 1995).

8. REFERENCES