LEADER-FOLLOWER FORMATION CONTROL OF NON-HOLONOMIC ROBOTS IN A REMOTE LABORATORY

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Abstract: This paper presents a remote laboratory for leader-follower formation control. The client-server architecture of the remote laboratory is based on Matlab and JIM at the server's side, and a Java applet created using Easy Java Simulations at the client's side. The implementation of the remote laboratory is described in detail and the educational value is outlined by presenting some experimental results for formation control of two mobile robots.

1 INTRODUCTION

Nowadays technology is evolving at an incredible pace, providing us with possibilities that a few decades ago were unimaginable. The development of communication and information technologies has completely changed the speed and penetration of information in today's society. The teaching activity in general has a lot to gain from the use of these new technologies. Remote and virtual laboratories are becoming increasingly popular. Remote laboratories, as compared to the classic on site instruction, present several advantages (Dormido, 2004): i) continuous availability of the laboratory for experimentation, ii) there is no need for the students to travel to the university's site in order to perform the experiments, iii) optimal exploitation of the resources, iv) easy access to different types of experiments. A very broad range of applications can make the object of remote laboratories, with some notable exceptions for example in the chemistry field where safety requirements can prohibit the use of a remote laboratory (Dormido, 2004). In particular, remote laboratories are becoming very popular in the field of control engineering mainly due to the interactivity that they provide to the distance teaching process. A few examples of remote laboratories designed for performing control experiments are given in (Vargas et al., 2009; Fabregas et al., 2009; Farias et al., 2010), to mention just a few. These remote laboratories are meant to remotely control a single process (water tank, ball and hoop, DC motor etc.) allowing the remote user to change the parameters of the controller, visualizing incoming data and enable a real-life view of the process itself.

The fields of robotics receives very much interest both from the academic and industrial communities worldwide, which means that proper education in this field becomes more and more important (Potkonjak et al., 2010). Building a remote laboratory for robotic experiments is a complex task due to the interdisciplinary character of this application. A few examples of remote laboratories with the purpose to experiment with robotic applications are presented in (Šafarič et al., 2005; Casini et al., 2009; Sayouti et al., 2010).

In the remote laboratory presented in this paper the final aim is to remotely control a group of mobile robots so that they move in a leader-follower formation on a predefined trajectory.

The proposed implementation is based on Matlab and Easy Java Simulations (EJS) (Esquembre, 2004). EJS is a free open-source tool for easily creating simulations in Java, and targets students, teachers and researchers who want to quickly create a graphical simulation. EJS was originally designed to be used by students for interactive learning under the supervision of educators with little programming experience. In this implementation of a remote lab, the graphical interface and the computational engine are separated. The graphical interface was created using EJS and is an applet that runs in the user's browser.

Matlab is the most commonly used program in teaching control engineering. In our remote laboratory implementation, the computational engine is rep-

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resented by Matlab, which runs at the server's side.

In the next section a description of the components that constitute the remote lab is given. In section 3 we discuss the application of the remote lab for controlling a formation of robots and in the last section some conclusions are drawn and the planned future work is outlined.

2 COMPONENTS OF THE REMOTE LAB

2.1 General Overview

The most popular architecture used for remote lab implementations is client-server. The client runs on the remote user's computer, who can access the functions of the remote lab through a graphical user interface. The server, which runs at the University's site, should be transparent for the user and insure the connection with the process. The client-server connection is made using the TCP/IP protocol, over Internet, as depicted in figure 1.

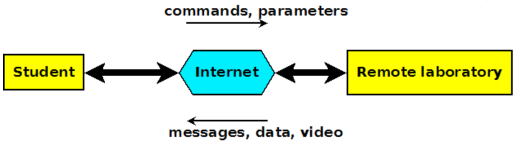


Figure 1: Client-server architecture.

Information is sent bidirectionally between the client and the server. The client sends commands to the server which are further sent to the process. From the server to the client comes data acquired from the process, real-time images of the experiment and different messages: the process is not connected to the server, changes in the state of the process, alarms when something goes wrong. Due to the high volume of data sent from the server to the client, a high speed internet connection is necessary. The camera has a separate internet connection so that the video is not delayed by the data coming from the process.

2.2 Hardware

While at the client's side a single PC with Internet connection is sufficient, at the server's side there are several hardware devices, as depicted 2. In our implementation, the server itself runs on a dedicated computer with permanent Internet connection. The computer used is powerful enough to efficiently run all the required software (Matlab, Apache Server, JIM) and it has enough memory to store the data coming from the process. It has been equipped with two network cards: one Ethernet card used for connecting to the Internet and a wireless card used to connect to a local WiFi network.

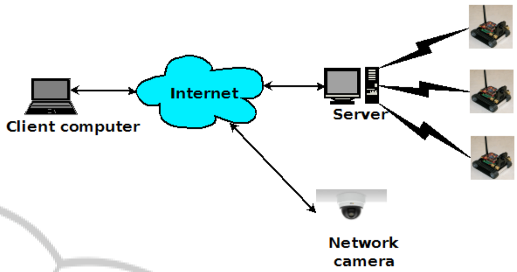
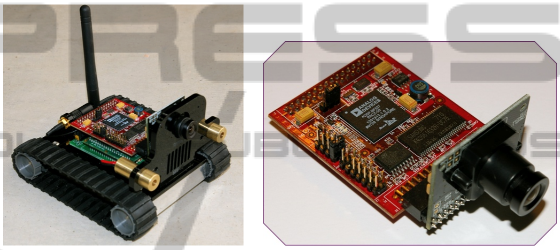


Figure 2: Remote lab hardware components.



(a) Surveyor SRV-1. (b) SRV1 Blackfin camera.

Figure 3: Mobile robot used in the remote lab.

The remote user can continuously monitor the controlled process by looking at images sent from a network camera via a separate internet connection, as shown in figure 2. Due to the nature of this application, namely mobile robots in motion, the camera has to cover a large area. For this reason, a PTZ (Pan-Tilt-Zoom) camera was chosen such that the user is able to move the view of the camera to the view of interest.

The process, in our case a group of non-holonomic robots, is connected to the server using wireless communication through a local WiFi network. The Surveyor-SRV1[1], shown in figure 3, is a tracked mobile robot equipped with a 500 MHz microprocessor, an on-board camera and WiFi communication. An expansion board is available for the robot with tilt sensors, a compass and GPS receiver. In the current experiments, the controlled signal is the duty ratio of the PWM signal sent to the motors and the output of the process is the distance between two robots measured using the on-board camera. The camera on the robots supports several resolutions for the images, however for our experiments it was chosen a resolution of 320 × 240 pixels, as a trade-off between computational time and measurement accuracy. The cam-

[1] http://www.surveyor.com

era uses YUV color representation, where Y represents the light intensity and the U and V are chroma components.

Surveyor-SRV1 is a differentially driven robot. The lack of wheel encoders makes the speed of the robot run in open loop. This aspect makes the control task more difficult particularly due to the nonlinearities of the motors and the offset in angular speed between the right wheel and the left wheel. Due to this latter aspect, lateral control of the robot is compulsory for maintaining the formation. The speed of the robot is in the range 20 cm/s - 40 cm/s with a nonlinear characteristic, containing a dead-zone until 20% of the total input range.

2.3 Software

The client-server software architecture of the remote lab is shown in figure 4. The communication between the client and the server is accomplished using a TCP/IP Internet connection. On the other hand, communication between the server PC and the mobile robots is accomplished using TCP/IP communication through a local network.

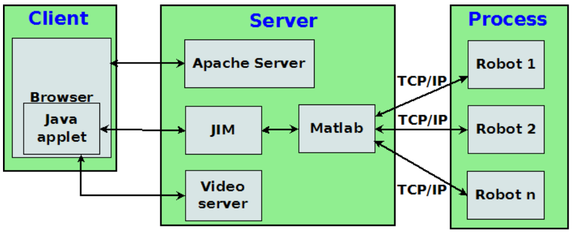


Figure 4: Remote lab software components.

The software requirements for the end-user are minimal, a Java enabled web browser, which insures the ease of use of the remote laboratory but also portability. The remote user downloads a Java applet which displays the graphical user interface, shown in figure 5. The Java applet was generated using Easy Java Simulations (EJS) (Esquembre, 2004). This applet provides a user-friendly graphical user interface for the user to access the functionalities of the remote lab. First of all, there are live images from the experiment's site in the top left side of the GUI. The buttons and the slider adjacent to the image of the process enable the user to control the orientation and the zoom of the PTZ network camera. Underneath this, there are buttons to manually control the robots, connect/disconnect the robots to the server, start/stop automatic control. The right side of the GUI is for displaying the data measured by the robots in the formation which consists of relative distance measurements and the values sent to the left and right motors of the robots. The values from the plots can be saved using a tool provided by EJS. Also on the right side, one of the panels is dedicated to experimenting with image processing functions available on the robot: color segmentation, edge detection and horizon detection.

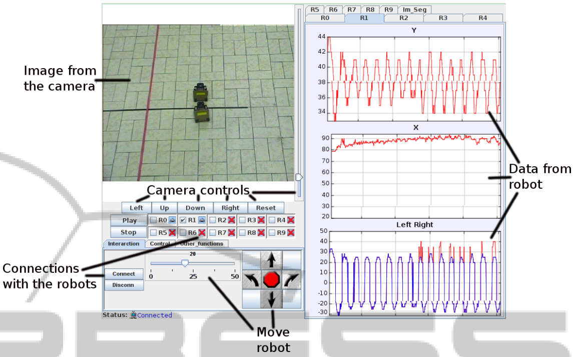


Figure 5: Graphical user interface displayed in the Java applet.

A diagram of the programs that presents the software components of the remote laboratory is shown in figure 4. JIM[2] (Java-Internet-Matlab) server is a free software tool written in Java that allows communication between a remote user and a Matlab server. The connection between the remote applet and JIM is implemented using a TCP/IP connection. JIM is able to communicate with Matlab using the functions defined in the JMatlink library (Müller and Waller, 1999).

Matlab has been chosen to be incorporated in the structure of the remote lab since it is the tool most widely used in the control engineering world. Matlab provides state of the art computational capabilities. Matlab's core computational capabilities are extended through several toolboxes. Information between the firmware on the robots and the server is exchanged by making use of the Instrument Control Toolbox[3]. Several TCP/IP connections are made in Matlab to the mobile robots. The commands issued by the user using the GUI are sent to Matlab which translates these commands into characters that can be processed by the firmware on the robots. The role of Matlab is also to receive the data coming from the robots and make it available to the remote applet through the transparent link provided by JIM server.

The camera is running a web server that can receive commands from a remote user. The user can control the PTZ network camera from the GUI. These actions are translated into HTTP queries which are sent to the web server on the camera. The HTTP

[2] http://lab.dia.uned.es/rmatlab/

[3] http://www.mathworks.com/products/instrument/

queries are translated into actions for the servos of the camera – pan and tilt – and for the lens – zoom action.

The firmware running on the robots is open-source and can be easily modified using C programming language. Some of the functionalities available are: real-time timing, image acquisition, image processing – using color segmentation and edge detection, integer number computations, floating point computations using a library, control of the motors using PWM signals etc. The tracking algorithm which consists of image processing for estimating the distance and computing the control value to be sent to the motors takes 70 ms. This value represents the sampling time of the process. All the robots have a static IP assigned so that they are easy to identify in the network.

3 CONTROL EXPERIMENT

A leader-follower formation assumes that there exists one or more leaders in the formation and the other robots, the followers, copy the actions of the leader. In this work, a single leader, column formation is used. This formation is similar to the cars on one lane of a highway, where cars follow each others and maintain a safe distance. Similar implementations of formation control of mobile robots are described in (Anderson et al., 2006) and (Klančar et al., 2009).

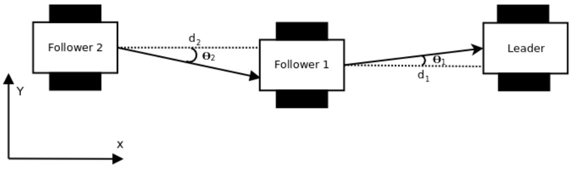


Figure 6: Leader-follower formation.

In a leader-follower formation, the followers should maintain a constant distance and a constant relative angle with respect to the robot in front. For the experiments, we set the distance reference to $d =$ 30 cm and the angle reference to $\theta = 0°$ (see figure 6).

Relative distance and relative angle are measured using image processing on images taken by the onboard camera. In order to distinguish the robots from the environment, a rectangular red marker with the dimensions 8.1cm × 3.6cm was attached to the back of the robots. The follower robot captures frames from the on-board camera and using adaptive color segmentation, the red marker is isolated in the image.

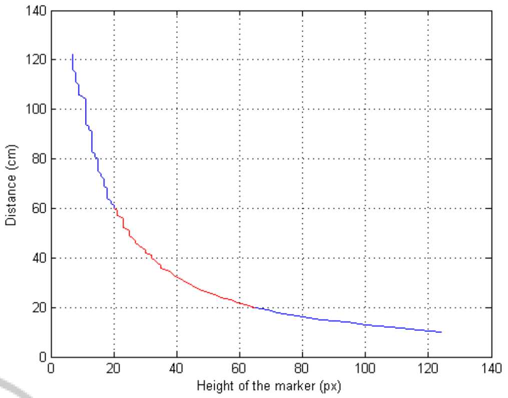


Figure 7: Measured distance - height characteristic.

The projection of the marker in the plane of the image is computed in pixels. The values of interest are the height of the blob and the position of blob on the horizontal axis. A relationship between the height of the blob and the real distance was determined experimentally, the result is shown in figure 7. The region of the characteristic depicted with red is almost linear, between 20 cm and 60 cm. On this region a 3^{rd} order polynomial was fitted, with as input the height of the marker in the image measured in pixels, and output the distance d between the robots measured in centimeters:

$$\begin{aligned} d &= -0.0004 \cdot h_y^3 + 0.0717 \cdot h_y^2 - \\ &\quad -4.53 \cdot h_y + 125.16 \end{aligned} \tag{1}$$

The accuracy of this measurement is between 1-4 cm, depending on the focus of the camera and the distance between the robots.

the position of the marker on the horizontal axis of the image is considered in order to estimate the relative orientation between the robots. Taking into consideration that the resolution of the image is 320 × 240, a 0° relative orientation is achieved when the center of the marker in the image, relative to the horizontal axis, is equal to 160 pixels. This measurement cannot exceed the field of view of the camera which is 60° in total. This measurement procedure is affected by errors when the marker is only partially visible in the image, either due to changing light or if the orientation angle between the robots exceeds the field of view of the follower's camera.

The control algorithm is implemented on the microprocessor of each robot, thus we have a decentralized formation control. So far, no direct communication among robots is possible. Communication can be implemented using a central communication point through the server, which would have the task to forward messages from one robot to the other.

The goal is to have a good longitudinal control on the robots so that the leader-follower formation is preserved. On the other hand, lateral control is also necessary for maintaining the formation and the marker

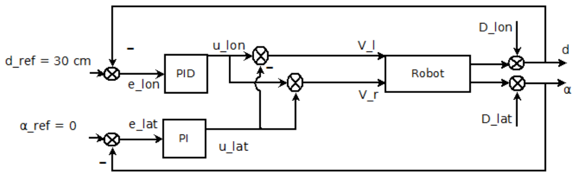


Figure 8: Control structure used for tracking.

in the field of view of the follower. A drawback of the Surveyor SRV-1 is the lack of wheel encoders so all the robots present an offset in the rotational speed of the left and right tracks. This offset means that for the same PWM values sent to both the left and right side, the robot will not drive straight as it should. In order to solve this issue, a second controller was added for the lateral dynamics.

The structure of the controller is presented in figure 8. The longitudinal controller is a PID. The reference distance is set constant $d_{ref} = 30$ cm. The measured distance is continuously disturbed by the movement of the robot in front. This longitudinal disturbance is denoted D_{lon} in figure 8. Due to the offset of the motors and the movement of the leader, there is a disturbance D_{lat} on the lateral dynamics of the system. A PI controller receives the error between the reference angle $\alpha_{ref} = 0$ and the measured angle α. The commands to the motors of the robots are obtained using the longitudinal and lateral control, according to the formula:

$$V_l = u_{lon} - u_{lat}, V_r = u_{lon} + u_{lat} \qquad (2)$$

where V_l and V_r are the PWM duty cycles sent to the left and right motors of the differentially driven robot; u_{lon} and u_{lat} are the outputs of the longitudinal PID controller and of the lateral PI controller.

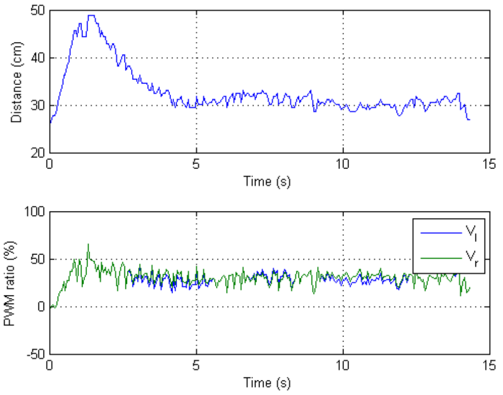


Figure 9: Tracking result for one leader and one follower.

The proposed control strategy shows good performance. In figure 9 it is presented the result for tracking of one robot using the proposed control strategy. The formation of two robots was running along a straight line, with the leader following a colored line on the floor. After a transient of 4 s in the beginning, the follower keeps a constant distance with respect to the leader in front.

In order to decrease the floor space necessary for the remote laboratory and to make it easier for the remote user to supervise the experiment, an ellipsoidal colored track of length 225 cm and at each end two semicircles with diameters of 176 cm was put on the floor. The leader of the platoon follows the colored track while the follower robots maintain the line formation. The task of the followers it is more difficult when the path is not straight. Turning of the robots can cause the formation to be broken or can induce oscillations in the lateral control that will propagate in the entire formation.

4 CONCLUDING REMARKS

This paper presented a remote lab for robotic applications. The remote laboratory was implemented using Matlab and EJS connection supported by JIM Server. The educational value of this remote lab comes from the fact that students will be able to experiment with this setup and tune the PID control.

This paper shows once again the added value that new technologies bring to the teaching process. Experimentation on the developed laboratory provides a fundamental educational feature: students can observe on-the-fly the resulting dynamics and be aware of some physical phenomena that are less obvious, difficult to explain from just a theoretical point of view.

Planned future work includes decreasing the minimum speed of the robots by changing the mechanical reduction of the motors, so that they are able to maintain the formation in a larger number on the ellipsoidal track on the floor. There are also plans of enhancing the functionality of the remote laboratory by adding more options to the graphical user interface: controller parameter changing, select between multiple controllers, perform identification experiments, auto-tuning.

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