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Identification and Control of an Autonomous Mobile Robot

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***Abstract*—In this paper we present a system identification and control strategy for track following of a differential drive autonomous robot system. The robot is built with off the shelf components and its main goal is to participate in mobile robotic competitions as well as to be used as a testbed for research and education experiments. The improvement of performance obtained by applying a controller, whose design is based on the system identification, is shown. From identification we get the model, then we design the controller and finally some tests are presented.**

I. INTRODUCTION

Mobile Robotics competitions are a common practice to disseminate robotics to the general public and attract students to engineering areas. Actually, a robotics project train students simultaneously in foundational aspects of designing, controlling, and programming robots and embedded systems [1]. Over 100 robotic competitions exist [2] and one of the most critical challenges in these competitions is the balance between the science knowledge involved and the entertainment value. Media attention is very sensible to the entertainment value and this is very important to attract sponsors. However, pure entertainment competitions lack of technical contributions. Many popular robotic contests in some TV channels deal with remote operated mobile "‘robots"’ and are completely out of scope of this paper. There are competitions much more science oriented, involving much more research relevance [3]. RoboCup [4] [5], for instance, mainly driven by the artificial intelligence community, is an example of a good balance between the entertainment value (with the association to the very popular soccer) and the scientific challenges involved for making autonomous robots able to interact with each other like humans do, with the challenge that in 2050 a humanoids robot team will be able to play (and win) a game against the human soccer world cup winner teams. For autonomous driving the Darpa Grand Challenge [6] in 2005 was a success as five fully autonomous robots were able to make a 175 miles from Los Angeles to Las Vegas winning a two million dollars award. In November 2007 Darpa Urban Challenge is scheduled to take place on November 3, 2007 in a location that will only be revealed in October. Several Science associations run their annual robotics competitions like the AAAI Mobile Robot Competition, the Association of Unmanned Vehicle Systems, etc. The IEEE Robotics and Automation Society is also defining the rules for a yearly robotics competition. Some universities run their own local competitions like the IARC at IST in the Technical University of Lisbon [7]. In this contest, a standard Autonomous Mobile Platform, so called *Rasteirinho*, has been widely used.

A. Related Work

Control of a mobile robot for following a track using image processing is been widely addressed (see [8], [9] and the references therein). It provides a good test bed for image processing and control algorithms.

Image processing took advantage of low cost cameras and increased hardware power and the robot is now able to extracting features from raw image [10] to simultaneously know its position while making a map of the environment using low cost web cameras instead of expensive Laser Range Finders.

The issue of Simultaneous Location and Mapping (SLAM) is widely addressed in [11], [12].

II. AUTONOMOUS MOBILE ROBOT PLATFORM

We built a low cost mobile robot with commercial off-the-shelf components. The total cost depends on the choices of each component, but the overall cost of the robot is under 200 Euros (of course, this price does not include the laptop cost, which we consider already available). The first robot of the series, so called *Rasteirinho*, is described in more detail in [13]. It uses a low cost USB card and motors, batteries and chargers of disassembled low cost electrical screwdrivers and drills. The laptop is easily attached to or removed from the robot because it is mechanically fixed to the robot by easily detachable Velcro bands. Moreover, the only electrical connection to the robot is through a single cable to the USB port. Figure 1 shows the mobile robot built where we may see several robot components and the final assembly. The advantage of such a simple robot is that it becomes possible to lend the robot to the students freeing the laboratories occupancy and providing a new challenging and unusual peripheral for the students own laptops.

III. MODEL IDENTIFICATION OF THE MOBILE ROBOT

The importance of having a model of the open-loop system in order to design a controller is a key factor to achieve

Fig. 1. The low cost Autonomous Mobile Robot.

a satisfactory closed-loop performance. Hence, this section, firstly presents an overview of the applied methodology that was performed to obtain a model of the Autonomous Mobile Robot (AMR). Then, the identification results are presented.

A. The Applied Methodology

Obtaining a model of a system depends on its purposes. In this paper, the objective is to obtain the open-loop model of the AMR, such that it can be used as a starting point to design the controller. One way to tackle the modelling problem is to obtain the model based on the physical characteristics of the system. However, the AMR is highly nonlinear, due to the intrinsic dynamics of a non-holonomic system, but also due to dead-zone effects of the motors, Coulomb friction and slippery of the wheels, etc. And, of course the identification of each parameter of the nonlinear model is a hard and prone-to-error task.

Therefore, the adopted strategy is to identify the system from experimental input/output data, such that the effects of the most important nonlinearities could be decreased. To achieve that, the motors were subjected to the same voltage ($V_{nominal}$) outside of their dead-zones, and the tests were performed on linear and soft-curved portions of the track, such that the intrinsic nonlinear terms of the AMR dynamics (i.e. the terms in *sin* and *cos*) could be mitigated.

The output data was the horizontal position of the center of mass of the track in the acquired image, and the input data was the differential voltage (δV) supplied to the motors:

$$V_{rigth} = V_{nominal} + \delta V$$
$$V_{left} = V_{nominal} - \delta V$$

where V_{rigth} and V_{left} are, respectively, the voltages applied to the right and left motors, and $V_{nominal}$ the voltage related with the tangential velocity of the AMR.

However, in open-loop, the AMR is not stable since for a constant (δV) the output diverge. Hence, a closed-loop identification strategy was applied. The loop was closed with a stabilizable constant gain K, and some experimental tests were performed on the track. The input of the closed-loop system was the horizontal coordinate of the center of the image, and the output was the horizontal position of the center of mass of the track in the acquired image.

With the obtained data, and using the MATLAB® Identification Toolbox, a closed-loop model ($G_{cl}(z)$) was obtained using the prediction error method and an ARMAX model.

From the well-known discrete transfer function of the closed-loop, i.e. $G_{cl}(z) = \frac{K \times HG_{ol}(z)}{1 + K \times HG_{ol}(z)}$, the open-loop transfer function can be derived, i.e. $HG_{ol}(z) = \frac{G_{cl}(z)}{K \times (1 - G_{cl}(z))}$, where $HG_{ol}(z)$ represents the discrete transfer function of the cascade connection $[(Zero - Order - Hold) \times G_{ol}(s)]$.

Finally, from $HG_{ol}(z)$, the continuous time transfer function of the open-loop model was derived, i.e. $G_{ol}(s)$.

B. Identification Results

The identification tests were performed with a sampling time of 0.05 seconds, $V_{nominal} = 0.3 \times V_{max}$ Volts (where $V_{max} = 5$ Volts), and a proportional gain of $K = 0.0015$. Figure 2 presents the control structure that was implemented in Simulink®, and then used to obtain the identification data.

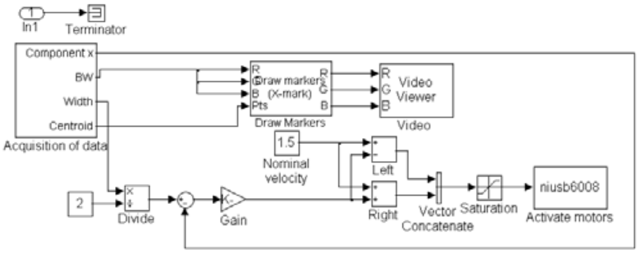

Fig. 2. Control structure used for identification.

Figure 3 presents one example of the identification data, i.e. the closed-loop response of the AMR following the track, when controlled by a proportional controller. The obtained closed-loop transfer function was the following:

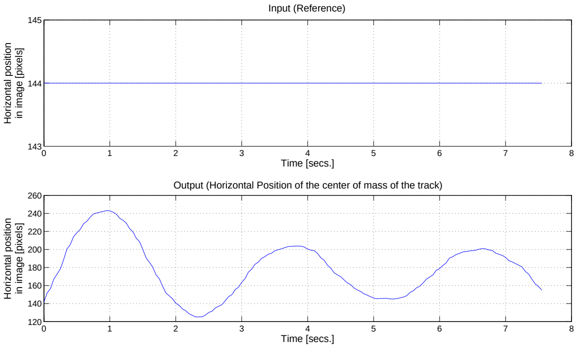

Fig. 3. One example of the obtained identification data.

$$G_{cl}(z) = \frac{0.01347}{z^2 - 1.969z + 0.9798}$$

Based on $G_{cl}(z)$, the following open-loop model was derived:

$$G_{ol}(s) = \frac{5.446}{0.001s^2 + 0.0004073s - 0.0009205}$$

Figure 4 presents the actual closed-loop response and the one obtained when the closed-loop system is simulated with the obtained $G_{ol}(s)$. As we can see the responses are similar enough to give some confidence on the obtained model, as far as the work and test conditions be similar.

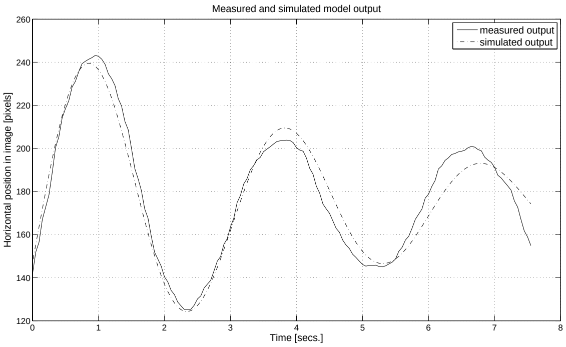

Fig. 4. Comparison between the actual measured output and the one obtained when the closed-loop system is simulated with the obtained $G_{ol}(s)$.

IV. CONTROLLER DESIGN

Once the system is identified, it is possible to design a controller that fulfills the performance specifications. The specifications for track following are mainly to guarantee system stability (even when modelling errors and unknown disturbances are present) and to assure a sufficiently fast and smooth (not very oscillatory) response.

The system root locus for a proportional gain K is presented in Figure 5. As can be easily deduced the stability margin of the closed-loop system is very small, and the fastest achievable settling time is 15 seconds (to achieve 95% of the stabilizing value).

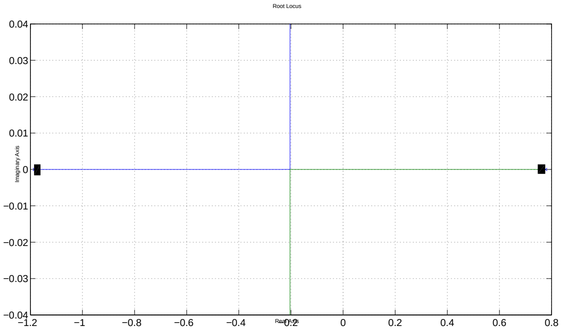

Fig. 5. Root locus for a proportional gain K (black squares denote the location of the open-loop poles)

In order to improve the transient response of the close-loop system, a continuous-time lead compensator was designed. The specifications were a time constant of 0.5 seconds and a dumping coefficient of 0.7, and the following lead compensator was obtained:

$$G_c(s) = 0.0015 \times \frac{5s + 10}{s + 10}$$

Figure 6 presents the root locus when the lead compensator is introduced into the control loop.

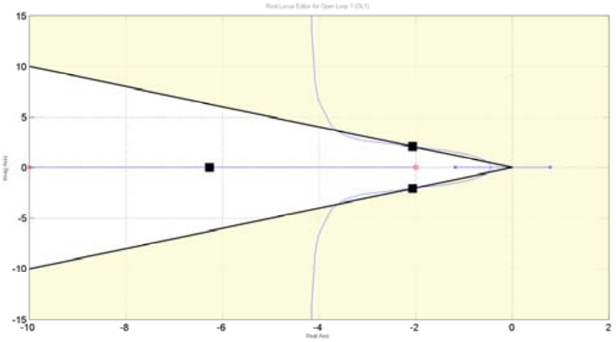

Fig. 6. Root locus with the lead compensator (black squares denote the location of the closed-loop pole when $K = 0.0015$).

Figure 7 presents the open-loop bode diagrams when the lead compensator is introduced into the loop. For a gain $K = 0.0015$, the stability margins are the following: 46.9 degrees for the phase margin, and 16.7 dB for gain margin. These results indicate that the closed-loop system should present good robust stability characteristics.

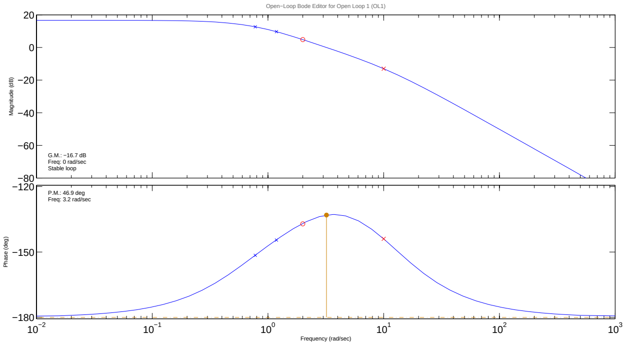

Fig. 7. Open-loop bode diagrams when the lead compensator is introduced into the loop, with a gain of $K = 0.0015$.

V. EXPERIMENTAL RESULTS

The main motivation of this paper is to develop and implement a controller that adjusts the AMR behavior in an autonomous driving mobile robot competition, and so the most important task to test is the track following ([14],[15]). The tests were performed on the track shown in Figure 8.

The control system was implemented in Simulink® over Windows® XP operating system. To achieve a constant sampling-time period in real implementation, the Real-Time Blockset for Simulink (by Leonardo Daga) was used.

Figures 9 and 10 present the implemented simulink blocks, which process the acquired image and control the motors. The obtained continuous-time lead compensator was convert into discrete-time by the zero and pole matching method, which yield the following controller:

$$G_c(z) = 0.0015 \times \frac{4.135z - 3.741}{z - 0.6065}$$

The track was covered starting in front of the zebra-crossing following as reference path the outer limit line (referring to

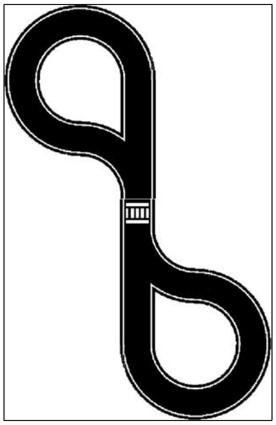

Fig. 8. Top view of the track.

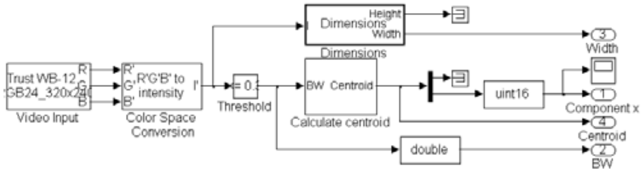

Fig. 9. Simulink block that performs image processing.

Figure 8, the AMR started its movement to bottom of the figure). The robot was stopped after one complete turn of the track. Figure 11 show the track following performance of the AMR. As can be seen from the results, the behavior of the AMR is fairly smooth and its overshoots are due to some shadows on track, and also to some imperfections on the floor.

In order to compare the behavior of the proportional controller with the lead compensator, a different experimental test was made, since the proportional controller was unable to complete a turn. In fact, this result was expected since the stability margin associated with the proportional controller was very small.

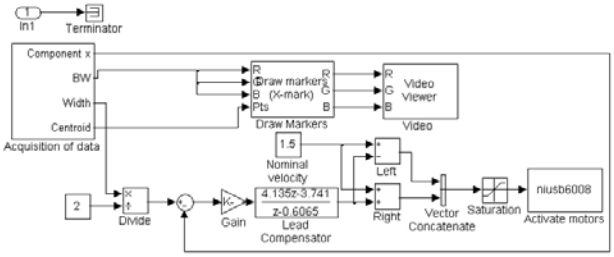

Fig. 10. Simulink block that controls the motors.

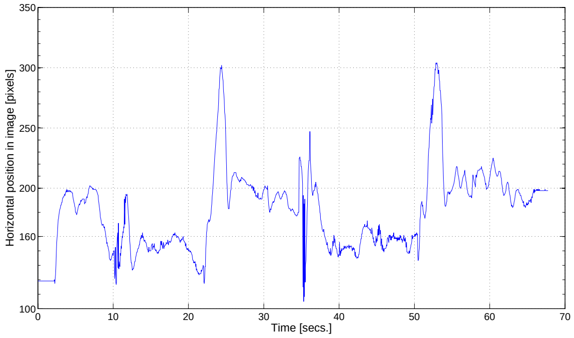

Fig. 11. Horizontal position of the center of mass of the track (reference = 160) .

The comparison between both controllers was based on the response to a step change on the reference of the closed-loop system. The results presented in Figure 12 show that the behavior attained with the lead compensator is far less oscillatory, much faster and also with much less stationary error than the performance attained with the proportional controller. These results reinforce the incapability of the proportional controller to circumvent the all track. Furthermore, in Figure 12 it can be seen that the transient behavior of the close-loop system when controlled by the lead compensator is compatible with the desired specifications. A movie of the robot following the complete track can be found in *http://www.dem.ist.utl.pt/∼cardeira/papers/Robotica2007/video.MPG*.

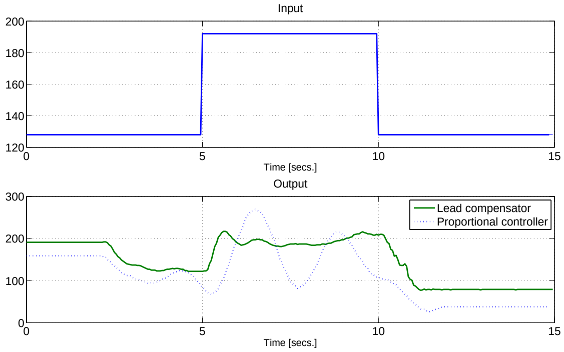

Fig. 12. Comparison of performance between the lead compensator and proportional controller.

VI. CONCLUSIONS

A closed-loop identification method was applied to obtain the model of the robot coupled with the image acquisition system. The applied identification approach has some drawbacks concerning the existing correlation between system input and output. Despite that fact, the obtained identification results seem satisfactory, since the designed lead controller, which was based on the identified open-loop model, behaved as expected when was subjected to a step change on the reference signal. The robustness of the lead compensator, compared with the proportional controller, was also shown, by its capability to control the AMR during a complete turn to the track.

Although the obtained results can be defined as very satisfactory, much work must be done to improve the performance of the AMR. A possibility is to apply hybrid identification and control techniques to improve the performance of the robot [16], [17].

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