Teaching Equipment for Training in the Control of DC, Brushless, and Stepper Servomotors

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Abstract—This paper describes teaching equipment for instruction in motor control developed in the Electronics Department of the University of Alcalá. This project (called Project DEDALO)[1] involved the development of complete electronic equipment for studying and carrying out experiments on the control of stepper, medium, and low-power dc and brushless motors. The use of a personal computer as user interface (for the setting up of different types of motors and controls, display of the control structures, signal display, generation of commands, etc.) makes the equipment very easy to use and highly versatile.

Index Terms—Educational experiments, motor control.

I. INTRODUCTION

USING mechanical actuators based on electric motors is one of the most widely used options in industrial and consumer applications. This growing demand, together with the call for better performance in systems using electric motors, explains why more and more electronic devices (controllers, drivers, etc.) are marketed, designed to facilitate and improve the control of electric motors. Moreover, great advances have been made in the field of electric motors, bringing about a significant improvement in the performance and range of different types, models, etc. For any application many different alternatives are now available, in terms of hardware control, output or type of motor.

Inevitably, the curricula of all teaching centers dealing with such matters have always included instruction on methods and devices for the control and driving of motors, both from the theoretical and practical points of view. The teaching equipment described in this paper aims to make this task easier, offering in a single environment, the possibility of testing different types of motors and different means of controlling and/or driving each one.

The equipment includes five hardware modules (boards), one for each type of motor (four in all) and another one for their control and driving and for the data acquisition and PC interface. Easy-to-use software, specially designed

[1] DEDALO is the Spanish acronym for Desarrollo de Equipos Didácticos de Asistencia en Laboratorio (Development of Teaching Equipment for Laboratory Assistance).

for teaching purposes, has also been developed; it allows the following functions to be carried out with a PC using Windows: selecting the type of motor to try out; setting up the different control methods; generating commands; on-screen display of the control system block diagrams, with information on the function and most important characteristics of the devices forming each block; visualization of the signals of greatest interest within each of the circuits used in the different control methods, etc.

II. SYSTEM ARCHITECTURE

The system (trainer) developed is shown in the general block diagram of Fig. 1. It will be seen that there are five modules or boards: one for interface, data acquisition, and control (main board), and four other for driving each of the types of motor to be studied.

A feature common to all the boards is the incorporation of several trial points for visualizing on an oscilloscope or computer screen the most important values appearing in the most significant points of the circuits making up the control system. At the same time, the component layout allows the user to identify the different devices that intervene in each control method.

The functions assigned to each of these boards is described below.

A. Main Board: Interface, Data Acquisition, and Control

The control board is the hub of the system, responsible for setting up, controlling, and supervising the system operation, in accordance with the selection made from the PC. In greater detail its functions are as follows.

1) Receiving from the PC in parallel port the setting and control commands for the type of motor selected by the user.
2) Sending to the PC information on the status of the equipment and the existence of any abnormality.
3) Sending to the PC the real-time captured samples of the various signals from the driving board in use. The software executed in the PC will thereafter automatically display them as appropriate.
4) Generating from a single 24-V power source the different voltages necessary for the motor driver boards.
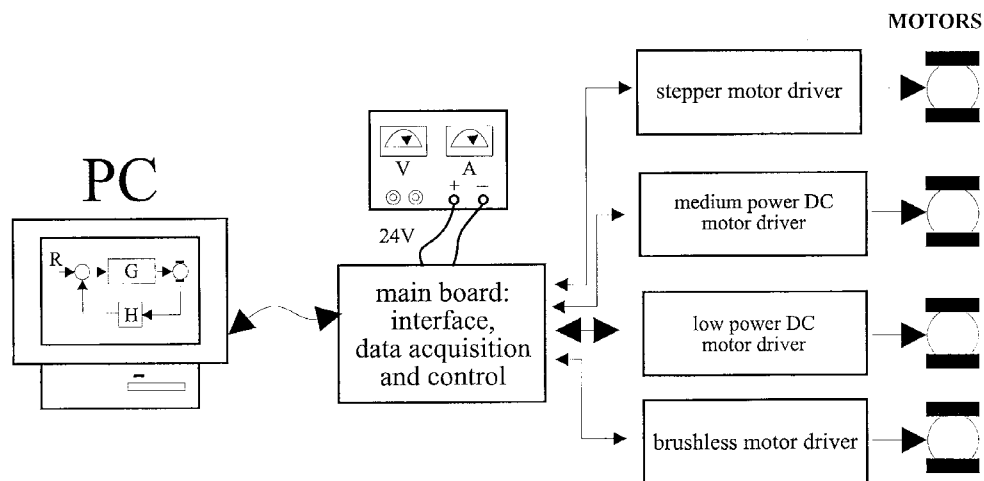5) Generating manual control commands, using an optical encoder.
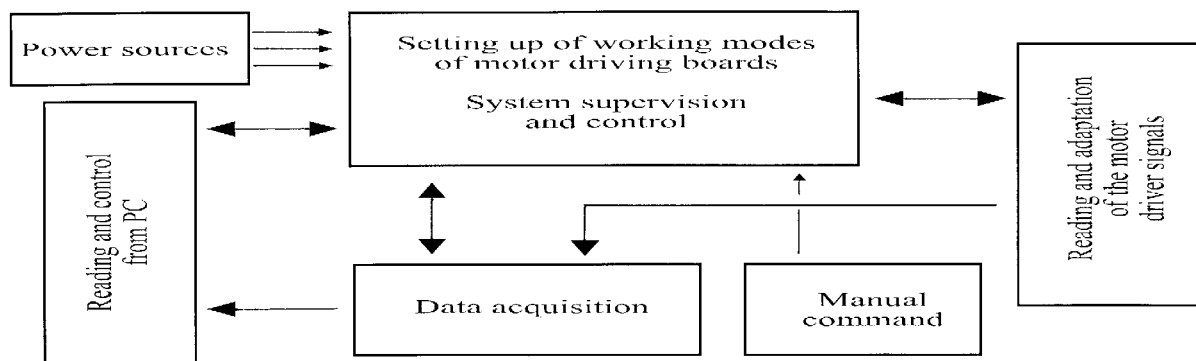
Fig. 1. General bolck diagram of teaching equipment.

Fig. 2. Block diagram of the main board.

6) Sending each of the motor driver boards the signals they need to work properly: operation-mode signals, actuation signals, and, depending on the type of board, command signal (open-loop control), phases, clock (step-by-step), etc.

Fig. 2 shows a diagram of the functional blocks of this board and Fig. 3 shows a photograph of the same.

The most important devices of the board include a micro-controller, two ASIC's for motor control, two FPGA's [1] containing all the logic necessary for data acquisition and setting up of the system. To this must be added the circuitry necessary for converting the digital codes into signals suitable for acting on the connected interface board.

The control board of the DEDALO system has a two-way interchange of data and commands with the PC through the parallel port. This guarantees a high rate of information interchange and also allows supplementary lines to be used for the control of data links. Data interchange is effected using frames up to 256 bytes long, with a final frame checking. Three one-way transfer control lines are also used: two from the PC to the control board and one from the control board to the PC. The information is transmitted byte by byte until each frame is completed, following a suitable protocol in the control lines. The transfer is asynchronous, the rate of transfer being limited by the slowest processor of them (similar to the IEEE488 interface); this feature means that the communication
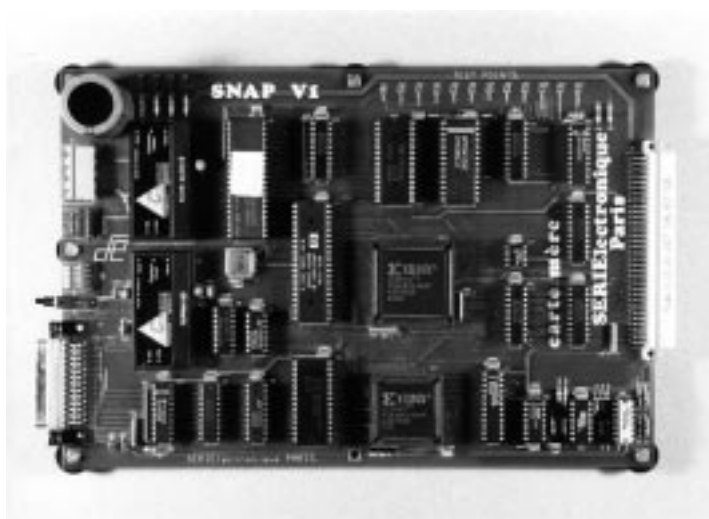

Fig. 3. Photograph of the main board.

is always done at the highest rate possible, regardless of the PC or microcontroller. The board allows selection of the control mode, of the circuit used, of the type of actuation signal, and of the origin of the command.

An open- or closed-loop control may be chosen.

1) *Open-loop control:* In this mode the commands are generated by a digital potentiometer on the board or by

commands sent from the PC. In open-loop control no additional action is necessary by the board.

2) *Closed-loop control:* In this case the command comes from the PC. Three different alternatives may be chosen:

a) By means of controller LM628 [2]: This is a 32-bit controller manufactured by the firm National Semiconductor, although the final actuation signal is a code of 8 or 12 bits. The digital control algorithm is that of a PID expressed by the following formula:

$$u(n) = K_p * e(n) + K_i \sum_{N=0}^{n} e(n)$$
$$+ K_d[e(n') - e(n'-1)] \qquad (1)$$

where $u(n)$ is the regulator output, $e(n)$ its input, n is the present sample, taken at intervals of $2048/f_{\text{clock}}$ (f_{clock} being = 8 MHz, i.e., the frequency of the general clock of the integrated circuit), $e(n')$ is the sample for the calculation of the derivative term of the PID (taken at intervals of whole multiples of n) and K_p, K_i, and K_d are the proportional, integral, and derivative constants, respectively. The modifiable digital control parameters are the PID constants and the sample interval for the derivative term, programmable from $2048/f_{\text{clock}}$ to $256 * 2048/f_{\text{clock}}$. Position or speed controls can also be carried out.

b) By means of controller HCTL1100 [3]: This controller, manufactured by Hewlett-Packard, works with less internal resolution than the LM628, but offers more alternatives in terms of controlling the different types of motors. The actuation signal may be obtained as a digital code and at the same time as a PWM signal with module and sign. Phases can be generated by an encoder, for brushless and stepping motors. Speed and position can be controlled by a discrete transfer function, with three adjustable parameters called A, B, and K, expressed by the formula

$$D(z) = \frac{K\left(z - \dfrac{A}{256}\right)}{4\left(z + \dfrac{B}{256}\right)}, \qquad (2)$$

It also offers the possibility of modifying the sampling period. The commands are codified in 8, 16, or 24 bits, depending on the type of control being used.

c) By means of control algorithms executed by the microcontroller: To give the system greater flexibility, there is also the possibility of carrying out control algorithms without resorting to any circuit for that specific purpose: the microcontroller itself executes them.

One of them is the microstep control for stepping motors. In this case, the microcontroller generates both the voltage references and the phase signals. The codes it generates subdivide each complete step

in ten intermediate positions or microsteps. To obtain a more or less even separation between microsteps, the currents through the windings I_A and I_B have to follow the sequences:

$$I_A = \sin\left(\frac{90\,n}{s}\right) \qquad I_B = \cos\left(\frac{90\,n}{s}\right) \qquad (3)$$

"s" being the total number of microsteps and "n" the present microstep ($1 \leq n \leq s$).

Once the controller has been chosen different actuation signals may be selected, depending on the motor driving board connected.

The available actuation signals are: analog voltage (unipolar or bipolar), PWM plus sign signal and PWM without sign signal (motor stopped at 50% working cycle; at more than 50% it turns in one direction, and at less than 50% in the opposite direction).

These signals are generated as follows:

1) *Actuation by analog signal:* A D/A converter converts the digital code provided by any of the three controllers into bipolar configuration.

2) *Actuation by PWM signal without sign signal:* A counter and a comparator convert the digital code provided by any of the three controllers.

3) *Actuation by PWM signal plus sign:* directly from the output provided by the HCTL1100 controller.

The "data acquisition" block transmits to the PC, through the parallel port, the signal samples related to the control of the motors (command, applied signal, etc.) and to the status and progress of same (rate, position, consumption, errors).

As regards control signals, it provides the desired rate value (or position value) as well as the voltage or working cycle value, as appropriate, of the actuation signal.

As for the actual status of the connected motor, the speed (or position) is captured, and in the case of a brushless motor, a sample is taken of the current running through the windings. In the case of stepping motors, activation phases are also given.

B. Driving Board for Medium-Power DC Motors

Fig. 4 shows the block diagram of this board and Fig. 5 a photograph of same.

This model is for controlling 24 V dc motors up to 50 A. The driving circuit consists of an H bridge formed by four n-channel MOS transistors; this allows for a four-quadrant control using a single power source [4], [5]. The bridge is controlled by a PWM signal from the adjusters of the main board.

The switching strategy of the H bridge is bipolar, i.e., the transistors of the H bridge are excited by crossed pairs according to the PWM signal. When the working cycle of the PWM signal is 50% the motor will be stopped. It is turned in one direction or the other by making the working cycle more or less than 50%.

The most important features of this module are:

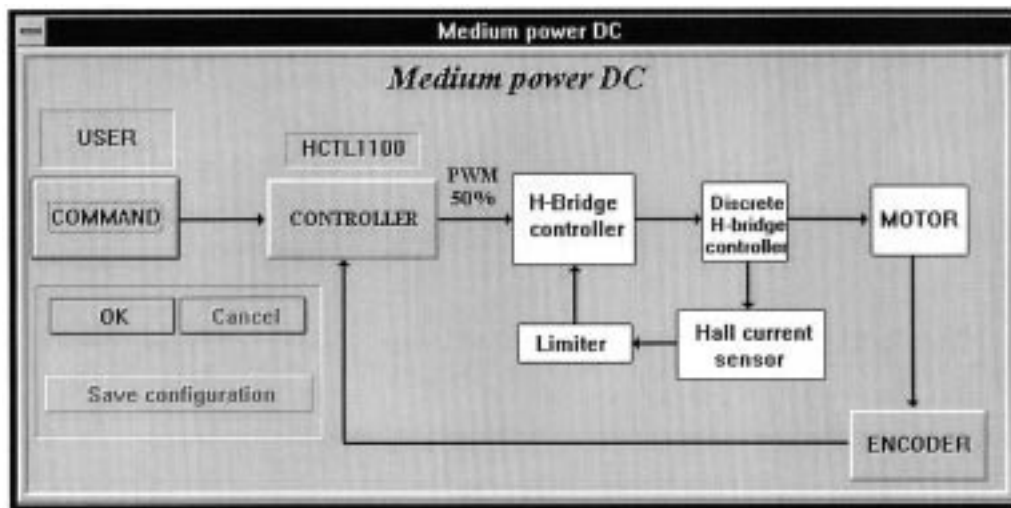1) Four quadrant control of motor with a single power source and n-channel MOS transistors.

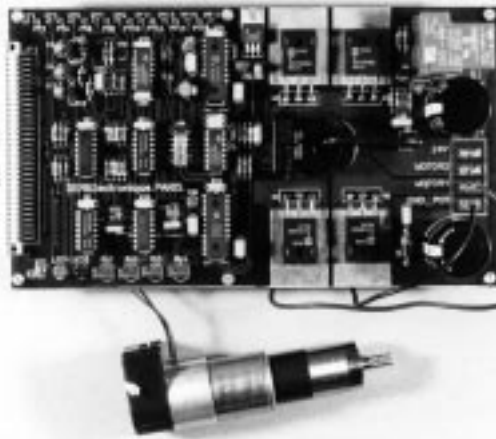Fig. 4.   Block diagram of the driving board for medium-power dc motors.

Fig. 5.   Photograph of the driving board for medium-power dc motors.

2) Power supplied to bridge after establishing control signals.
3) Excitation of MOS transistors by ASIC's; this prevents the simultaneous excitation of two transistors on the same side of the bridge.
4) The use of nonaudible driving frequencies.
5) Protection against power drops or failure in any bridge transistor.
6) Monitoring of motor current by a Hall-effect sensor.
7) Overcurrent protection. The motor current can also be manually adjusted to the desired value. If a momentary overcurrent is detected the bridge is blocked and normal working of the motor is immediately restored when the overcurrent has passed. Only if the abnormality persists for a pre-established time will the main board shut down the circuit. A LED lights up to show these fault situations.
8) Possibility of setting a speed or position control of the motor, as chosen on the main board, by a feedback coming from encoders located in the motor shaft.

C. Driving Board for Low-Power DC Motors

This board (Figs. 6 and 7) enables trials to be carried out on 24-V dc motors up to 2 A, using the commands sent from the main board.

Three different motor-driving or -control modules have been developed.

1) Linear control of current or voltage. This involves two operational output amplifiers, set up as a linear bridge so that four-quadrant control can be maintained with a single power source (AAOO unipolar power source)
2) Current servocontrol. This involves an integrated circuit L292 [6] which includes the motor driving bridge and primary current feedback stage. It also incorporates a voltage-internal PWM converter, as the control signal is bipolar analogical (positive for one turning direction and negative for the opposite).
3) Control by means of n-channel MOSFET transistor bridge with various driving modes, namely:
   a) PWM for bipolar excitation of bridge. If the working cycle is 50% the motor is stopped; if it is less than 50% the motor turns in one direction, and if greater, in the opposite direction.
   b) PWM for unipolar excitation of the bridge plus a sign signal to indicate the turning direction of the motor.
   c) Excitation with an analogical unipolar signal (converted in the same circuit to PWM to excite the bridge) plus a sign signal to indicate the turning direction of the motor.

All these driving methods are based on two single integrated circuits.

Regardless of the working mode used, the board allows the following:

1) Self-setting up for each mode of operation, according to the signals received to this effect from the main board.
2) Use of command signals received from the main board, which allows in all cases a control of the speed or position of the motor.

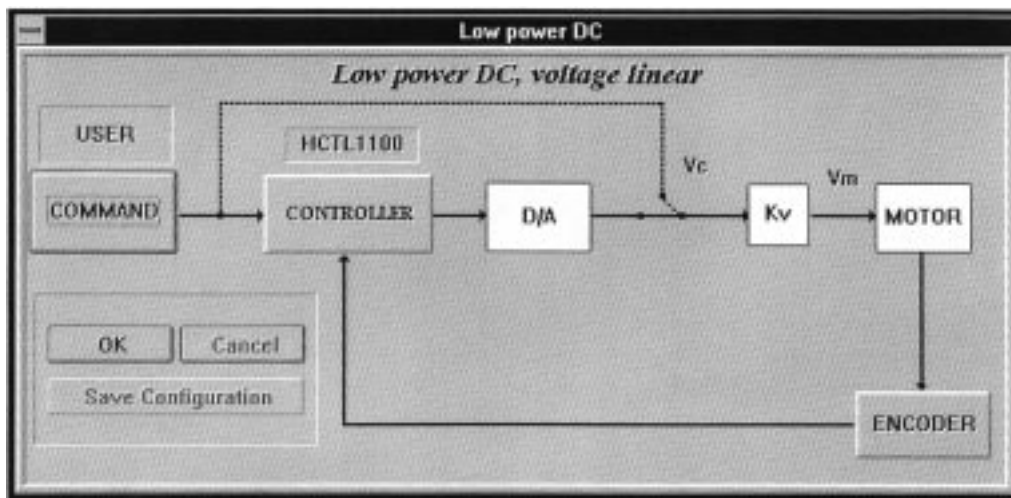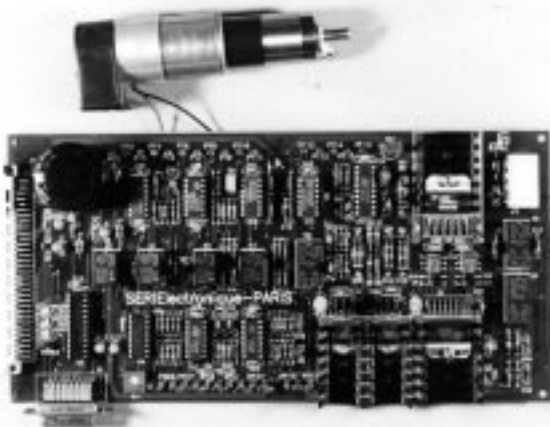Fig. 6.   Block diagram of the driving board for low-power dc motors.

Fig. 7.   Photograph of the driving board for low-power dc motors.

3) A potentiometer, located in the same board, can also be used to generate the driving command (thereby allowing trials to be carried out eliminating the need of having the main board available). In this case, obviously, only an open-loop control is possible.

4) An additional connector has also been included so that the board can be used together with other user-specific hardware, always providing that the levels and demands of the signals in question are respected, in accordance with two possibilities:

  a) Using the adjuster outlets of the main board as motor driver inputs designed or set up by the user.

  b) Using the command signals (without passing through the adjusters of the main board) as drivers for the user's own adjuster. The output of this adjuster can be connected into any of the board drivers.

D. Driving Board for Stepper Motors

The driving board developed (block diagram—Fig. 8; a photograph—Fig. 9) allows bipolar, two-winding stepping motors to be controlled. Its basic function consists of transforming the signals from the main board into signals strong enough to drive the motor.

Its architecture is based on two subsystems [7], [8].

1) Phase signal chopper ($A, B, C,$ and D) which allows adjusting of the current running through the windings. A comparison between the voltages proportional to the current running through the windings and a reference voltage (two in the case of a microstep) fixed by the user tunes the phase chopper in to the rhythm imposed by an oscillator (also adjustable by the user).

2) Two H bridges, one for each winding, incorporated into the same integrated circuit next to the free circulation diodes.

The allowed operating modes are those of a bipolar stepping motor.

1) Full (or single) step with the two windings excited.
2) Full (or single) step with one winding excited.
3) Half step.
4) Microstep.

The first three modes can be executed by means of two different techniques:

1) Receiving three signals from the microcontroller of the main board: clock, turning direction, and working mode. A transfer circuit then generates as appropriate the phases $A, B, C,$ and D. Fig. 6 shows the block diagram and Fig. 7 shows a photograph of a motor working in half-step mode and based on the transfer system incorporating the CI L297.

2) Receiving the phase signals ($A, B, C,$ and D) directly from the main board. These signals in turn can be generated in the microcontroller 80C51 or in the controller HCTL1100 (for which it has to receive the signals from the motor encoder), as the user chooses.

The interest of the microstep mode lies in the possibility of making the transition of the motor between two consecutive steps more gradual, as well as being able to use intermediate positions not possible with other modes (full step or half step). Although one complete step has been split into ten divisions,
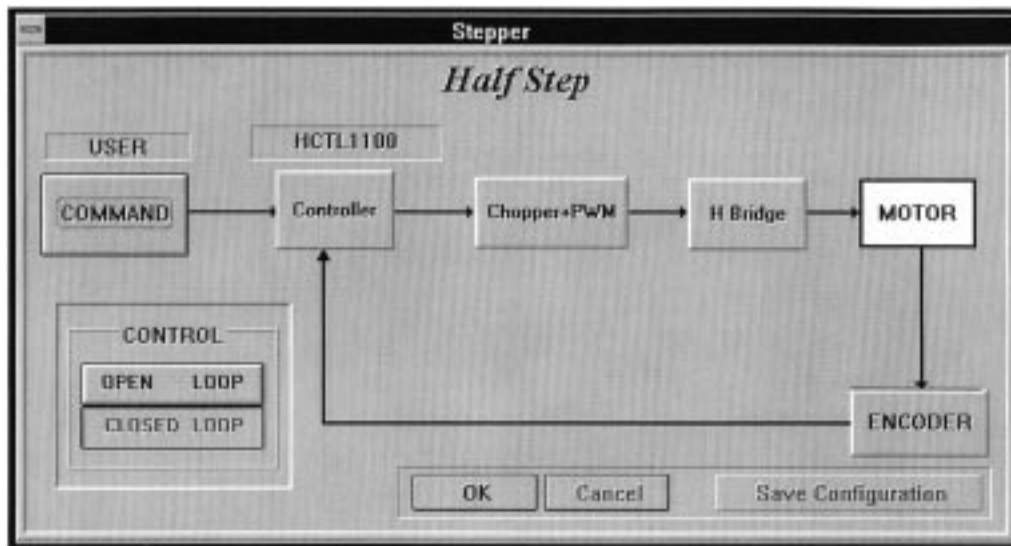
Fig. 8. Block diagram of the driving board for stepper motors.

Fig. 9. Photograph of the driving board for stepper motors.

$s = 10$ from (3), the microprocessor of the main board could be reprogrammed for any other microstep setup.

Of the different systems available for microstep mode working, the one incorporated is that which varies the reference voltages of the phase-chopping system, by sinusoidal approximation. In this case, two voltages are needed, separate and $90°$ phase-shifted, which the main board sends codified in 6 bits. Subsequent electronic processing is carried out on this driving board.

The board also incorporates a LED that, when out, indicates the motor is working properly; if the motor is not working properly the LED lights up or flashes (both windings or only one are not conducting current).

E. Driving Board for Brushless Motors

Brushless motors [9], [10] have important advantages over dc motors in terms of the torque/speed ratio, heat dissipation, lack of brush location problems, radio-frequency interferences, lack of electric arcs, etc. They are therefore being used ever more widely in industrial applications of robotics, numerical control, machine tools, etc. It was therefore considered important to include a brushless motor model in the equipment developed.

The driving module for brushless motors, developed within the DEDALO project, allows the driving of brushless motors of counter-electromotive force and trapezoidal current and of sinusoidal counter-electromotive force and trapezoidal current (it is planned to include control of motors of counter-electromotive force and sinusoidal current in the future). Both "wye" and "delta" connection of the windings (phases) is possible. The driver has been designed for 24-V motors up to 10 A.

The following control modes may be used: control by voltage (with analog command or PWM) or by current. This, together with the possibility of choosing open-loop or closed-loop control, means that a great variety of trials can be carried out to put these motors through their paces in the different control modes, and that comparisons can be made with dc motors. By way of example, Fig. 10 shows the block diagram corresponding to control by current. Fig. 11 shows a real-life version of this board.

It should be observed that in all cases the signals indicating the position of armature relative to the field coils can be obtained by Hall sensors or by the regulator. In the last case, the regulator itself monitors the encoder inputs and generates the appropriate sequences accordingly.

Adjustment potentiometers, also included, allow the following options: fixing the maximum current running through the motor (which can be up to 10 A), selecting the amplitude of the command signals, and generating the command signal for open-loop control.

The system's features also include current limiters, protection against overheating and voltage drops, fault detector and indicator, as well as inputs for qualification, braking, and selection of turning direction.

III. SOFTWARE INTERFACE

The motor-control hardware described above is complemented by a software interface that allows the user to become
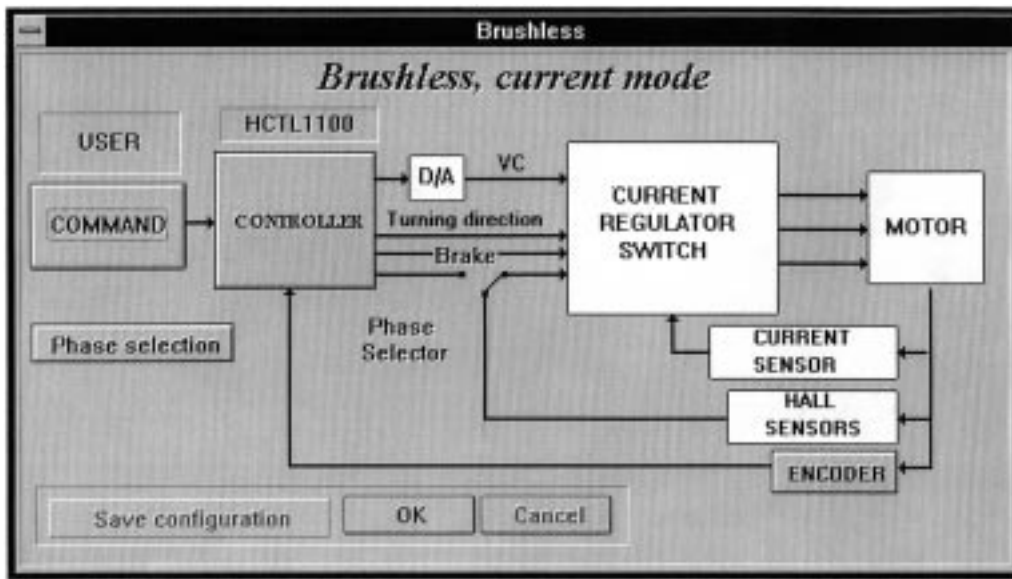
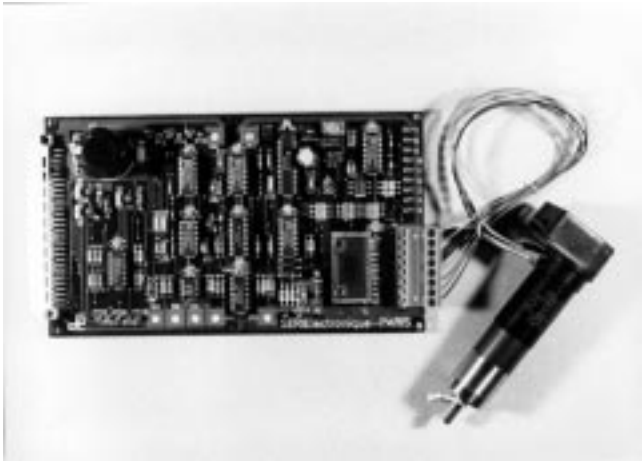Fig. 10. Block diagram of control by current of brushless motors.

Fig. 11. Photograph of the driving board for brushless motors.

completely familiar with the equipment, also giving a general idea of its operation and possibilities. This interface allows the user to set up the motor driving stages, generate commands, visualize test signals, etc.

The software is written in C++ for WINDOWS (3.1 or later version) [11], [12], thereby offering an attractive, user-friendly package (including the option of choosing from three languages: Spanish, English, and French) completely adapted to the latest trends (see Fig. 12 showing the Main Menu).

The working mode has been designed so that the user is obliged from the start to create a "work session." Each "work session" brings together a group of files that store the following information: commands generated, responses obtained from the motors, error measurements, different board setups, etc. Each time a "work session" is activated, the user can work with the aforementioned data. Some of the most frequently used files making up a "work session," such as the motor setup ones, can be imported from former sessions, thereby eliminating the need to generate them anew.

A. Setting Up of Operating Modes

Whenever work is started with the software it is necessary to set up the system operating mode for the type of control desired. The system can be re-set up at any moment, although work can be carried out only on the motor connected to the driving board at that moment, automatically detected by the system.

Depending on the motor chosen, different operating modes are offered. For each mode on the setup screen, a block diagram appears with the possible setups. This block diagram has two objectives: first, that the user has an overall vision of how the control is selected, and secondly, that the control loop itself can be set up with the greatest ease and precision.

Fig. 13 shows one of these screens. Providing that the working mode permits it, the setup allows the following:

1) selection of the type of command,
2) selection of regulator or controller,
3) selection of encoder.

In the window that appears during the setting up of the different modes, blocks are also shown that cannot be set up. Nonetheless, if an attempt is made to access them, a more detailed diagram appears of the structure of the blocks. The user is thereby given a better idea of the control of the main integrated circuits involved in that block, as shown in Fig. 14.

B. Command Generator

This system allows the user to create a command (of position or speed) and then see the response of the system.

For speed commands the system incorporates a graphical editor, as shown in Fig. 15. It works along much the same lines as a function generator. It is possible to work either with predefined signals (triangular, square, sinusoidal) or with signals defined by the user (trapezoidal).

After carrying out a trial with the command defined by the user, and once the data acquisition is complete, the PC screen shows the response of the control system.
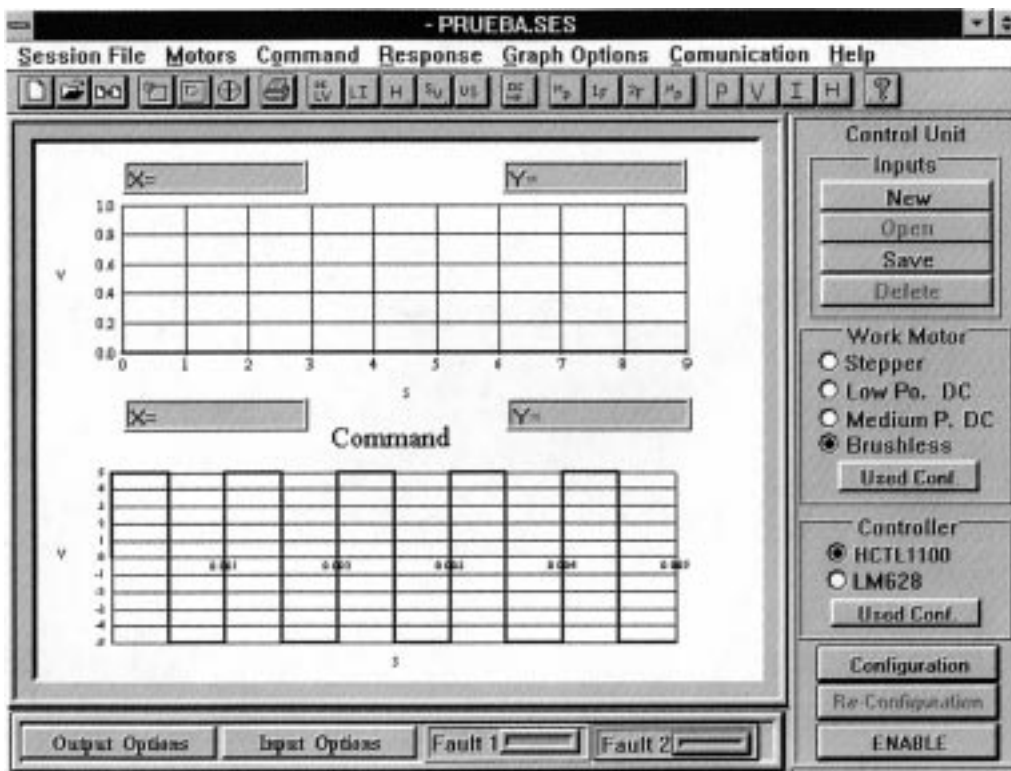
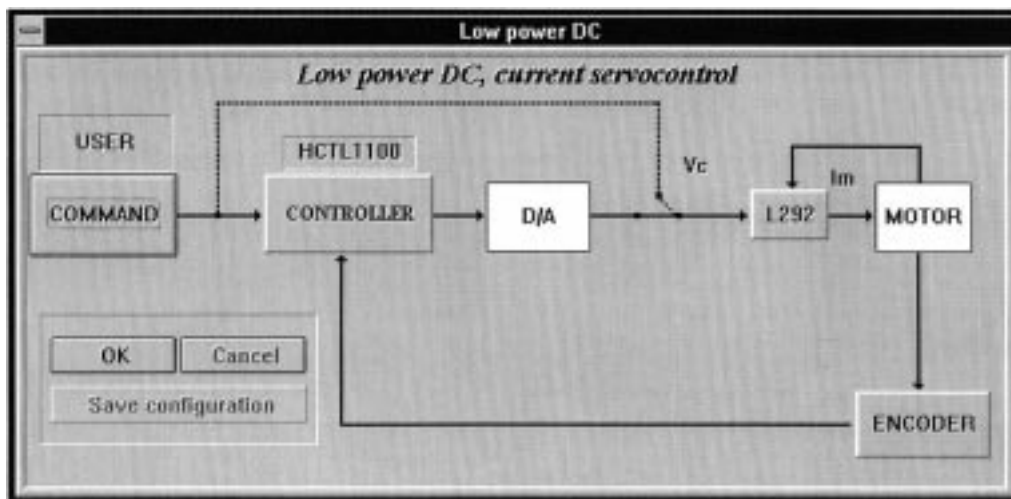Fig. 12. Screen of the main menu of the interface software.

Fig. 13. Example of setup screen of interface software.

C. Signal Visualization

As already mentioned in the descriptions of the boards, there are several trial points. A block diagram shows all the trial points, emphasising those directly visualizable on the PC screen. When one is selected, the subsequent acquisition shows these signals on screen, without having to use an oscilloscope. Fig. 16 shows an example of a trial points screen.

D. Help

As in any WINDOWS application, a help option is included. This gives a precise description of the operation of the system

and of the different control modes that the motors respond to. Theoretical aspects are also included, to facilitate an understanding of the control being used. Also included is a tutorial that allows the user to work the system directly, using only the software and without having to connect any board to the PC. Fig. 17 shows the help screen.

E. Other Important Features

As well as the aforementioned options, the system includes other features to further improve its performance. These include the following.
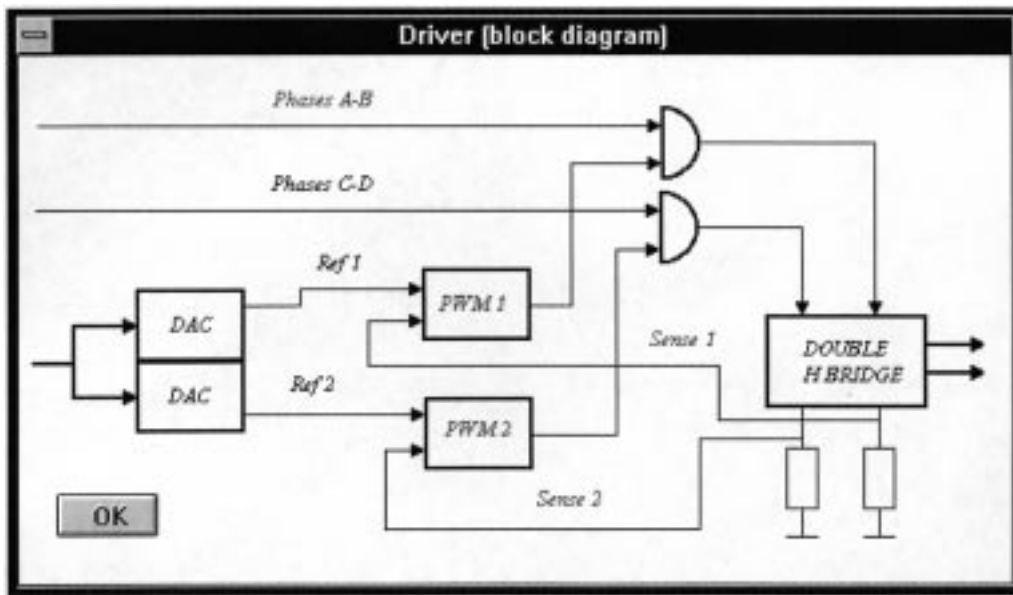
Fig. 14.   Example of setup screen. More detailed structure of a block.
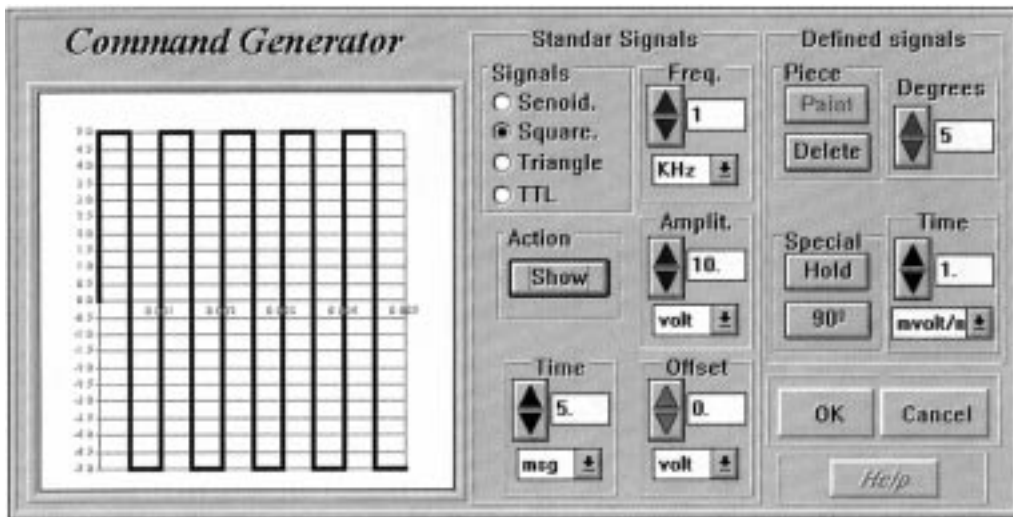

Fig. 15.   Command generator screen of the interface software.
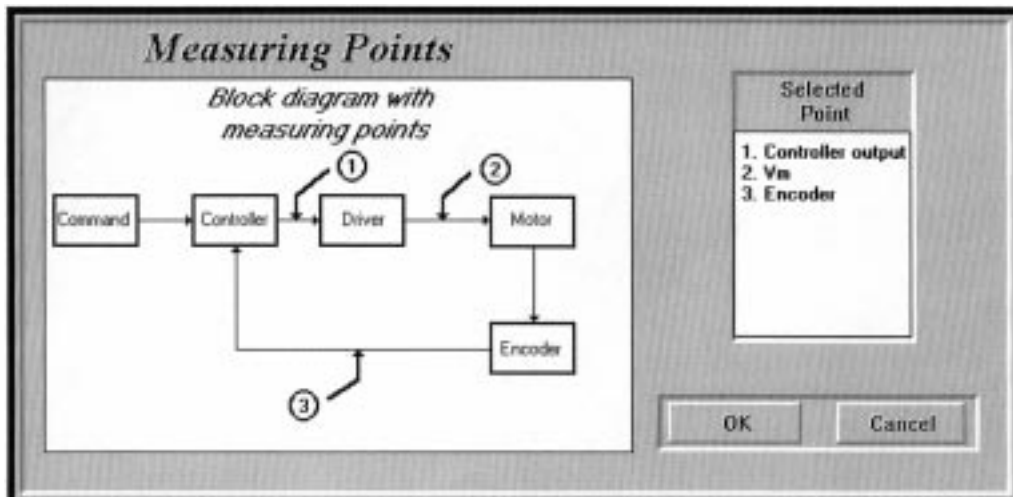

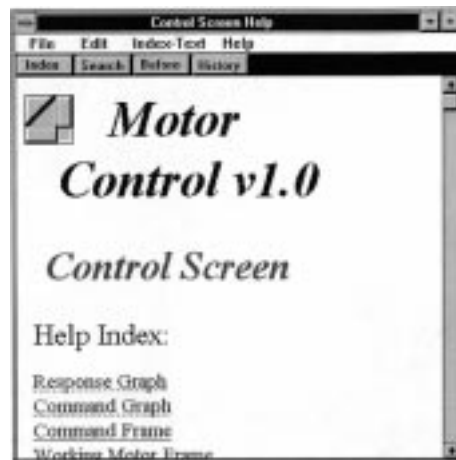Fig. 16.   Example of trial points screen of the interface software.
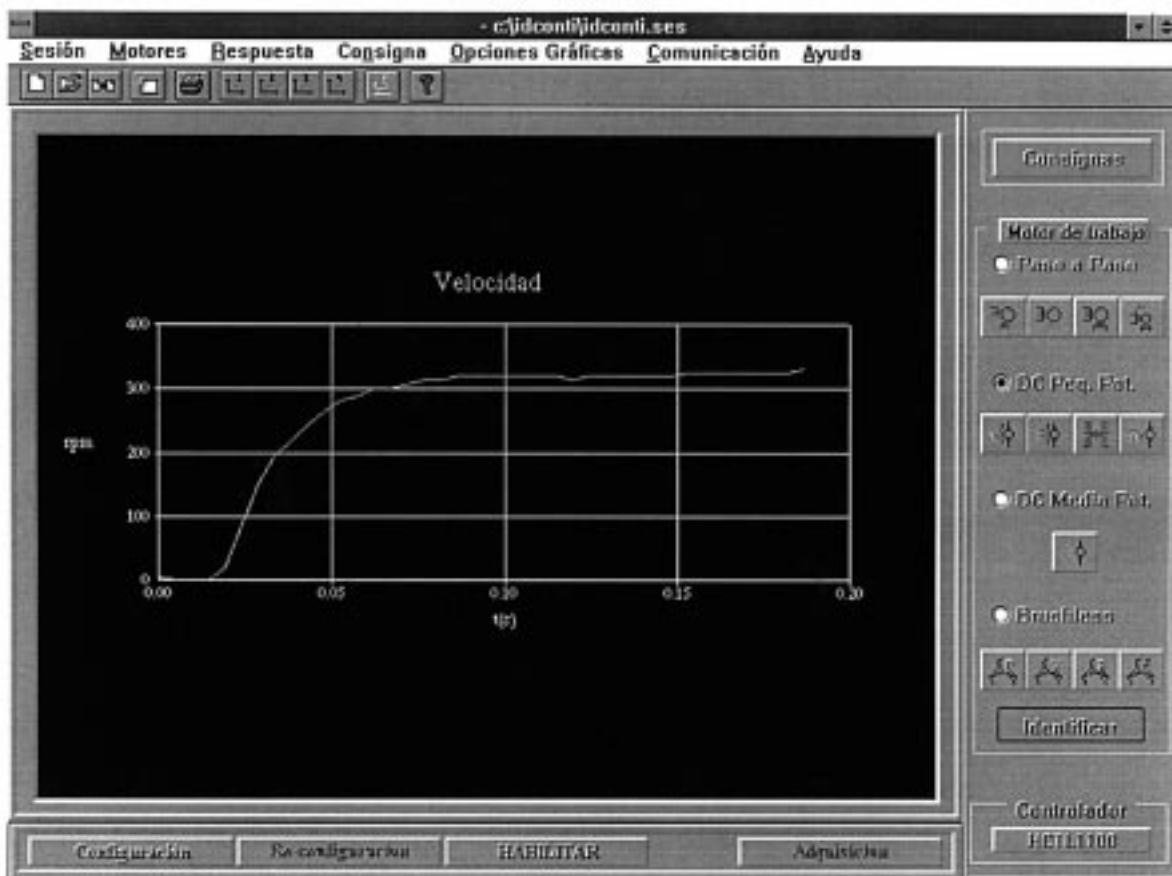
Fig. 17. Help screen of the interface software.

Fig. 18. Result of the dc motor identification.

1) *Signal analyzer:* This allows all the signals to be analyzed simply using tools like zoom and cursors (to make absolute and relative measurements).
2) *Alarm signals:* These warn the user of possible faults or anomalies in the different modules or boards being used at any one time.
3) Data format *MATLAB/SIMULINK-compatible:* A data output format has been included, compatible with these calculation tools. This allows the two systems to be integrated (trainer and mathematical tool) and the user

is thereby enabled to carry out more advanced studies on the control of motors and to obtain conclusions in a simple way.
4) *Printing of results:* All working signals can be registered in the printer, which is set up for WINDOWS.

IV. NOTES FOR USE IN INSTRUCTIONS

The equipment is suitable for use at various teaching levels (final year undergraduate students and bachellor and postgraduate courses), since the trials that users may carry out range
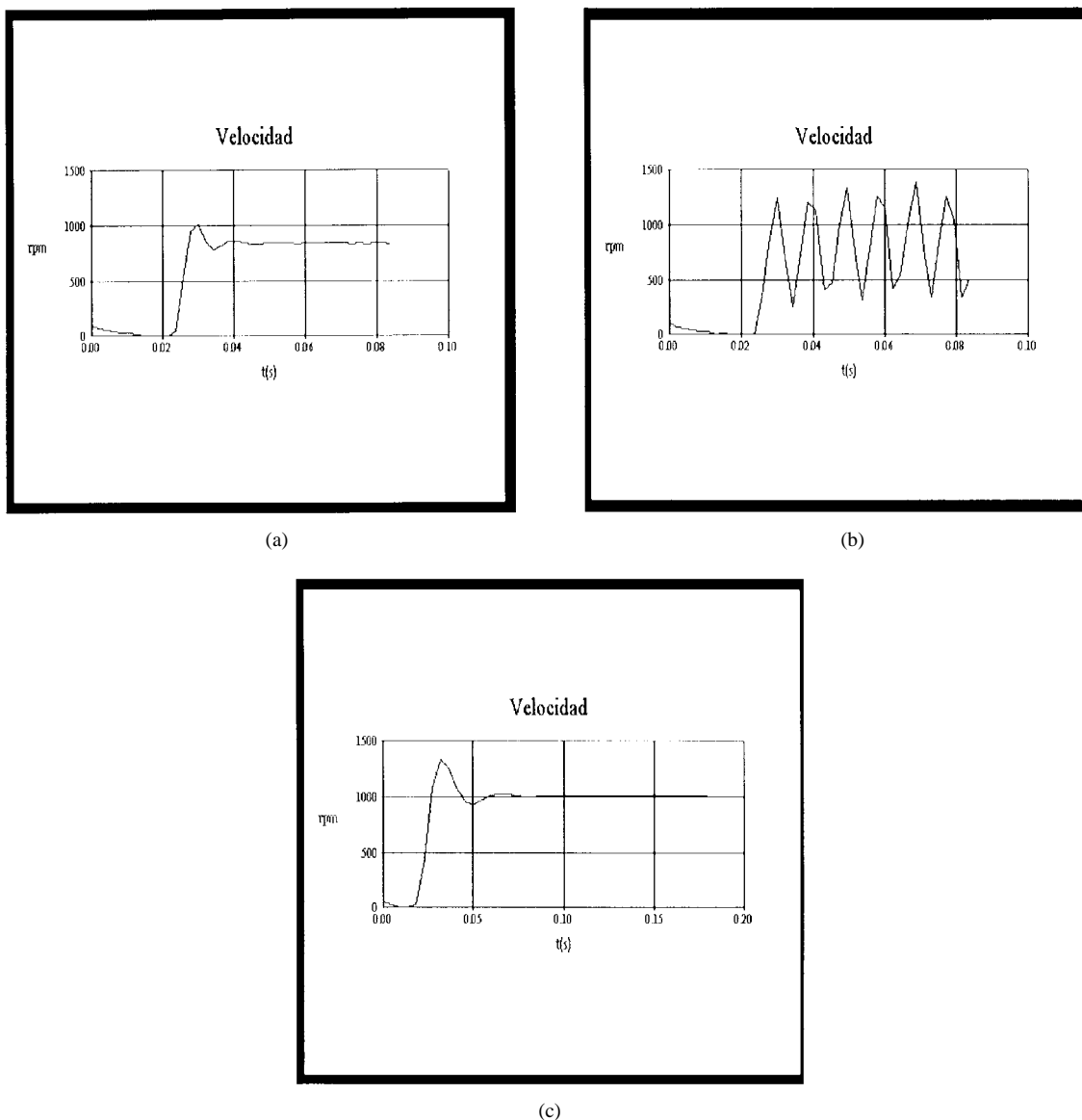
(a)

(b)

(c)

Fig. 19. Typical responses of the DC motor control.

from very simple ones (studying the different control modes of different types of motors, the most important characteristics of each type of motor, control concepts in the open and closed loop, control of position and speed, sensors used for the control of motors, etc) to more complicated trials wherein the user may study in detail, for example, the performance of the different types of control for each type of motor, transitory responses for different loads and different control parameters, the effect of sample time, establishing differences between analog and digital controls, a detailed study of hardware solutions (devices and circuits), design of and experimentation with different control algorithms, the effect of the various control parameters, responses to different command signals (set points), etc.

On every practice the pupil chooses the type of motor under test, selects the desired control options, and sets the variables (electrical and mechanical) to monitor. The software tool designed provides facilities for selecting the motor, control mode, type of controller, origin and set point, as well as data acquisition during on-line control.

A typical session working with this equipment includes:
1) Motor identification in open loop. Fig. 18 shows the obtained results with a dc motor.
2) Control mode simulation using specific tools such as MATLAB or SIMULINK.
3) Testing of different control solutions (P, PI, PID, zero-pole filter, etc). The user can check the response of the closed-loop control system changing controller parameters, sample time, etc. Fig. 19 shows typical responses of dc motors under test.
4) Checking the waveform of electrical magnitudes in the motor (currents and voltages). Besides different protection systems againts overcurrent and overvoltages can be observed. Fig. 20 shows the current through each step motor phase, when chopper system acts.

V. Conclusions

The equipment developed within the DEDALO project has been designed for carrying out detailed studies on stepping,
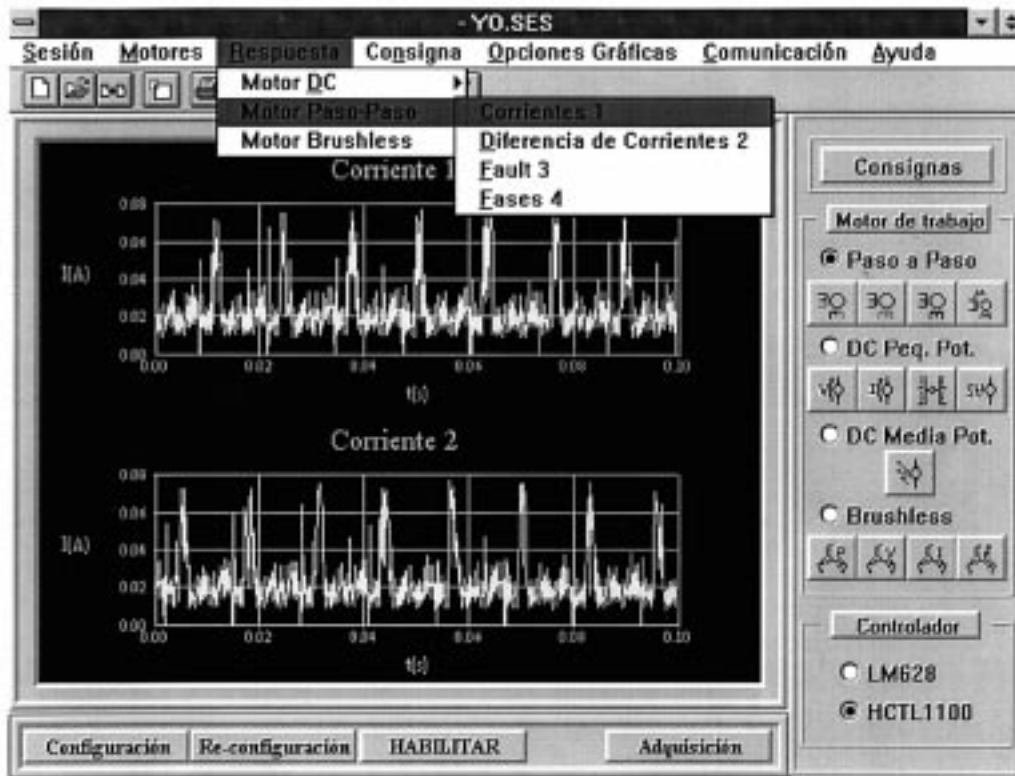
Fig. 20. Current through each step motor phase, when chopper system acts.

dc (low and medium output), and brushless motors. Its most important feature is that different types of control can be tried out on each type of motor. Moreover, the guiding principle throughout has been one of making it user-friendly, working with a PC in Windows environment, to select and set up the control modes and define the commands, and visualize the evolution of the most important variables intervening in the control loop versus time. In short, this electronic equipment is an important tool in the teaching of motor control. Its design has taken into account teaching aspects, ease of use, variety of motors, alternative control methods, and interfaces with the mathematical control tools.

The equipment developed and put into practice has been used for carrying out laboratory trials on control system and servomotor items in the Escuela Politécnica de la Universidad de Alcalá de Henares (Polytechnic School of the University of Alcalá de Henares). The following conclusions can be drawn from this experience:

The learning of many concepts of control and servomotors, which are difficult to understand in a classroom situation, is made much easier. Experimentation with different control structures is made easier, to see how they perform in practice and how they are affected by the different modifications that can be introduced. Students are encouraged to devise their own trials and examine the results. The time needed for carrying out the trials is cut down, meaning either that trials can be carried out in greater detail or new ones can be undertaken in the same time. All this has brought about a noticeable increase in the quality of teaching in this matter, a greater interest by students in learning and, in short, better performance of both human and material resources.

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