Identification and development of a real-time motion control for a mobile robot's DC gear motor

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Abstract: This paper proposes a real-time motion control of a wheeled mobile robot. An effective Proportional-Integral-Derivative (PID) controller has been synthesised for the robot's speed. In the process, owing to the shortage in the chosen gear motor characteristics, we need to model the robot's gear motor. Most of identification and computation techniques presented in this research use intelligent tools in order to obtain best desired performances of the closed loop system. The proposed technique consists of comparing between presented methods in order to get the best system's response. We apply sets of techniques and experiments to test the speed response of the gear motor using a Digital Signal Processor (DSP) of Texas Instruments integrated in a digital development tool.

Keywords: gear motor; DSP; PID controller; speed control; modelling; identification.

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1 Introduction

A mobile robot can move intelligently in both known and unknown environments. It is able to communicate with all elements that surround it owing to its sensors and all the communication units. Numerous control methods can be developed to make the robot navigate using different approaches. The Proportional-Integral-Derivative (PID) controller has been chosen and designed to control the robot's speed.

In 1942, Ziegler and Nichols introduced a heuristic tuning method which makes it an efficient solution to control systems (Ziegler and Nichols, 1942). The best tuning of the three functions, Integral, Proportional and Derivative, allows us to have both transient and steady-state responses (Poulin et al., 1996; Kumar et al., 2013). Despite the popularity and the evolution of PID controllers nowadays, their practical use in industries encounters several problems (Rocco, 1996; Girirajkumar et al., 2010), that is why more than 90% of controllers are based on the most simple design of PID algorithms (Rubaai, 2008). PID controller is well known in both academic and industrial applications (Åström and Hägglund, 2001). It is characterised by its low cost and the simplicity of its control structure. It handles, with the appropriate tuning, variations of temperature, level, pressure, flow and many other variables (Åström and Hägglund, 2004; Kumar et al., 2011).

Subsequently, this best PID obtained structure was translated into a real-time motion algorithm implemented on a processing unit. In our case, we are interested on the Digital Signal Processor (DSP) developed by Texas Instruments which is considered as the first manufacturer of C2000 DSP family. The TMS320LF2407 is a perfect product to fulfil our tasks thanks to its high speed calculation of real-time motion algorithms (Jang et al., 1998). It is dedicated to develop optimised applications for motor's numerical control especially in mechatronic and robotic fields. The DSP is integrated on the Motion Starter Kit MSK2407 which represents a platform to design, develop and implement a motion control software application. To quickly develop and test motion control algorithms, the MSK2407 DSP board uses the 30/40 MIPS computational power of the TMS320LF2407, combined with a double event manager able to drive up to 16 PWM and 16 A/D converters. The embedded CAN interface may be used to connect the board to multiple-axis structures (Technosoft, 2002).

In order to obtain the best control's response and to develop the PID controller, we define an adequate system model and all the necessary speed measures. Each front driving wheel of the mobile robot is equipped by a gear motor that unfortunately we couldn't obtain its characteristics. As the transfer function of the system which depends essentially on the motor's speed can't be fixed, an identification study occurs to determine an adequate model of the gear motor.

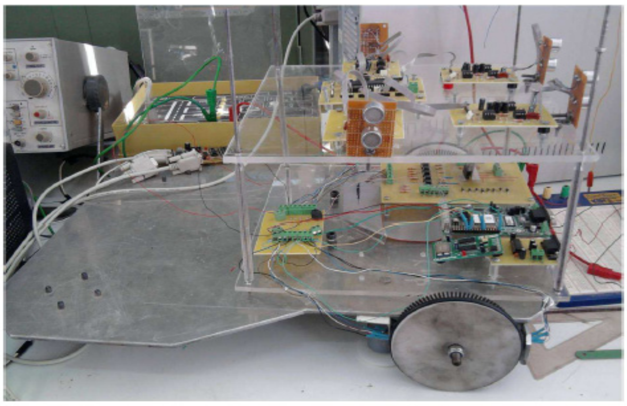
We present in Section 2 the designed robot with a description of important components needed to elaborate this work including a presentation of the MSK2407. Section 3 moves to focus on the modelling and the identification study of the DC gear motor in order to determine the system's transfer function. The PID controller synthesis is provided in Section 4. Finally, conclusions are drawn in Section 5.

2 Description of the robot

We have designed a mobile robot with an aluminum platform equipped with two DC gear motors used to control both of the front wheels. The two other free wheels in the back maintain the robot's balance. On each driving wheel, two optical encoders are mounted to measure the position, velocity and acceleration of the robot. Control and power modules are designed for operations. As a programming tool, we have used the MSK2407 offered by TECHNOSOFT and based on a DSP. The robot can remotely navigate and avoid obstacles owing the BeeProto communication module and the ultrasonic system operating with the micro-controller PIC. Our robot is presented by Figure 1.

This paper takes different steps to develop the adequate PID controller for the robot's speed so we opt for modelling the gear motor (Guo et al., 2015). We introduce in this part the used gear motor and the way to extract information about the speed from the optical encoders.

Figure 1 The designed mobile robot



2.1 Gear motor MFA 919D

We use a DC gear motor designed by the company Como Drills. It contains a DC motor followed by a mechanical reduction gear to reduce the shaft speed. RE-540/1 motors characteristics powered by 12V are summarised in Table 1.

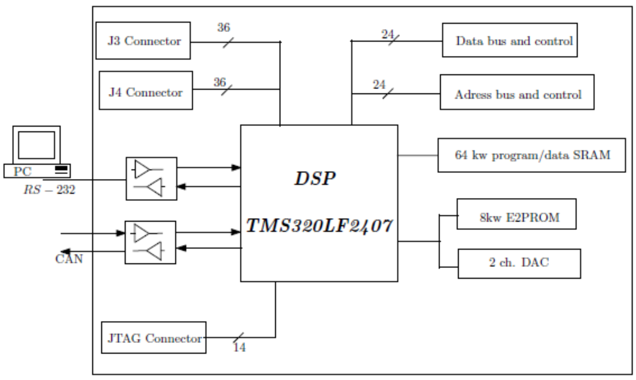
Table 1 DC motor's characteristics

	Idling efficiency	*Higher efficiency*
Speed (RPM)	15.800	13.360
Current (A)	0.52	2.85
Torque (g.cm)	–	154.4
Locking Torque (g.cm)	–	1000

2.2 *MSK2407*

The MSK2407 DSP board is equipped with 64-kword external SRAM memory. That memory can be used as a data memory or as a program memory or both. It is also equipped with a 8-kword serial SPI-connected E2ROM. For performance evaluation and debugging, the MSK2407 DSP board includes a two-channel 12-bit serial SPI-connected D/A converter with simultaneous update. The MSK2407 DSP board offers direct access to all of the F2407 Input/Output signals through four expansion connectors. Two connectors contain the data bus, the address bus and the control signals required to add new interfaces. The other two connectors are dedicated for interfacing with power modules. Each of these connectors includes all the basic Input/Output signals required to control a DC, AC or step motor. Through these connectors the MSK2407 DSP board can be linked with one or two external power modules of various types and powers, adapted to specific applications. Figure 2 presents the block diagram of the MSK2407 DSP board. The board includes an RS-232 interface, used for communication with the PC and a CAN transceiver that permits to connect several MSK2407 DSP boards using a CAN-bus network (Technosoft, 2002).

Figure 2 TMS320LF2407's bloc diagram



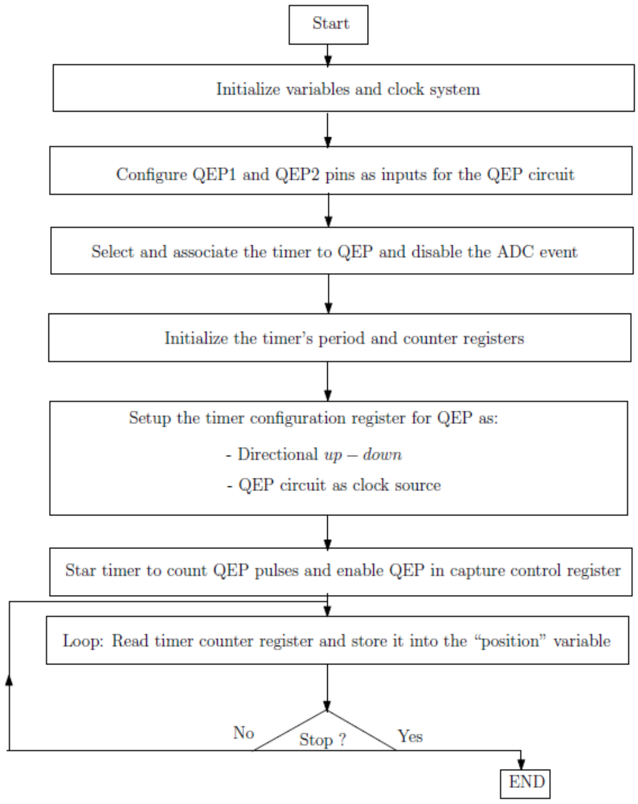
2.2.1 *Motion control applications for the MSK2407 kit*

DSPMOT is an integrated, graphical-environment analysis tool for digital motion control applications. It offers the possibility of analysing the DSP program variables by using online watches, or offline tracking of real-time stored data. Furthermore, a point-to-point linear interpolation reference generator block may easily be included into the DSP application and its parameters may be set in the Windows environment of the DSPMOT program. Similar facilities may be used for speed or current controllers. At the advanced level, several applications can be created, executed and tested.

2.2.2 *QEP circuit*

The main purpose of this circuit is to measure and store position information from an incremental encoder. The Quadrature Encoder Pulse Circuit is enabled to decode and count the quadrature encoded input pulses on pins *QEP*1 and *QEP*2. A General Purpose Timer is associated to QEP applications. Figure 3 presents the QEP algorithm allowing to get the position information of the gear motor.

Figure 3 DSP program flow chart for QEP circuit application



2.2.3 *Optical encoder*

To detect the exact position of the robot during its navigation and consequently its speed, we need to use an adequate sensor. On each driving wheel, we put two incremental encoders of type HEDS 9000. Each sensor is facing the other. As every optical incremental encoder module, this sensor uses its light emitting diode and unique photodetector array to generate two quadrature signals (Merry et al., 2010). The HEDS 9000 is used to detect the relative rotary position, it is known by its high resolution, count capacity and reliability of the two channel quadrature output.

3 Modelling and identification of a DC gear motor

A DC motor is an excellent machine for applications based on speed control. Thanks to improvements of digital electronic, this speed control is frequently realised by a numerical control law. To obtain a mathematical model of the system, two approaches can be used. First, we need modelling where we use physical and chemical equations describing the dynamic behaviour of the system. The second approach is the identification of the system as a black box with appropriate experimental measures.

3.1 Modelling of the DC gear motor

The main objective of this approach consists of extracting the transfer function of the system that describes a relation between the power voltage *U* and the rotation speed Ω. The equivalent scheme of a DC motor is presented by Figure 4.

The block diagram corresponding to the general scheme of a DC motor is presented by Figure 5. It permits to elaborate the mathematical model of the electrical motor response.

The transfer function of the DC motor is expressed as:

$$H(p) = \frac{\Omega(p)}{U(p)} = \frac{K_c}{(R+Lp)(Jp+f)+K_eK_c}$$

As the system is presented by a second order model, the transfer function can be written as follows:

$$H(p) = \frac{K}{1+\frac{2z}{\omega_n}p+\frac{1}{\omega_n^2}p^2}$$

with:

$$K = \frac{K_c}{Rf+K_eK_c}, 2z\omega_n = \frac{Lf+RJ}{LJ}, \omega_n^2 = \frac{Rf+K_cK_e}{LJ} \qquad (1)$$

Figure 4 Equivalent scheme of a DC motor

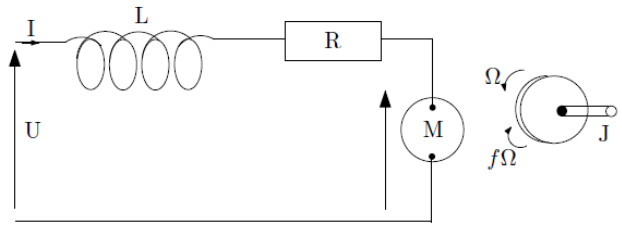
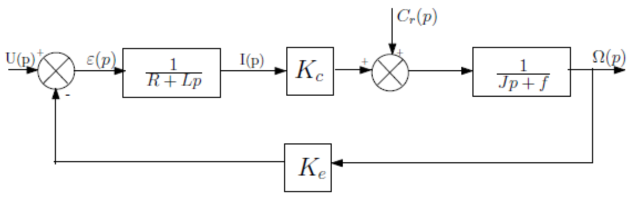


Figure 5 Block diagram of the speed model of the DC motor



3.2 Comparative study of different identification methods

According to system (equation (1)), it is not possible that the transfer function depends on the gear motor parameters. We found ourselves with a shortage of the MFA 919D motor's parameters values, that is why we proceeded to an experimental study. We aim by this part to obtain parameters *K*, *z* and ω_n that represent, respectively, the process gain, the damping factor and the system's proper pulse. These parameters require the knowledge of the step response of the system powered by a step signal of 12V.

3.2.1 Extraction of the speed information using optical sensors

In this part, we have developed an algorithm implemented on the DSP to extract the robot's position and speed. The information of the rotary position is obtained from the optical encoder module generating two quadrature signals. We visualise those channels with a scope to ensure the phase shift of the outputs. Two quadrature outputs extracted from one wheel are presented by Figure 6.

With the QEP circuit integrated on the MSK2407 board, we can extract from those signals the number of pulses generated by the sensors and, then, we are able to locate the robot and calculate subsequently its speed (TMS320F/C240 DSP Controllers, 1999). The integrated algorithm on the DSP TMS320LF2407 results the curve described by Figure 7 and which represents the number of generated pulses by the optical sensor HEDS 9000.

With the appropriate conversion operation, we extract from the pulse counts the position and then the step response of the robot's speed. First, the resulting step response presents disturbances. Then, we introduce a low first order filter which reduces the high frequencies and tolerates passing the lower frequencies. We show the step response before and after using the filter in Figures 8 and 9.

Figure 6 Two quadrature channels (see online version for colours)

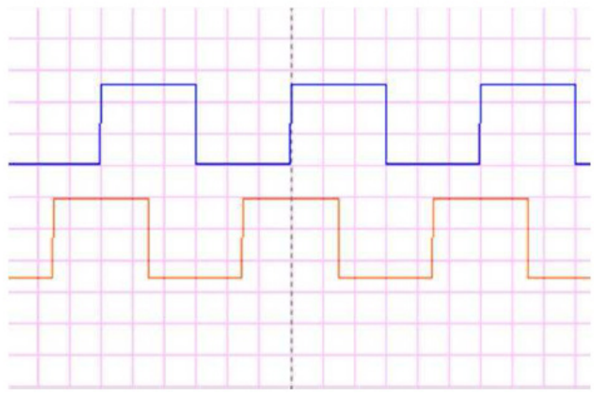


Figure 7 Pulses count based on DSP algorithm

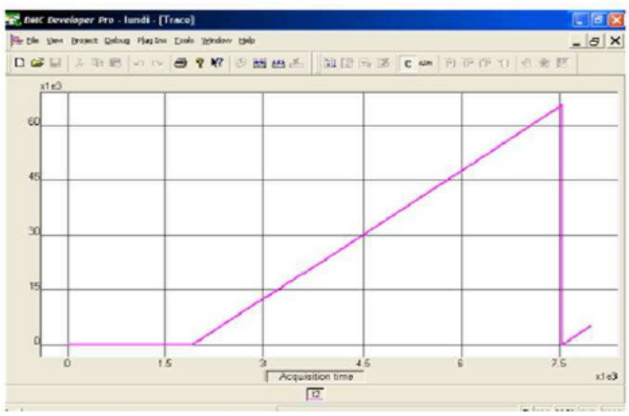


Figure 8 Initial step response

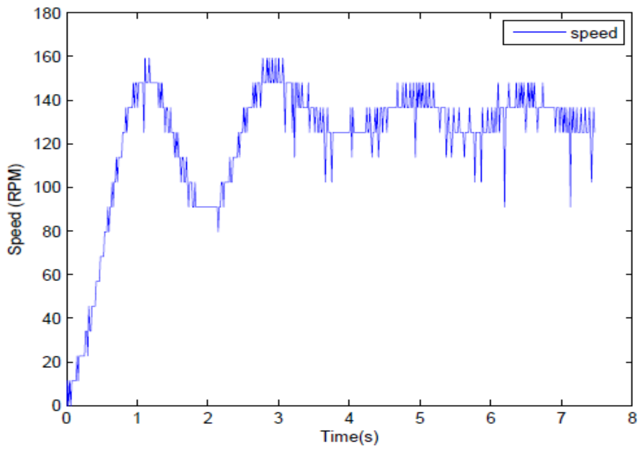
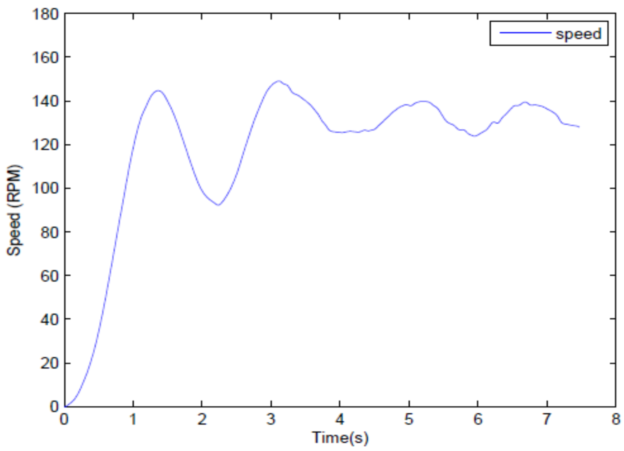


Figure 9 Filtered step response



3.2.2 *Parametric estimation of the model*

To identify our system, several methods of parametric estimation are available in the order of obtaining the best estimated parameters of the mathematical model. The most prevalent method is the prediction error that uses techniques of least squares. It consists of minimising the criterion based on the prediction error (Arshad et al., 2010). This criterion represents the difference between the measured output of the system and the predicted ones. In the process, we are based on the knowledge of a set of experimental measures extracted from the gear motor. The output of the system can be described by the following recurrent equation:

$$y(k) = -a_1 y(k-1) - a_2 y(k-2) + b_1 u(k-1) + b_2 u(k-2)$$

The applied control applied in experiments shows that we can't identify b_1 and b_2, so we note $u = u(k)$.

The last equation becomes:

$$y(k) = -a_1 y(k-1) - a_2 y(k-2) + bu$$

which can be presented in a condensed matrix form as:

$$y(k) = \Theta^T \psi(k)$$

with:

$$\Theta^T = [a_1 \;\; a_2 \;\; b]$$

and

$$\psi^T(k) = [-y(k-1) - y(k-2) u]$$

The objective is to find the best procedure to estimate the parameters of the vector Θ.

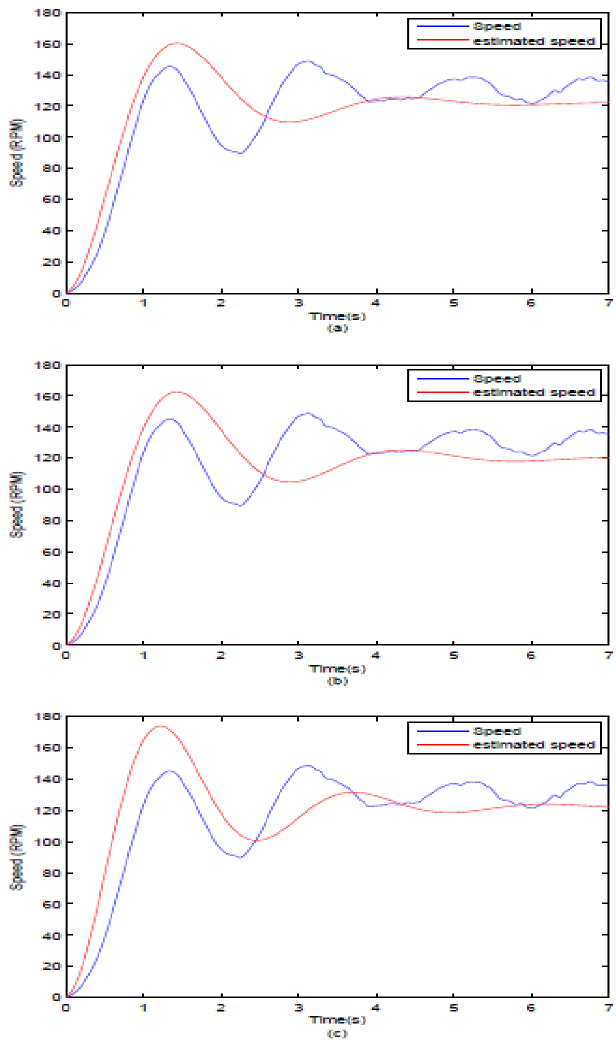
In the following part, we describe several methods of parametric estimation.

3.2.3 *Parametric estimation of ordinary least squares*

In this section, we propose the use of different algorithms of parametric estimation of ordinary least squares. These methods are essentially non-recursive algorithm, recursive algorithm and recursive algorithm with a forgetting factor. Firstly, we estimate parameters of the mathematical model. Then, the recursive algorithm of parametric estimation of ordinary least squares (RLS) allows the treatment of the measured inputs and outputs sequence by sequence. Finally, we use the forgetting factor λ in the calculation of the adaptation gains matrix.

Behaviour of the gear motor's estimated speed based on previous methods is presented in Figure 10.

Figure 10 Real and estimated speed behaviours based on parametric estimation of ordinary least squares using (a) non-recursive algorithm, (b) recursive algorithm, and (c) recursive algorithm with a forgetting factor



Obtained curves show bad results. Consequently, we opt for a different estimation method. We choose the genetic algorithm to estimate the gear motor speed.

3.2.4 Genetic algorithm

This algorithm is a set of methods based on techniques drifted from the natural selection, for each individual we define a fitness and a probability. Based on this information a group of chromosomes is selected to undergo three common stages: selection, crossover and mutation. The implementation of the genetic algorithm follows different steps described in the diagram presented in Figure 11.

Figure 12 shows the simulated result using the genetic algorithm.

Obtained results from the different methods show that the genetic algorithms are the best way to estimate the speed of the gear motor MFA 919D (Saad et al., 2012; Sheta et al., 2014).

The mathematical model can be written as follows:

$$H(p)=\frac{10.82}{1+8.5p+4473p^2}$$

The genetic algorithms consist of an original approach and a heuristic technique of optimisation. The objective is not to find good approximations but to obtain the best and the most satisfying solutions (Nie et al., 2014; Akopov, 2014).

Figure 11 Diagram of the genetic algorithm

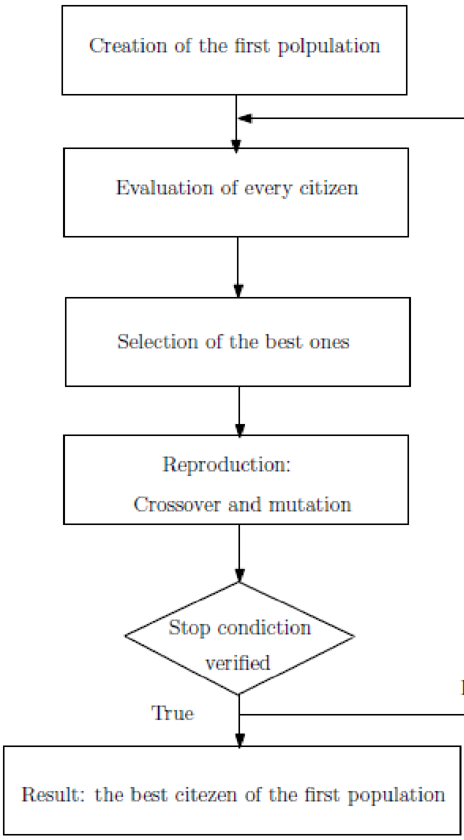
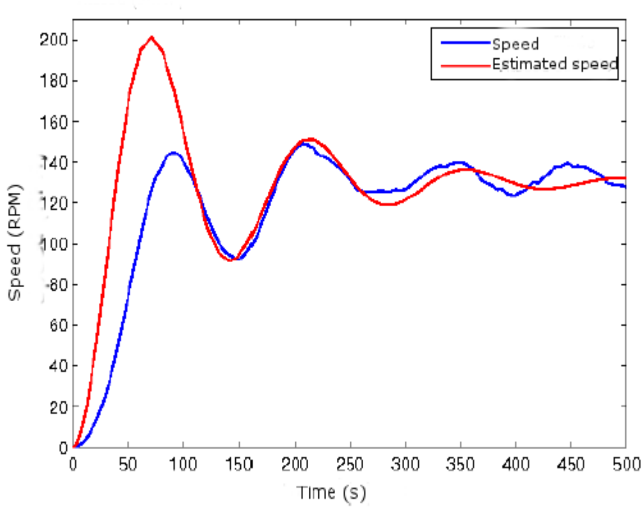


Figure 12 Resulted speeds with the genetic algorithm



4 Speed control of a DC gear motor

It is necessary to manipulate the speed in the study of a DC motor. We had then to choose a control method. Our aim is to implement a classic PID controller to a DC gear motor to have as a result a stable, accurate and a fast system. The PID controller depends on three terms: Proportional, Integral and Derivative. Each component has a different effect on the system when performing in a closed loop.

Within a PID regulator, we try to minimise the error resulting from the difference between the calculated processor and the desired value. We adjust the control inputs of the processor (Åström and Hägglund, 1995).

We can conclude different effects of each component of the PID controller in Table 2 (Ang et al., 2005). Those effects appear when increasing the values of the three terms of the PID controller.

We denote $u(t)$ the obtained result in adjusting the error $\varepsilon(t)$. The PID controller is described by the control expression:

$$u(t)=K_P\left[\varepsilon(t)+\frac{1}{T_I}\int\varepsilon(t)\,dt+T_D\frac{d\varepsilon(t)}{dt}\right]$$

T_D and T_I are time constants for the integral and derivation actions.

The transfer function is:

$$R(p)=K_P\left(1+\frac{1}{T_I p}+T_D p\right)$$

On the experimental field it is impossible to realise this controller. To minimise the influence of the exceeding, we replace $T_D P$ by the filtered derivative transfer function:

$$\frac{T_D p}{1+\frac{T_D}{N}p}$$

Table 2 Influence of the PID components

Closed loop performance	K_P	K_I	K_D
Rise time	Decrease	Small decrease	Small decrease
Overshoot	Increase	Increase	Decrease
Setting time	Increase	Increase	Decrease
Steady-state errors	Decrease	Large decrease	Minor change
Stability	Degrade	Degrade	Improve

4.1 Performance in open loop

The transfer function is described by:

$$H(p) = \frac{K}{1 + \frac{2z}{\omega_n} p + \frac{1}{\omega_n^2} p^2}$$

Performing in an open loop, we can describe our system by the function:

$$OLTF(p) = H(p)R(p) = \frac{K\omega_n^2 K_p T_d \left(p^2 + \frac{1}{T_d} p + \frac{1}{T_i T_d} \right)}{p\left(p^2 + 2z\omega_n p + \omega_n^2 \right)}$$

4.1.1 Simulation results

Pole placement of a system can give a good idea about its performance. A wise choice of the pole positions can therefore adjust the performance of the system. The compensator design that we use is an efficient analytical and synthetic tool presented by Evans in 1948. It is called the root locus.

Based on Figure 13, we can notice that the system has two oscillatory poles. This result proves that the PID controller developed is not the best choice. The two poles are very near to the imaginary axis. The system will have no security margin for of stability; this way, the poles can move to the right side of the imaginary axis.

First, we aim obtaining two zeros z_1 and z_2 distant from the imaginary axis to guarantee the system stability. The two poles of the system $H(p)$ are:

$$p_{1,2} = -0.009 \pm 0.05j$$

We choose the two zeros z_1 and z_2 as:

$$z_{1,2} = -0.1 \pm 0.05j$$

The identification of the two equations gives us:

$$p^2 + \frac{1}{T_D} p + \frac{1}{T_I T_D} = 0$$

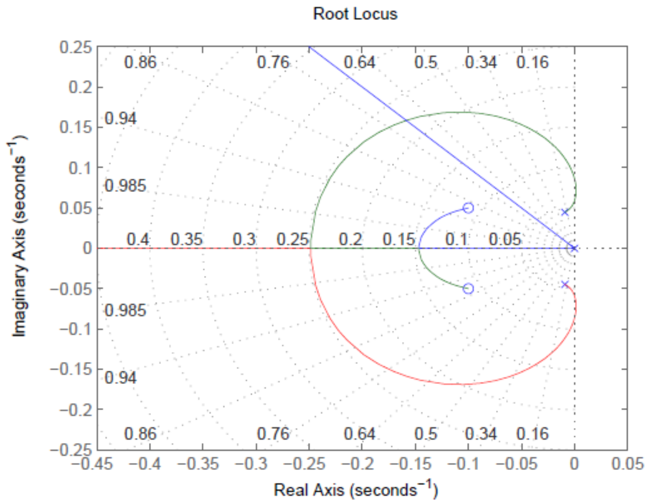
$$p^2 + (z_1 + z_2)p + z_1 z_2 = 0$$

As a result:

$$T_D = \frac{1}{2(z_1 + z_2)} = 5s$$

$$T_I = \frac{T_d}{(z_1 z_2)} = 16s$$

Figure 13 Root locus plot (see online version for colours)



4.2 Performance on a closed loop

Our regulated system is described in Figure 14: system zeros on an open loop are fixed sufficiently distant on the left side to move the system's poles to the left. So, the system on a closed loop is from the third degree, it operates like a second degree system in cascade with a first degree system. Our mission is to synthesise the second order system to have a damping factor of 0.7, a minimal response time and stability margin relatively equal to 45°. Finally, we get $K_P = 3.52$.

The PID controller is described by the function:

$$R(p) = 3.52\left(1 + \frac{1}{16p} + 5p \right)$$

Figure 15 represents the step response of our system.

The zeros of the transfer function on an open loop show important and undesirable exceeding. The transfer function of the closed loop system is presented as follows:

$$\frac{\Omega(p)}{C(p)} = \frac{K\omega_n K_P (T_I T_D p^2 + T_I p + 1)}{T_I p^3 + C_1 p^2 + C_2 p + C_3}$$

with:

$$\begin{cases} C_1 = \left(2z\omega_n T_I + K\omega_n^2 K_P T_I T_D \right) \\ C_2 = \left(\omega_n^2 T_I + K\omega_n^2 K_P T_I \right) \\ C_3 = KK_P \omega_n^2 \end{cases} \tag{2}$$

To avoid those unwanted phenomena, we change the control laws to obtain a control based only on the proportional and derivation actions. Figure 16 shows the structure of the system. The transfer function on a closed loop becomes:

$$\frac{\Omega(p)}{C(p)} = \frac{KK_p\omega_n^2}{T_I p^3 + C_1 p^2 + C_2 p + C_3}$$

Constant values of C_1, C_2 and C_3 are given in the system (equation (2)). Simulation results are given by Figure 17. We see that there is no more exceeding on the step response.

Although our looped system has two conjugated complex poles and a real pole, the step response is non-periodic. The real pole is a filter of a first order that the cut-of-frequency ω_{c1} = 0.098 rd/s which is significantly inferior to ω_{c2} =0.22 rd/s of the second order filter. Thus, the first order filter eliminates the oscillations resulting from the second order filter.

Figure 14 Structure of a regulated system in a closed loop

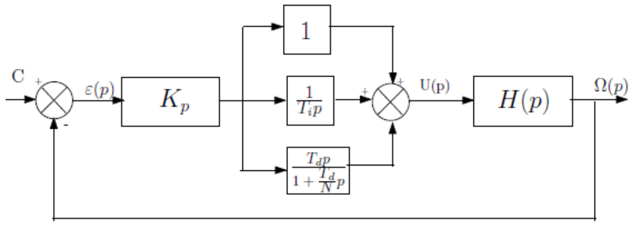


Figure 15 Obtained step response (see online version for colours)

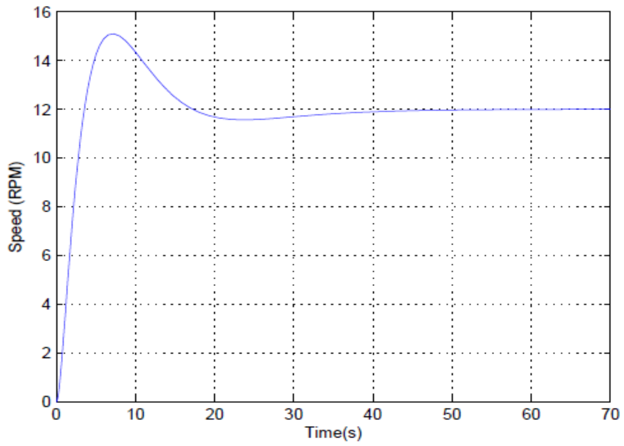


Figure 16 Modified structure of the system

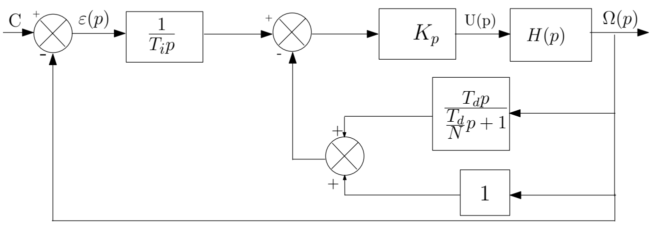
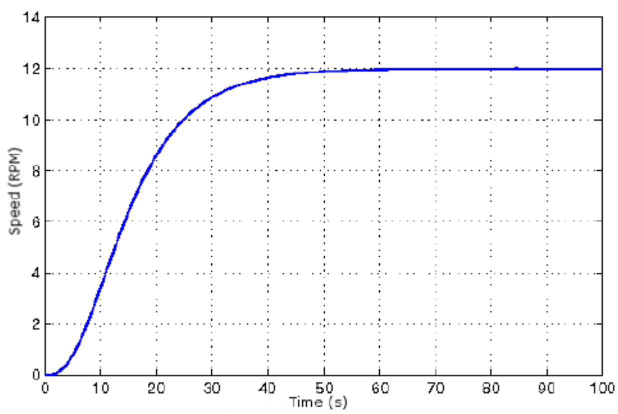


Figure 17 Regulated step response (see online version for colours)



5 Conclusion

The study of the DC gear motor seems necessary in order to control the mobile robot. First, we have defined the mobile robot's system and have compared different identification methods. We have extracted the optimised step response of the speed obtained with a genetic algorithm. This algorithm proved its high potential of escaping being trapped at a local minimum. Then, regulation of the oscillatory system has been ensured with a PID controller. The proposed approach is to move the poles to the left owing to the integral and derivation actions. So, the proportional action guarantees a nice margin of stability. To avoid a step response of a system with high exceedance, we opt for a different structure of the PID controller based only on the proportional and derivation actions.

The most robust control loops are based essentially on PID, which represents the most used form of system feedback. Despite many stability problems encountered in the use of PID controllers, they will continue to be used in the future in both academic and industrial fields. Refined Ziegler–Nichols, pole placement and different modern techniques of optimisation are necessary methods to overcome these difficulties.

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