Experimental Analysis of the Dynamixel AX-12 Servomotor and its Wireless Communication

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Abstract. In this paper, it is detailed the dynamic model of the Dynamixel AX-12 servomotor, which is widely used in legged robots and in humanoid robots specially. Experimentally, it is determined its parameters and a theoretical and practical comparison of the internal position controller is performed. Additionally, in the search of applications with bipedal gait, a velocity controller is designed and implemented with satisfactory results. The experiments are done by sending the control law and receiving measurements between the servomotor and a remote PC via Zigbee wireless communication protocol.

Keywords: Servomotors, experimental analysis, velocity control, humanoid robots, Zigbee.

1 Introduction

Thanks to recent technological achievements, Advanced Robotics, who studies robots with marked characteristics of autonomy [1], has acquired an important zenith that allows not only to develop interesting theoretical proposals but also to perform experimental validation through very novel and ingenious prototypes. Today, advanced robots with better promises of performance are constituted by legged robots, mainly because they have better mobility on terrains that are no conditioned, on inclined surfaces and on environments with obstacles.

Legged robots, in general, have been frequently studied since the 1970s and, in particular, prototypes of anthropomorphic or humanoid robots have been a reality since the mid-1990s [2]; for example, the Asimo robot from Honda [3], the QRIO robot from Sony [4] and the HRP-2 robot from Kawada [5]. Currently, there are also low cost educational humanoid robots like the Nao robot from Aldebaran Robotics [6] and the Bioloid robot from Robotis (a Korean company).

The Bioloid robot from Robotis (see Fig.1) can be constructed as a humanoid robot with 18 degrees of freedom (6 per leg and 3 per arm) with a Dynamixel AX-12 servomotor in each joint. There are many and varied tasks that use this robot as a prototype for experimental tests; see for instance [7,8,9,10], among others. In this way, the main purpose of this paper is experimentally analyze the performance of, for first instance, a single Dynamixel AX-12 servomotor with the intention to glimpse the possible applications in the field of Advanced Robotics that this Bioloid robot can perform, in particular: bipedal gait.

The Dynamixel AX-12 servomotor has also been studied in [11] where it is determined its pulse transfer function through a Box-Jenkins procedure [12], in this work it is also showed graphs of its position control performance. In [13] an exhaustive analysis of the same servomotor is described and through reverse engineering it is illustrated each one of its parts, it is determined various parameters of the dynamic model (as the viscous friction coefficient, the static friction, the motor-torque constant and the armature resistance), it is calculated the assumed PID controller gains and it is presented simulations and experiments for its position control; however, the model is not so easy to reproduce since it uses a setpoint generator trying to run, without a modification, the servomotor proper functions (which as we shall see, they are not so convenient for velocity control applications, for instance). Likewise, in [14] it is performed a calibration of the measurements provided by the servomotor; concluding that it is necessary some adjustments in each one, with the exception of the angular position measurement. In [15] the latency of this servomotor is analyzed.

Fig. 1. Bioloid humanoid robot

In this paper, the dynamic model of the Dynamixel AX-12 servomotor is detailed, its parameters are determined experimentally and a theoretical and practical comparison of the internal position controller is performed. Additionally, in the search of bipedal gait applications, a velocity controller is designed and implemented showing satisfactory experimental results. The experiments are done by sending the control law and receiving measurements between the servomotor and a remote PC via Zigbee wireless communication protocol.

2 Modeling and Characterization

Fig. 2 describes a block diagram of the Dynamixel AX-12 servomotor (Table 1 details its variables and parameters). As can be seen, this servomotor is composed of a DC motor, a gearbox with reduction ratio $1\!:\!r$ (where $r = 254$) and an ATmega 8 microcontroller. The power stage corresponds to an "H" bridge which is driven by the microcontroller PWM output. It has a direct temperature housing measurement for protection through a thermistor connected to the ADC2 input. To measure the angular position q of the load axis a 10 KΩ potentiometer (MuRata SV01) is connected to the ADC0 input. And the data sending to and from the servomotor is achieved via an UART TTL level half duplex serial communication at 1 Mbps.

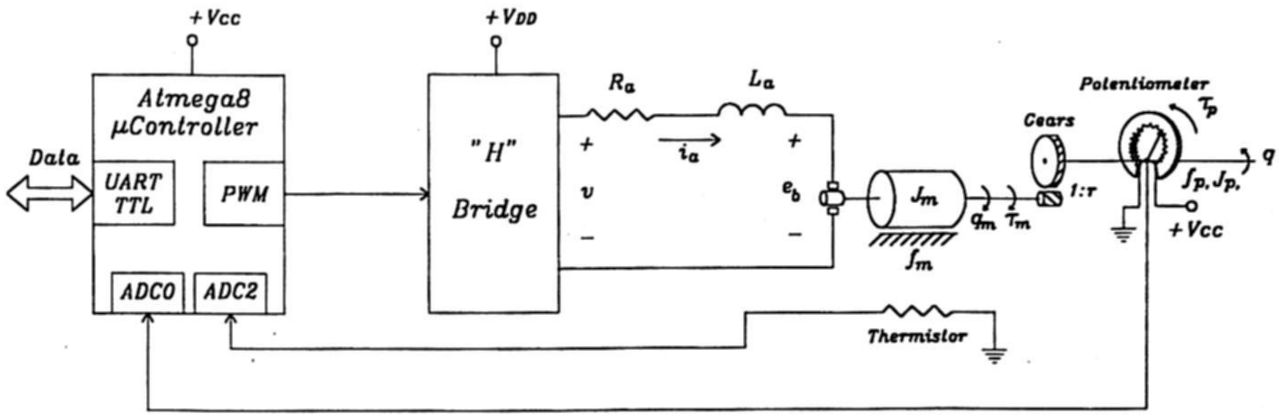

Fig. 2. Block diagram of the Dynamixel AX-12 servomotor

According to specifications, the servomotor can provide feedback measurements of position, speed and load torque. However, as noted in Fig. 2, the servomotor only has direct measurement of its position (also in its housing temperature, but this measure is for protection issues), so it is presumed that the other two given measurements are just estimated data. The microcontroller ADC0 has 10 bits of resolution and the potentiometer is used in a working interval of $[0 - 300]\pi/180$ [rad], therefore the resolution in the angular position measurement is

$$\frac{\frac{300\pi}{180}[\text{rad}]}{(2^{10}-1)[\text{bit}]} = \frac{0.29\pi}{180}\left[\frac{\text{rad}}{\text{bit}}\right].$$

The microcontroller PWM also has a resolution of 10 bits, such that one can manipulate 1023 armature voltage levels (typically, $V_{DD} = 12.15$ [V]).

2.1 Servomotor Model

To modeling the servomotor, it has been considered that the armature voltage is equal to the average voltage at the terminals of the "H" bridge after the PWM. For purposes of the actual friction on the servomotor, it has been only considered the viscous friction model. Now, to obtain the servomotor model it has been used a very similar procedure that is described in [16]. Therefore, the electrical part is governed by

$$v = R_a i_a + L_a \frac{di_a}{dt} + e_b \tag{1}$$

where $e_b = K_b \dot{q}_m$ and the mechanic part by

$$J_m \ddot{q}_m = \tau_m - f_m \dot{q}_m - \frac{\tau_p}{r}, \tag{2}$$

$$J_p \ddot{q} = \tau_p - f_p \dot{q} \tag{3}$$

where $\tau_m = K_a i_a$ and $q_m = rq$. In this formulation, it is assumed that the dynamic effects of the gearbox and the potentiometer sensor are included in (3). Finally, neglecting L_a and substituting (3) into (2), then this result into (1), we have the dynamic model of the servomotor expressed through

$$\frac{rR_a}{K_a}\left[\frac{J_p}{r^2} + J_m\right]\ddot{q} + \frac{rR_a}{K_a}\left[f_m + \frac{f_p}{r^2} + \frac{K_a K_b}{R_a}\right]\dot{q} = v, \tag{4}$$

$$A\ddot{q} + B\dot{q} = v \tag{5}$$

with $A = \frac{rR_a}{K_a}\left[\frac{J_p}{r^2} + J_m\right]$ and $B = \frac{rR_a}{K_a}\left[f_m + \frac{f_p}{r^2} + \frac{K_a K_b}{R_a}\right]$.

Table 1. Variables and parameters of the AX-12 servomotor

Symbol	Description	Units
q	Angular position of the load axis	Rad
v	Armature voltage	V
q_m	Angular position of the motor shaft	Rad
τ_m	Torque in the motor shaft	Nm
i_a	Armature current	A
e_b	Back electromotive force	V
τ_p	Load torque due to potentiometer and gearbox	Nm
R_a	Armature resistance	Ω
L_a	Armature inductance	H
K_a	Motor-torque constant	Nm/A
K_b	Back electromotive force constant	Vs/rad
r	Gear reduction ratio	
J_m	Motor inertia	Kg m^2
f_m	Viscous friction coefficient of the rotor	Nm
J_p	Potentiometer and gearbox inertia	Kg m^2
f_p	Viscous friction coefficient of the potentiometer and gearbox	Nm

2.2 Parameterization of the Servomotor Dynamic Model

The model of the servomotor (5) can be seen, in terms of the angular speed $\omega = \dot{q}$, in the following manner:

$$A\dot{\omega} + B\omega = v\,. \tag{6}$$

In such a way that for a constant input voltage $v = v_1$ with $\omega(0) = 0$, we have that the solution of (6) is given by

$$\omega(t) = \frac{v_1}{B}\left[1 - e^{-\frac{B}{A}t}\right] \tag{7}$$

where the static gain of the system is $k_s = \frac{1}{B}$ and its time constant is $\tau_s = \frac{A}{B}$.

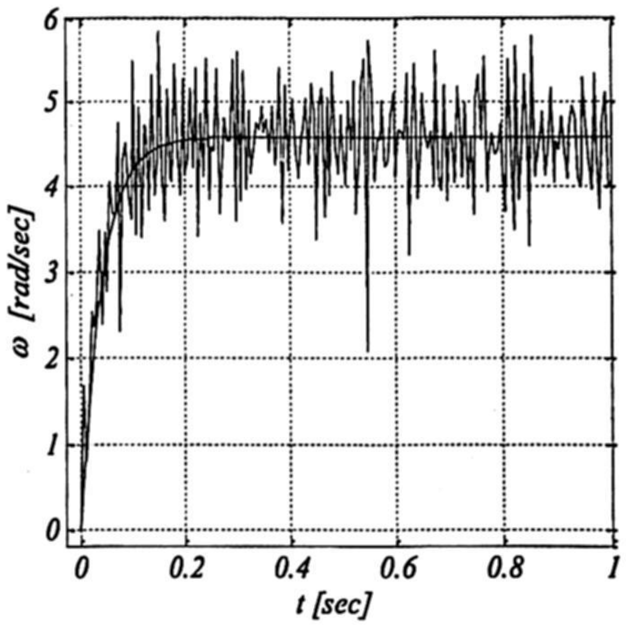

Fig. 3. Graph of ω vs t for parameterization of the servomotor (the continuous line shows the experimental data and the discontinuous one the ideal data)

For the parameterization, the servomotor was fed, with null initial conditions, with a constant armature voltage of 8 [V] and by means of a real-time vision system (well calibrated at 200 frames per second) it was obtained his graph of angular velocity[1] versus time, which is shown in Fig. 3. Additionally, the steady state angular speed was measured by a tachometer resulting $\omega_{ss} = 4.57$ [rad/sec]. In this manner

$$B = \frac{v_1}{\omega_{ss}} = \frac{8}{4.57} = 1.7505 \tag{8}$$

and, from de experimental graph $\tau_s = 0.04$ [sec], hence

$$A = B\tau_s = 1.7505(0.04) = 0.0700\,. \tag{9}$$

In Fig. 3, it is presented the ideal response of (7) with the determined parameters (by a discontinuous line); as can be observed, in average, the experimental response is very similar to the ideal one.

1 The vision system measures its angular position and by a numeric Euler differentiation is calculated this angular velocity.

2.3 Internal Position Controller Gains

The studied servomotor has an internal position controller. In order to obtain the closed-loop model it is assumed that it has programmed a PID controller (typical for servomotors in general). To determine the PID gains the servomotor is subjected to a constant desired input $q_d = \frac{10\pi}{180} = 0.1745$ [rad] (a small one with the intention that do not exist saturations in the demanded armature voltage) and with null initial conditions (with no angular speed limits and the default internal parameters for the compliance). Again, the experimental plot was obtained with the real-time vision system properly calibrated (see Fig. 4). From this plot we proceeded to compare simulations in closed loop to finally find that there exist only proportional and derivative actions (which seems reasonable since, if the output is the angular position, the servomotor possesses an integral action perse), so the control law would be

$$v = k_p(q_d - q) + k_d \frac{d}{dt}(q_d - q) \tag{10}$$

with gains $k_p = 80$ and $k_d = 0.3$. It can be noted that this proportional gain is too large, in fact, in this experiment, the maximum armature voltage is demanded at the beginning and it is of the order of $v = 80(0.1745) = 13.96$ [V] (slightly bigger than the maximum supported).

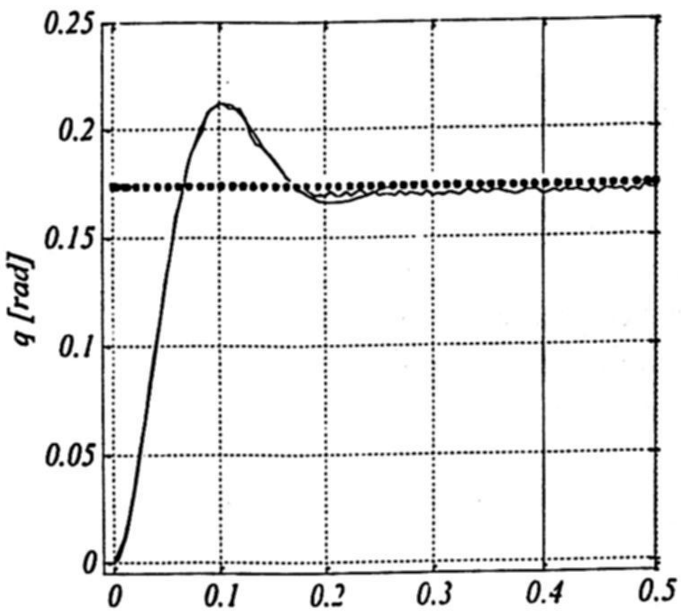

Fig. 4. Evolution versus time of the angular position (the continuous line shows the experimental data, the discontinuous one the simulated data and the dotted one the reference)

Fig. 4 presents the comparison between the simulated and the experimented. Observe that the transients are quite similar, however, the experiment showed a steady-state error, which is attributed to the other components of the unmodeled friction and to the quantization effects in both the control law and the angular position measurement.

3 Velocity Control

The tasks entrusted to legged robots and especially humanoid robots usually have to do with the movement or gait of the robot. Due to the above, there exist an interest in designing a velocity controller for the servomotor under consideration, which we must to remember that has an internal position controller. The designed controller is based on a feedforward component with the intention to deliver the servomotor torque needed to perform the desired movement. For its design, it is defined the following velocity control objective

$$\lim_{t\to\infty} \dot{e}(t) = 0 \tag{11}$$

where $\dot{e} = \dot{q}_r - \dot{q}$ is the angular velocity error and $\dot{q}_r$ the velocity reference.

Now, consider the servomotor model (5) with internal position control law (10), then do the next change of variables "$u = q_d$", where u is the new input of the system. With the above, the system (5) and (10) is

$$A\ddot{q} + B\dot{q} = k_p(u - q) + k_d \frac{d}{dt}(u - q)\,. \tag{12}$$

The designed control law is expressed by

$$k_d\dot{\xi} + k_p\xi = A\ddot{q}_r + B\dot{q}_r\,, \tag{13}$$

$$u = q_r + \xi \tag{14}$$

where ξ is a new state variable added to the system.

The closed loop equations of the system is obtained by substituting (13) and (14) into (12), being

$$A(\ddot{q}_r - \ddot{q}) + (B + k_d)(\dot{q}_r - \dot{q}) + k_p(q_r - q) = 0\,,$$

$$A\ddot{e} + (B + k_d)\dot{e} + k_p e = 0\,.$$

The coefficients of this linear differential equation are all positive so that $e(t)$ and their derivatives tends exponentially to zero as time approaches infinity. This demonstrates that the controller (13)-(14) guarantees the proposed velocity control objective (11) for the servomotor. In fact, with the particular parameters, its eigenvalues are $-14.6464 \pm 30.4687i$ ($i = \sqrt{-1}$). It is worth noticing that this design corresponds to a feedforward dynamic controller that depends entirely on the servomotor parameters (and on the internal position controller gains).

4 Experimental Analysis

To corroborate the developed theory, the servomotor performance and the Zigbee wireless communication (included in the Bioloid robot) it is performed experiments under the scheme illustrated in Fig. 5. The Bioloid robot, through the CM-510 control unit (composed basically by an ATmega 2561 microcontroller) can send position commands to the internal controller and receive measurements of the angular position to a remote PC via the Zigbee protocol. The components to make this possible are shown in Fig. 5. This communication scheme allowed to carried out experiments with an average sampling period of 0.010 [sec].

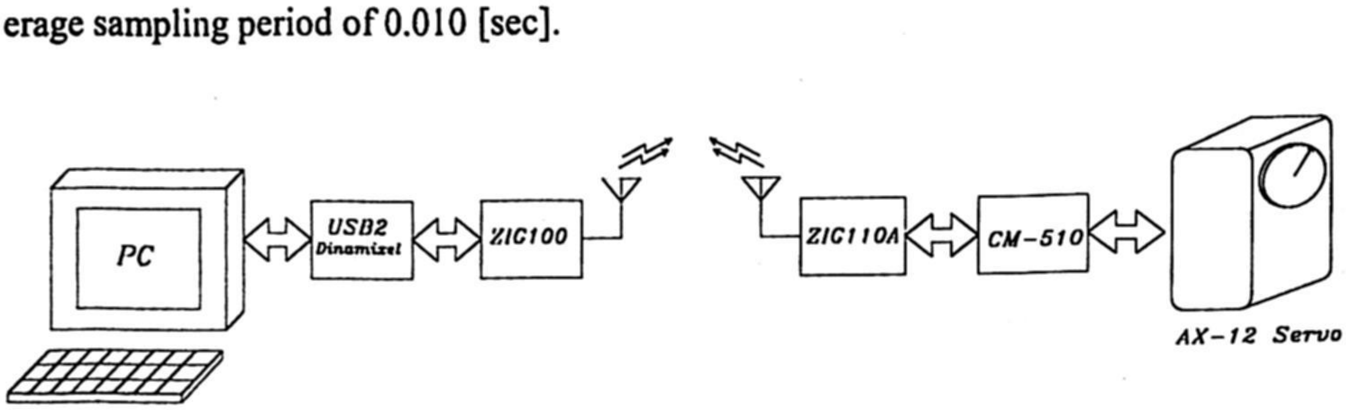

Fig. 5. Experimental scheme

For the experiment, the CM-510 control unit was only used for the sending and receiving data via Zigbee while the controller (13)-(14) is completely programmed in the remote PC (where are also stored all the variables, including the experiment time).

Fig. 6 illustrates the graphs of the angular position time evolution in the experiments for the velocity control with initial conditions equal to rest and with $q_r(0) = 150$ [deg]. In the dotted line it is shown the reference angular position, expressed by

$$q_r(t) = \frac{5\pi}{180}\sin(2\pi(5)t) + \frac{150\pi}{180}$$

which corresponds to a sinusoidal signal with frequency of 5 [Hz], amplitude of 5 [deg] and with an offset of 150 [deg], a small one to do not cause saturations in the control law. In the discontinuous line is observed the graph when the internal position controller is used without modifications and in the solid line is presented the graph when the designed velocity controller (13)-(14) is applied. It should be noted a better performance with the proposed controller, both in amplitude and in phase.

5 Conclusions

It has been described the dynamic model of the Dynamixel AX-12 servomotor, which is widely used in legged robots and in particular for bipedal locomotion of humanoid robots. Experimentally, it has been determined its parameters and it has been performed theoretical and practical comparisons of its internal position controller. Additionally, in the search of bipedal gait applications, where periodic functions for the joint positions are used, it has been designed a velocity controller with satisfactory performance in the experimental results. The command sending and measurement receiving between the Bioloid robot and a remote PC was implemented via Zigbee wireless communication protocol, which also had an acceptable performance.

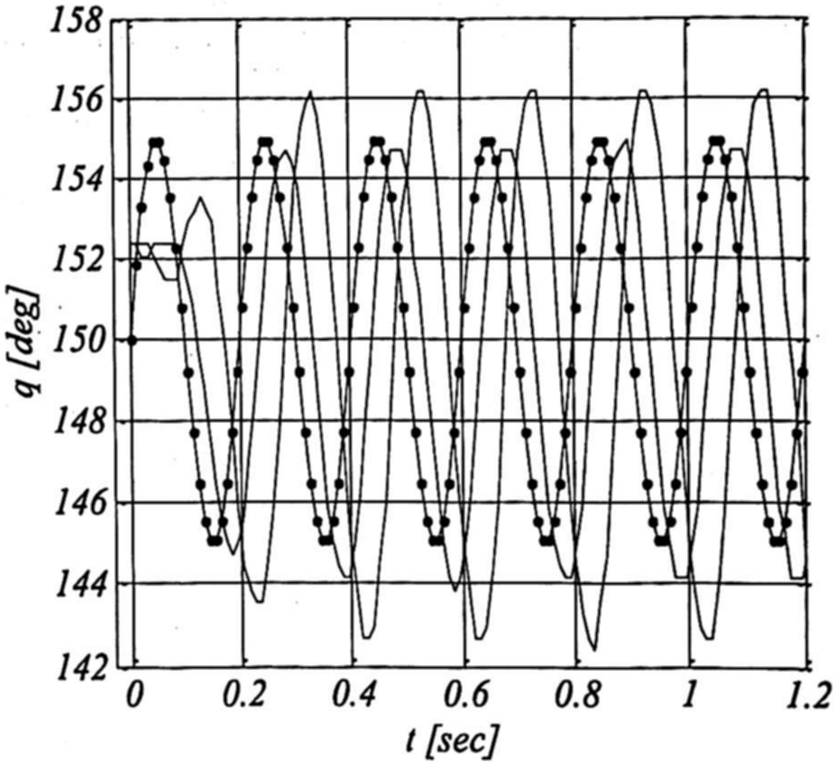

Fig. 6. Temporal evolution of the angular position (the continuous line shows the experimental data with the designed controller, the discontinuous one with just the internal position controller and the dotted one the reference)

It should be noted that the servomotor only offers direct measurement of its angular position in such a way that the other measurements provided are just estimated data. There exist a 10-bit resolution for both the angular position measurement and the applied armature voltage. The internal proportional controller gain is too large which provokes saturations in the armature voltage if the desired angular position is relatively large; this situation declines, in great measure, the servomotor functionality.

6 Acknowledgements

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