ICIC Express Letters
Part B: Applications
Volume **7**, Number **10**, October **2016**

ICIC International ©2016 ISSN 2185-2766
pp. **2103–2109**

UNDERGRADUATE CONTROL SYSTEMS LAB USING LEGO NXT SYSTEMS

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Received March 2016; accepted June 2016

Abstract. *Laboratories are essential component of control education, yet traditional ones are costly and require considerable space. This paper introduces a low-cost platform using LEGO NXT system and NXC software for teaching control systems laboratory in undergraduate courses. The platform could be used to demonstrate: 1) parameter identification technique by the experimental data modeling approach; and 2) cross-coupled control. The paper describes the use of these demonstrations during two lab sessions and illustrates and helps students understand the control theory.*
Keywords: LEGO NXT system, Parameter identification, Cross-coupled control

1. **Introduction.** Control of any dynamic system invariably involves the use of Laplace transforms, discretization, state space, and so on. Therefore, the control concepts are seemingly impractical and difficult to understand for undergraduate engineering students, and teaching control systems courses can be quite challenging. Using laboratory platforms in control education usually could help student gain intuitive feel for the system and experience the control theory in a practical context, thereby enhancing their understanding. Suitable laboratory platforms should meet the most academic and practical needs possibly, and need to be low-cost, robust, and adaptable to different controllers. It must also function in a current software environment and be easy to obtain.

Among different laboratory platforms for implementation of control design methods, the LEGO Mindstorms NXT system has at least three advantages [1]. Firstly, it is good for education because LEGO is a well-known toy, students already have a basic knowledge of its use and construction of various mechanisms. Secondly, it provides good possibilities for creating wireless networks via Bluetooth connection. The last but not the least is low cost. One recent trend to make computer science courses more exciting and interesting to students is the use of programmable LEGO Mindstorms robots [2] and the low cost LEGO NXT educational set is indeed adequate for simple experiments in evolutionary robotics [3].

The LEGO Mindstorms NXT kits give the students a rich software environment. In [4] the authors use LEGO NXT and LABVIEW to introduce robotics and mechatronics to senior undergraduate students. To work within an existing software environment, RWTH

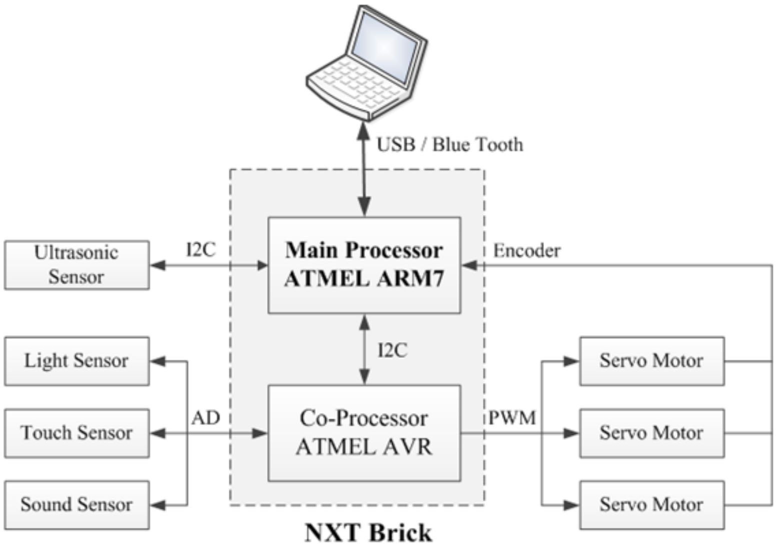


FIGURE 1. LEGO Mindstorms NXT 2.0 system architecture

Mindstorms NXT Toolbox for MATLAB [5] might be selected as a programming language for the LEGO robot control. Wadoo and Jain [6] teached a control systems laboratory for undergraduate engineering students using LEGO NXT kits and ROBOTC software. The most popular programming language is NXC language [7], which is free of charge and supports all of the commands provided by the ARM7 microcontroller.

The NXT kit contains an NXT brick, commonly called the "brick," which receives a program via Bluetooth or a standard USB connection. It has various connectors for motors and sensors, as shown in Figure 1.

The experimental platform in this paper consists of the LEGO Mindstorms NXT kit and NXC software and it serves as

(a) a tool to quickly build various mechanisms, and

(b) a platform to implement system identification theory and control design.

The outline of this paper is as follows. Sections 2 and 3 provide a description of the theory that the paper is based on, including parameter identification of LEGO NXT motor and cross-coupled control. The model of LEGO NXT motor is defined in Section 2. Two experiments were conducted in Section 4, followed by some discussions and concluding remarks in Section 5. The advantage of this research is to offer a useful practical guidance to allow conducting control experiments without too many time-consuming trial-and-error phases.

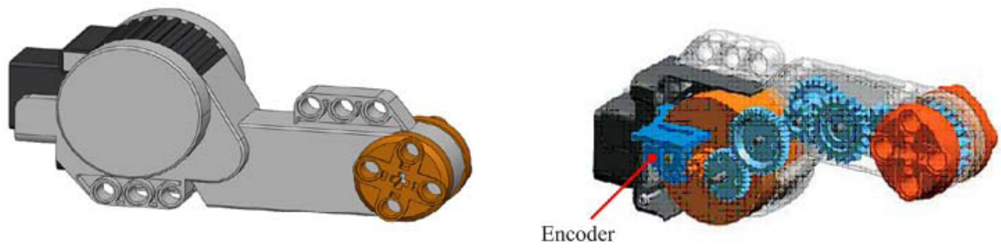
2. **DC Motor Parameter Identification.**

Motors are devices that convert electrical energy into mechanical movement. The LEGO NXT comes with three servo motors. These servos are powered by a DC motor, controlled through a rotary encoder, as shown in Figure 2. The built-in encoder has a resolution of 360 counts per revolution of the axle. Therefore, every time the robot wheel spins one wheel rotation, the robot counts 360 encoder counts.

A precise model of the DC motor used in a control system was desirable. The parameters of LEGO NXT motor may be derived using system identification by the measured input/output data.

Two different approaches are usually adopted for system identification of linear systems.

(1) Time domain approach [9]: A measure of the time response of an open-loop system can be derived using a step input.



(a) Photo (b) Internals

FIGURE 2. LEGO servo motor [8]

(2) Frequency-domain approach [10]: A measure of the frequency response of a stable system can be derived using a sinusoidal input. Those measurements can be used to produce a Bode plot of the frequency response.

The time domain step response identification method was utilized in this research. The model identification is done by identifying the parameters in a simple DC motor mode in a voltage-to-speed form [11]:

$$\frac{\Omega(s)}{V(s)} = \frac{K}{\tau s + 1} \tag{1}$$

where K is the DC gain and τ is the time constant.

Given a constant motor terminal voltage V with magnitude M, its Laplace transform is

$$V(s) = \frac{M}{s} \tag{2}$$

Then the speed response $\omega(t)$ for Equation (1) is

$$\omega(t) = L^{-1}\{\Omega(s)\} = MK\left(1 - e^{-\frac{t}{\tau}}\right), \quad t \geq 0. \tag{3}$$

To enable the motor speed control, the following NXC command is used

$$\text{OnFwd(OUT\_B, Pow\_B)}$$

where the motor connected to output port B is set to move forward at the power level Pow_B.

The general shape of the response can be seen in Figure 3, which stands for the step response of a first-order system.

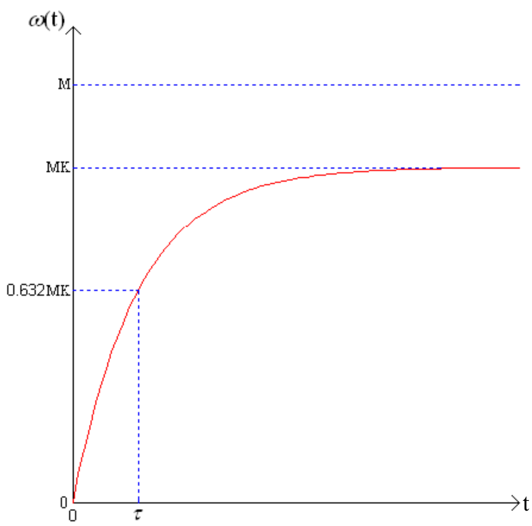


FIGURE 3. Step response of a first-order system

As the plot shows, a first-order system will have reached 63.2% of the final steady-state value after one time constant τ. Note that the steady-state response is MK.

3. **Cross-coupled Technique [12].** In the case of a differential-drive robot, most conventional controllers consist of two individual control loops, one for each motor. One drive loop receives no information regarding the other. The load disturbance in one drive loop causes an error that is corrected only by its own loop while the other loop carries on as before, and, consequently, an orientation error is caused in the resultant path. An improvement in the path accuracy can be achieved by providing cross-coupled control, as shown in Figure 4. The motion system of the mobile robot is composed of two individual motor control loops. Cross-coupled technique considered disturbance errors and distributed them between both loops at the same time. Then the correction signal from the cross-coupled controller is fed again to the input of each control loop to keep them coordinated.

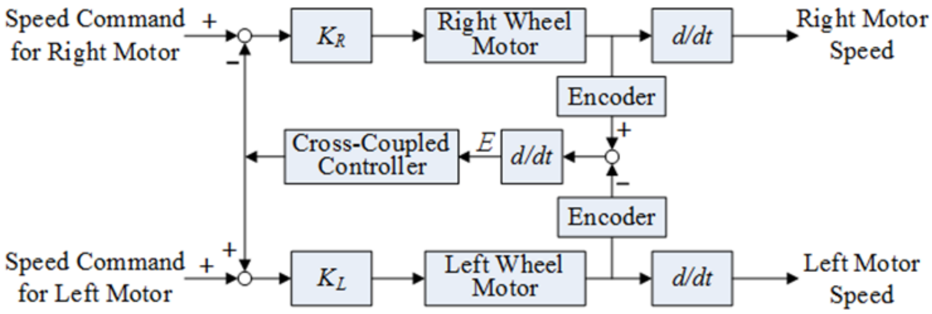


FIGURE 4. Cross-coupled structure

The measurable states in LEGO motor are only the angular position through a built-in encoder with a resolution of one degree and the motors are controlled through a closed loop transfer function, as shown in Figure 6. The rotational speed ω may be estimated from a rate change of the measured angular position, i.e.,

$$\omega = \frac{\Delta\theta}{\Delta t} \tag{4}$$

Let G_L and G_R be the transfer function for left and right motors of the differential-drive robot. Then the motion system for the mobile robot with cross-coupled control is described as

$$\begin{bmatrix} \Omega_R \\ \Omega_L \end{bmatrix} = \begin{bmatrix} \frac{K_R G_R (1+K_L G_L)}{1+K_R G_R + K_L G_L} & \frac{K_L G_L K_R G_R}{1+K_R G_R + K_L G_L} \\ \frac{K_L G_L K_R G_R}{1+K_R G_R + K_L G_L} & \frac{K_L G_L (1+K_R G_R)}{1+K_R G_R + K_L G_L} \end{bmatrix} \begin{bmatrix} V_R \\ V_L \end{bmatrix} \tag{5}$$

where V_L and V_R are speed commands for left and right motors. Similarly, Ω_L and Ω_R are the Laplace transform of actual speeds for left and right motors.

A part of NXC program that can be used for the realization of the cross-coupled control for a straight line motion is given below. In this case the students are given a set of point speed at the power level Pow_B = Pow_C initially.

```
OnFwd(OUT_B, Pow_B);
OnFwd(OUT_C, Pow_C);
Count_B = MotorRotationCount(OUT_B);
Count_C = MotorRotationCount(OUT_C);
errBC = Count_B − Count_C;
Pow_B = Pow_B − KL ∗ errBC;  //KL: P gain for the left motor
Pow_C = Pow_C + KR ∗ errBC.  //KR: P gain for the right motor
```

4. **Experiments.** The NXT Direct Commands Library offers blocks to access NXT services such as sensor reading, motor control, file handling, and device management. These services are a part of the standard NXT brick firmware. This mode is suitable for applications that require external resources like MATLAB, ActiveX components, special I/O devices like joysticks, or extra computational power and memory.

The NXT brick is capable of communicating with digital sensors via I2C which is a very popular communication bus for connecting low speed peripherals. The sampling period of 20 ms is typically utilized in these following experiments.

Two projects are described in this paper, both based on motor control. The first one is a parameter identification of LEGO NXT motor and the second one is a cross-coupled controller for a LEGO mobile robot.

4.1. **Modeling of a LEGO motor system.** The goal of this section will be to estimate the values for K and τ in Equation (1) by analyzing the response of the motor to a step input voltage. A step function will be input to the motor, and the signal from the encoder will be recorded. The LEGO motors have built-in rotation sensors which give an estimate of the speed using the following relation

$$1\frac{count}{ms} = 166.67rpm \tag{6}$$

where rpm stands for "resolve per minute" and $count$ is the encoder counts.

A step input is provided to the motor at 90% power for a period of time (here taken to be 1 second).

$$U(t) = \begin{cases} 90\% \text{ power}, & t \leq 1s \\ 0\% \text{ power}, & t > 1s \end{cases} \tag{7}$$

where the maximum speed of the motor corresponds to a power of 100%.

The steady-state rotational speed in this experiment is 133rpm, as shown in Figure 5. Thus the DC gain K in Equation (1) is

$$K = 133/100 = 1.33$$

The red solid line in Figure 5 is the actual speed step response. The time constant represents the time that it takes the system's step response to reach 63.2% of its final steady-state value. Thus, the time constant is estimated as

$$\tau = 0.084$$

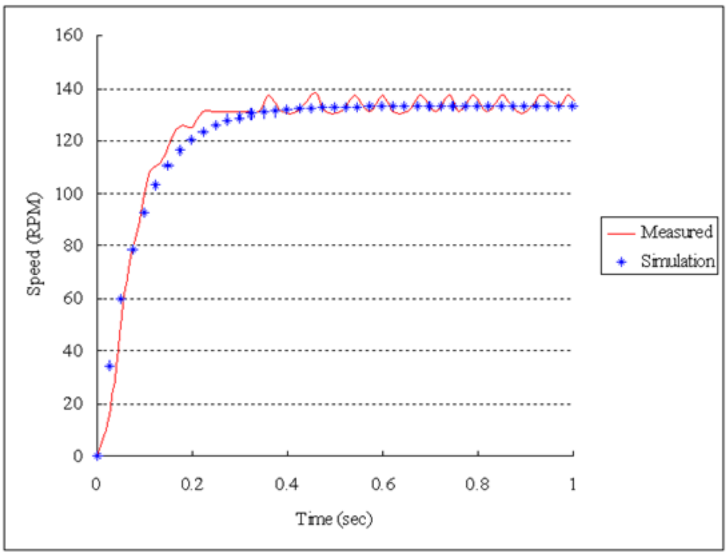


FIGURE 5. Comparison of step response

Using these values for K and τ, the transfer function for the DC motor is therefore given by

$$\frac{1.33}{0.084s+1} \tag{8}$$

Note that the output of the response is a data log, which can be exported from the LEGO NXT brick in ***.xls*** format and can be used to generate a plot between the distance θ (and speed) with time.

The measured response (red solid line) was compared with the simulated response using Equation (8) (blue dotted line), as shown in Figure 5.

4.2. **Cross-coupled control.** The differential drive is a two-wheeled drive system with independent actuators for each wheel. The name refers to the fact that the motion vector of the robot is sum of the independent wheel motions. The differential-drive robot is instructed to travel in a straight line for a period of 1.5 second at power = 90% in this experiment.

The objective of this experiment is to compare the speed difference $\boldsymbol{E}$ in a straight motion, which is defined as

$$E = \Omega_R - \Omega_L \tag{9}$$

where Ω_R and Ω_L are right and left actual motor speeds, respectively.

For comparison, the robot moves in a straight motion with cross-coupled control and without cross-coupled control, respectively. Without loss of generality, let cross-coupled controller be unity in the feedback loop. The proportional gain in the forward loop is $K_R = K_L = 0.000205$ in Figure 4.

The measured speed difference with/without cross-coupled controller is plotted as the red/blue line in Figure 7 where the legend cc for red line stands for cross-coupled. For the same speed command, the speed difference $\boldsymbol{E}$ usually exists because the two motors have different parameters or different disturbances acting on. Figure 7 shows that the cross-coupled controller could effectively reduce the internal disturbances to improve the speed difference.

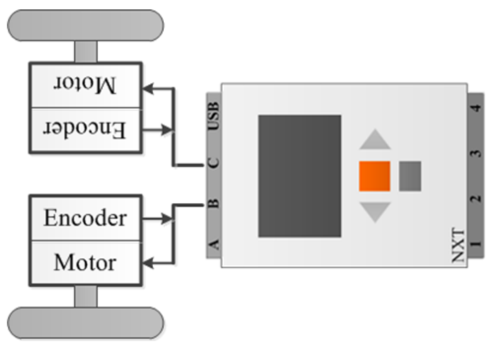


Figure 6. LEGO robot with differential drive

5. **Conclusions.** The idea of open hardware and software solutions for LEGO Mindstorms NXT kit offers the ease to use and the low cost. The NXC software is free of charge and could work on a larger selection of operating systems (Windows, MAC, OSX, LINUX). Thus the platform using LEGO Mindstorms NXT kit and NXC software can be viewed as an efficient tool for the control engineering education. This paper covers how solving real problems in lab provides the students with a holistic approach to understanding control engineering. For this purpose, we have chosen a tracking robot as our plant. We performed experiments on the real platform, a LEGO based robot, which allowed us to show the significant improvement for tracking performance when cross-coupled controller complements an open-loop controller.

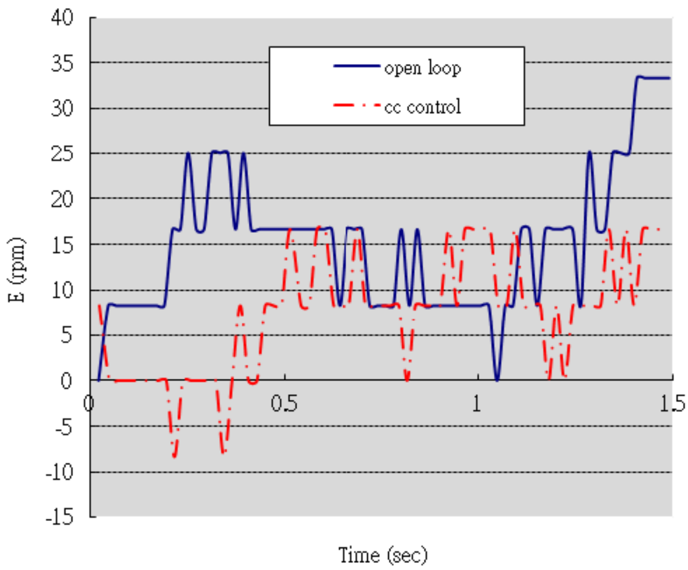


FIGURE 7. Comparison of speed difference between right and left motors

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