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# **AC 2012-5473: A MECHATRONICS EXPERIMENT: INTRODUCTION TO LINEAR MOTORS**

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# A Mechatronics Experiment: Introduction to Linear Motors

## Abstract

Linear motors are becoming actuators of choice for industries relying on high-precision linear motions due to linear motor characteristics and recent advances in electronic controls. A novel teaching module consisting of a two-hour lecture and a two-hour lab/demonstration introducing linear motors is developed for third-year undergraduate mechatronics engineering students. The module resides in a required Introduction to Mechatronics course. The experimental portion of the module, emphasized in this work, addresses two linear motors: a linear stepper motor with a microstepping drive and a linear brushless motor with commutation and position feedbacks and an appropriate servo-motor drive. Students' increase in knowledge is verified by an instrument.

## Introduction

Linear motors are used with increased frequency in high-technology industries like integrated circuit manufacturing (used for mask aligning and wire bonding), computer numerical control (CNC) machining, robotics, and transportation. As direct drive machines linear motors do not require rotary-to-linear motion conversion to achieve linear motions. In addition, with recent advances in power electronics, their position, velocity, and acceleration accuracy far surpass their rotary equivalents. Today, linear motors are capable of achieving speeds up to 5 m/s (3 m/s average), and sub-micron accuracy<sup>1,2</sup>. In railway transportation, linear motors are used in magnetic levitation (maglev) train systems allowing achievement of high speeds unattainable by conventional trains<sup>3</sup>. However, most textbooks on electrical machines for undergraduate engineering students either do not cover linear motors at all or provide only a cursory coverage of the topic<sup>4</sup>.

Since, in general, linear motors with accompanying controllers are expensive; their use in engineering education was fairly limited. Atencia *et al.*<sup>5</sup> designed a low cost linear induction motor that can be used for undergraduate education.

## Curricular Context

At our institution, Electromechanical Devices is a required course for second-year students majoring in mechatronics engineering. In this course students learn about transformers, DC motors, AC motors, stepper motors, etc. Students are also given a cursory exposure to the theory of linear motors in a one-hour lecture.

Students are further exposed to linear motors through a two-hour lecture and a two-hour lab in an Introduction to Mechatronics three credit-hour junior-level course. This is also a required course in our curriculum. By the time students take the Introduction to Mechatronics course, they were already exposed, in lecture, to stepper motors as well as synchronous three-phase motors through the Electromechanical Devices course. Thus, the module on linear motors can be thought of as building on the scaffolding of the previous course. Scaffolding and

experimental approach to engineering education as best practices are already well established in engineering education theory and practice.

## Experimental Setup

There are two laboratory setups used for this module. The first laboratory setup consists of a simple linear stepper motor SL-015A-TJK from Shinko Inc. (Figure 1.) controlled by a Compumotor S6-series microstepping drive from Parker Hannifin Corporation, a parallel port interface, and a shareware program, TurboCNC<sup>6</sup>. The complete hardware setup is shown in Figure 2. After the appropriate connections are made, students use DIP switches to change microstepping options of the drive, run the TurboCNC program, operate the motor in jogging mode single-stepping the motor, and measure the linear motion of the motor using a mechanical dial indicator with 0.001" precision. The placement of the dial indicator is shown in Figure 3.



Figure 1. Linear Stepper Motor Forcer on a Track



Figure 2. Linear Stepper Motor Forcer on a Track Connected to a Microstepping Drive and a Parallel Port Interface

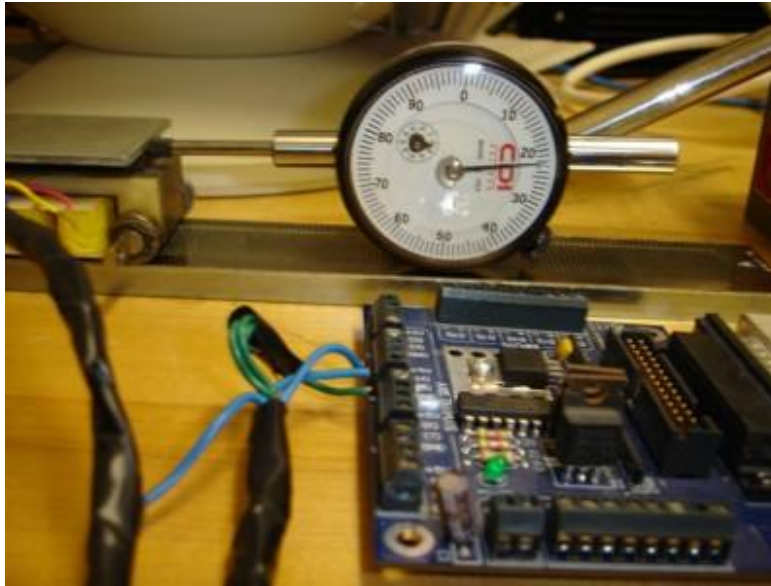


Figure 3. Linear Stepper Motor Experimental Setup Showing Exercise in Progress

The second laboratory setup consists of a three-phase linear motor with an 8 inch U-track by Trilogy Systems, a Renishaw position sensor (linear encoder), and Parker Automation GV6 Gemini servo controller (Figure 4.) with an associated software package, Motion Planner. After setting the appropriate parameters in Motion Planner for the given linear motor, students write a program to control the motor via software.



Figure 4. Linear Brushless Motor Setup

### Procedure

At the beginning of the lab session students are reminded of regular stepper motors. A bipolar stepper motor shown in Figure 5. is operated by the laboratory setup similar to the one

presented in Figure 2. Conveniently, the same setup can be used to operate this bipolar stepper motor as well as the linear stepper motor. Then, another bipolar stepper motor is disassembled to expose the rotor with the permanent magnet and a bearing (Figure 6a) and the stator with eight windings corresponding to two phases of the stepper motor (Figure 6b).

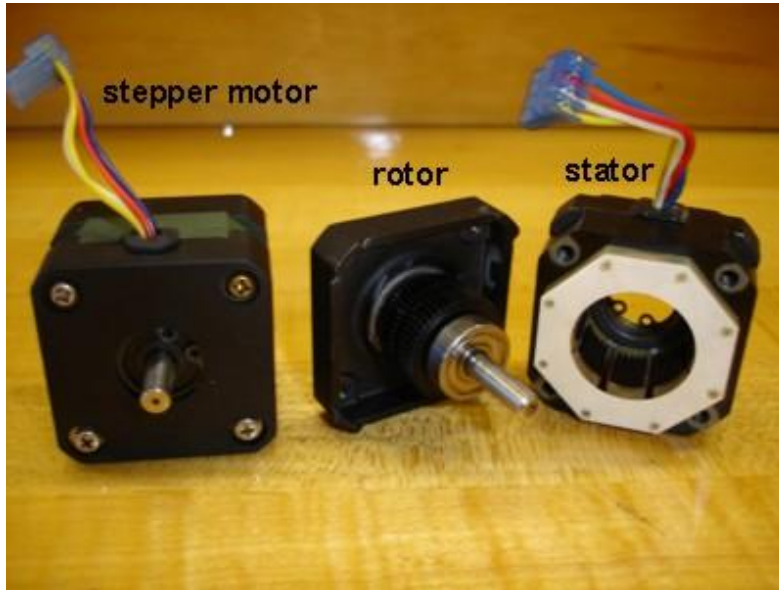


Figure 5. Bipolar Stepper Motor Used to Verify the Correct Operation of the Microstepping Drive and Software

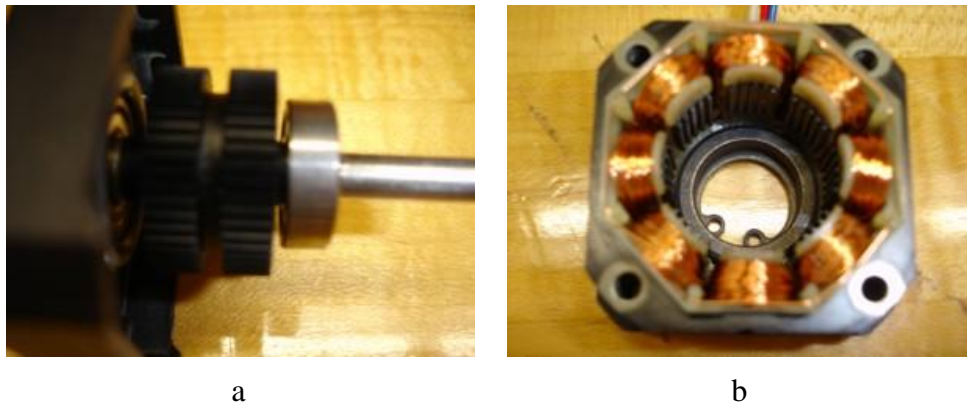


Figure 6. Bipolar Stepper Motor: Rotor (a) and Stator (b)

Then the bipolar stepper motor is disconnected from the microstepping drive and the linear stepper motor is connected. However, before connecting the linear stepper motor, the forcer (stepper motor stator equivalent) is separated from the track (Figure 7) and compared to the stator of the stepper motor. Then, the forcer is placed back onto the track and connected to the microstepping drive. Two strong permanent magnets and four bearings ensure that the forcer coils are close to but not touching the track. The TurboCNC program is used to apply single steps in either direction to the linear motor. A screenshot of the program is depicted in Figure 8.





Figure 7. Linear Stepper Motor: Forcer (Bottom View) with Four Windings (in the middle), Two Permanent Magnets (around the shafts), and Four Bearings

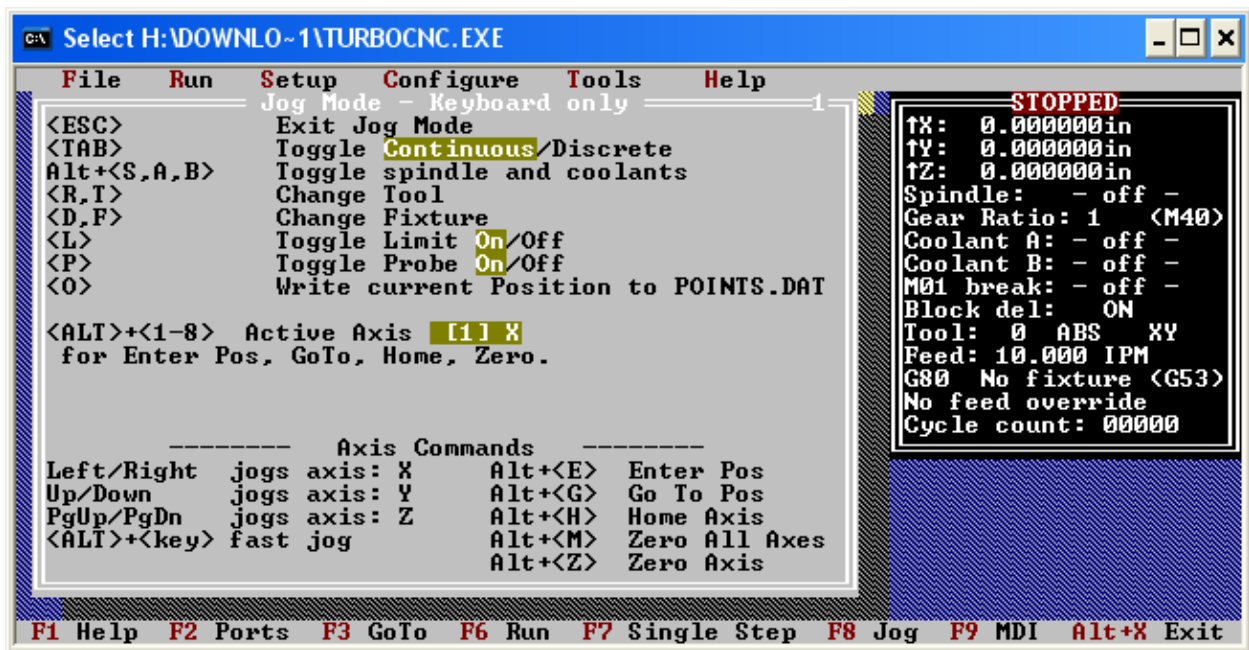


Figure 8. Screenshot of the TurboCNC Program Operating the Motor in a Single-Step Mode

Since the microstepping drive can operate many different motors an appropriate operating current for the linear stepper motor is selected (0.32A) by a set of DIP switches. This setting was constant for the duration of the exercise. After measuring the winding resistance of  $2.8 \Omega$  students could easily calculate the voltage at which the motor operates as well as its power requirements. Then, by setting the appropriate DIP switches on the microstepping drive students would select a number of microsteps per full step. Finally, after engaging and zeroing the dial indicator, students command a number of step pulses using the TurboCNC program (one keystroke for one step pulse) and stop when the dial indicator shows 0.1" (one full rotation of the dial).

The linear brushless motor used in the second exercise is a state-of-the-art ironless (ironless forcer) three-phase servo motor (aircore or U-motor) made by Parker Hannifin Corporation<sup>7</sup>. The forcer includes three Hall-effect switches for commutation feedback, and a thermostat switch to prevent overheating of the motor. In addition, the laboratory setup includes a Renishaw RGH22A analogue non-contact optical encoder<sup>8</sup> for position feedback with resolution of about 20µm. The forcer is placed on a u-shaped track which includes two sets of permanent magnets, one set on each side of the forcer thus allowing the forcer to freely move along the track as shown in Figure 9. The servo driver is a programmable Gemini GV6 series servo drive/controller from Parker Hannifin Corporation. The drive is connected to the computer via an RS232 cable and the serial-to-USB port converter. To program the drive, students use a set of commands created in Motion Planner<sup>9</sup>.

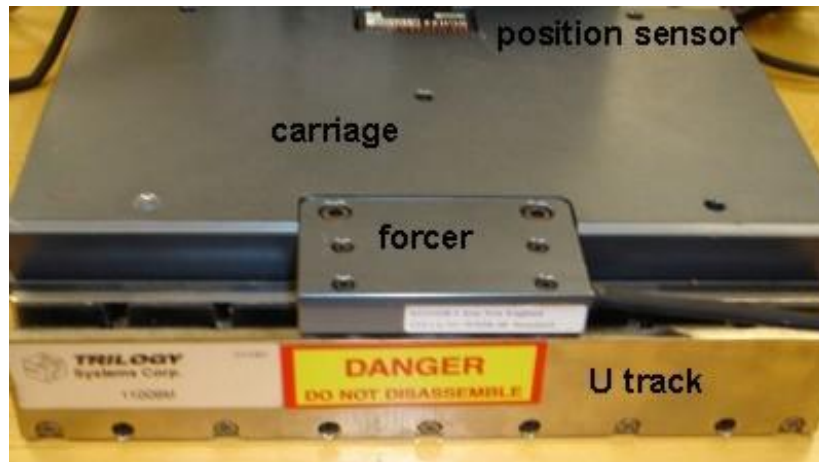


Figure 9. Linear Brushless Motor from Trilogly with U-track, Carriage, and Renishaw Position Sensor

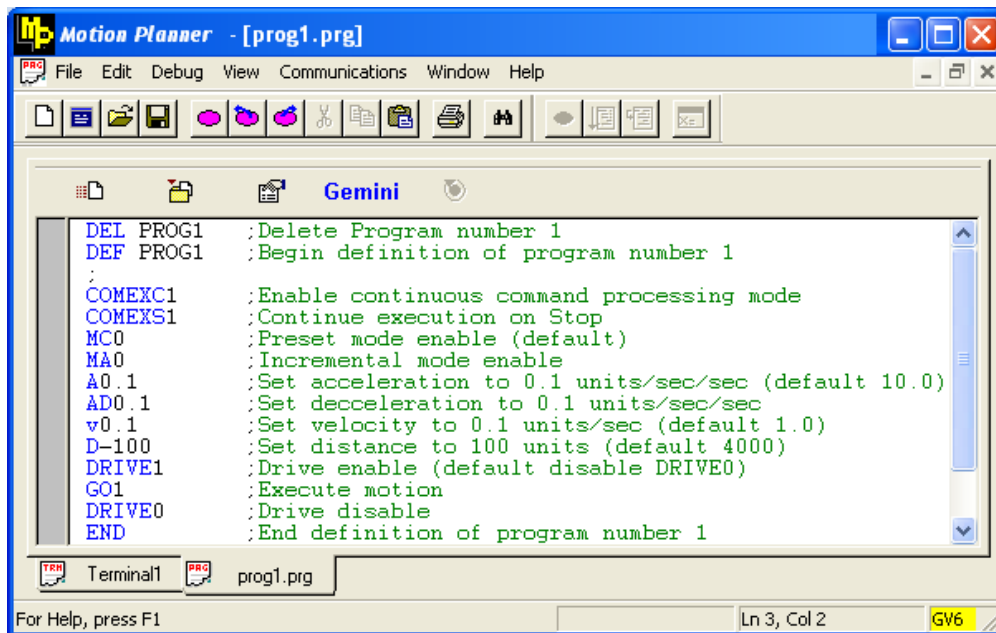


Figure 10. Screenshot of the Motion Planner Sample Program

Figure 10 is a screenshot of the Motion Planner window with a sample program entered. The program number 1 executes a motion using a trapezoidal velocity profile. Acceleration and deceleration are equal. Basic program execution is demonstrated. Then, the students are asked to create their own programs to achieve some more complicated motion. For command syntax students are referred to the Gemini Series Programming Reference<sup>9</sup>.

## Results

Table 1. presents the results of the precision test run with the linear stepper motor while selecting various DIP switch settings on the microstepping controller. The controller was made to operate in full step mode with 200 steps/rev rotary stepper motors. So, the minimum setting of 200 steps/rev represents full steps. Most of the experiments were conducted for constant total distance of 0.1” (one full revolution on the dial indicator) since the effect of individual microsteps could not be observed on the dial indicator for higher settings. The only exception was for the 50,000 steps/rev setting which would require an unduly large number of steps. Since students were pressing a keyboard key once for each step, repetition of 1500 keystrokes was deemed unnecessary.

Table 1. Experimental Data for the Linear Stepper Motor Exercise.

DIP Switch Setting (steps/rev)	Number of steps	Total distance traveled (inches)	Distance traveled per step (inches)
200	6	0.1	0.16667
400	12	0.1	0.00833
1000	30	0.1	0.00333
2000	60	0.1	0.00167
5000	150	0.1	0.00067
10,000	300	0.1	0.00033
25,000	750	0.1	0.00013
50,000	150	0.01	0.00007

While this exercise could benefit from using a data acquisition system to obtain measurements quickly, the author has chosen a pure mechanical instrument (the dial indicator) to build students’ appreciation and feel for these high precision motions. When observing the motor at higher microstep precisions students were not able to discern the motion of the motor with the naked eye.

The second exercise used Motion Planner to create more complicated motions. A simple loop moved the forcer back and forth 20 times. A number of sample programs described in the



programming reference helped in programming the servo drive/controller. Students appreciate the theoretical simplicity of linear motor operation and their high precision applications. They also appreciate the programming capabilities of the Motion Planner software in controlling the motor.

### Assessment and Evaluation of Student Learning

A simple instrument was developed to measure how much students learned about linear motors in this teaching module. The instrument was administered and the results evaluated for one group of students. The instrument consists of two tests, a pre-test and a post-test. The tests are administered before the linear motors teaching module, and immediately after. The tests are graded from 1 to 5, where 1 means the answer is missing or is wrong, while 5 means the answer is complete and accurate. The results of the two tests as well as the test questions are shown in Table 2. The table includes student test score averages per question for two tests on a scale from 1 to 5, and the difference (in percent) between the two. Eight students participated in the assessment process.

Table 2. Linear Motor Test

Num.	Question	Pre-test	Post-test	diff (%)
1	What is a linear motor?	3.33	4	16.75
2	How does a linear motor work?	2.67	4	33.25
3	Name at least two different types of linear motors.	1.33	4.75	72.00
4	What is the main advantage of linear motors when compared with other actuators?	2.33	4.75	50.95
5	What is the main disadvantage of linear motors when compared with other actuators?	2.17	4.75	54.32
6	What are the major industrial applications of linear motors?	2	4.63	56.80

The results show a remarkable gain in students' knowledge of linear motors. However, the instrument is simple, only measures the differences in factual knowledge, and is administered to a small number of students to allow any meaningful statistical analysis.

In general, linear motors and their controllers are expensive and thus prohibitive for implementation in engineering education. However, the used equipment market through e-Bay made the described exercises possible. The first laboratory setup with the linear stepper motor was purchased for under \$250, while the second laboratory setup with a modern ironless motor and a Gemini GV6 drive was purchased for under \$600. Of course, many alternative laboratory setups are possible. For instance, for the first exercise, students could build their own stepper motor controllers from scratch using a few electronic power components and microcontrollers of their own choice. The most difficult part in developing this teaching module was finding the correct cable connectors for drives/controllers.

## Summary

A laboratory teaching module with two exercises dealing with linear motors is developed. One exercise verifies the precision of linear movement generated by a linear stepper motor with a microstepping drive. The other exercise shows the use of software for controlling a state-of-the-art linear brushless motor with commutation and position feedbacks. Students' increase in knowledge of linear motors is verified. The exercises are presented in sufficient detail for possible adoption either as lab exercises or as in-class demonstrations.

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