Three Phase Ironless Linear Motor with Sensored Control

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Objectives

This project is about designing a linear motor with the following characteristics:

- high acceleration
- zero cogging
- good performance in both high/low speed applications

Introduction

In the context of industrial 4.0, automotive industry is looking for new approaches to enhance productibility. Part of this revolution is about applying advanced machines into traditional manufacturing process where Linear motor is a perfect example. Linear motor excels conventional conveying system by its high speed, strong force and incredible precision[1]. Several automation companies have already made success in replacing conveyor belts with linear motors. Ocado Technology, recognising itself as a high-tech company, wants to keep in pace with this revolution.

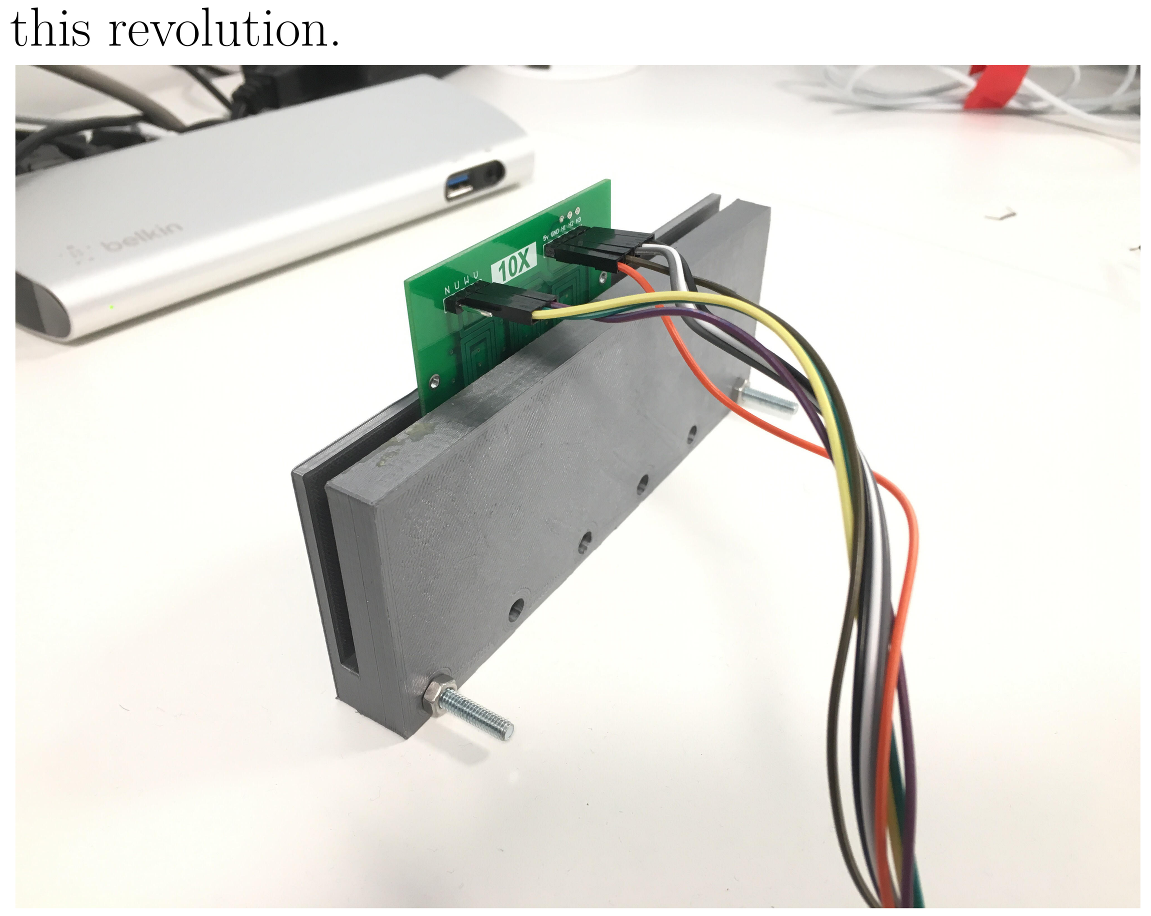

Figure 1: A working prototype

There are two potential usage scenario of linear motor in Ocado:

- Replacing the existing conveying belt with linear motors
- Build long distance maglev railway transporting groceries.

The Theory in Brief

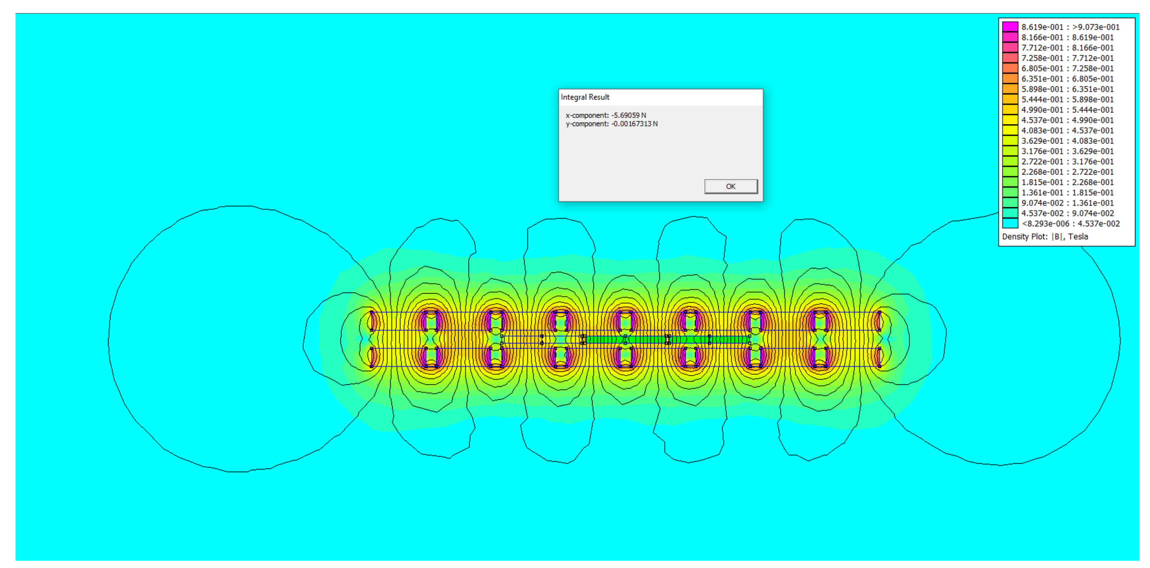

Figure 2: Magnetic field simulation of stator

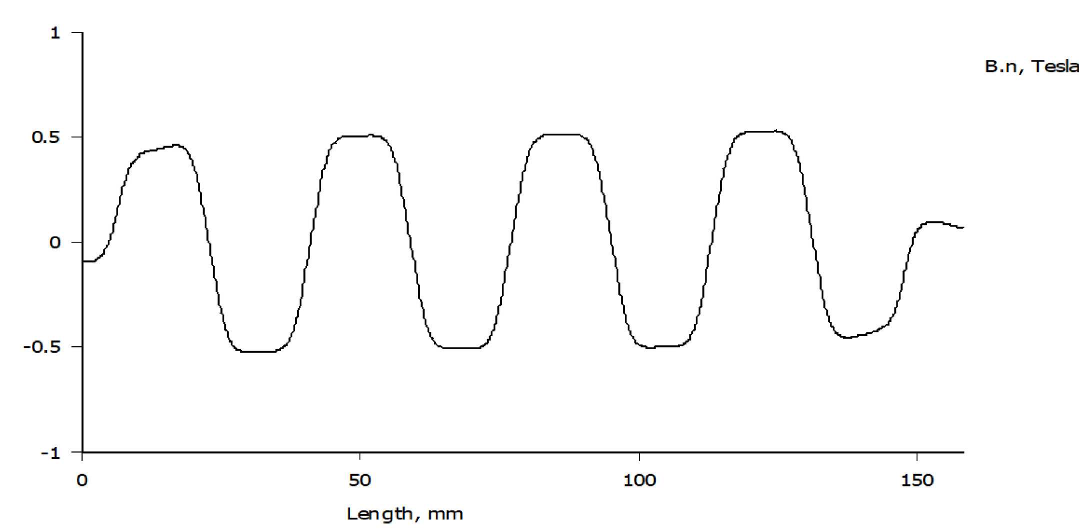

Figure 3: Magnetic Flux density plot in normal direction

As illustrated in figure3. Two alternating N-S magnets arrays facing each other have a sinusoidal shaped $|\mathbf{B}|$ plot.

The force exerted on the rotor are calculated by Lorenz's Law, which in this occasion is expressed as:

$$\mathbf{F}(\mathbf{x},\mathbf{y}) = N \sum_{p=1}^{3} I \oint \mathrm{d}\boldsymbol{\ell} \times \mathbf{B} \tag{1}$$

where N is the number of turns, p is coil winding phase, $\mathbf{l}$ is a vector whose magnitude is the length of wire, and whose direction is along the wire, aligned with the direction of conventional current flow $\mathbf{I}$.

In order to obtain maximum resulting torque and lowest force ripples, $\mathbf{I}$ also needs to be a sinusoidal but with 90° phase shift to $|\mathbf{B}|$. Thus we introduce the six step commutation, which approximates three phase AC to six step square waves, whose frequency is determined from the Hall-effect sensor feedback, making it suitable for digital MCU control.

Commutation

As shown in Figure 4, a conventional six transistor, three phase inverter bridge allows the motor drive to connect each terminal to either the positive DC bus, the negative DC bus, or leave the terminal open. The electrical cycle is subdivided into six commutation steps. For each step, the bus voltage is applied to one of the motor three phase windings whereas the ground is applied to a second winding. The third winding remains open. The successive steps are executed in the same way except that the motor phase winding changes to generate a rotating magnetic field. Pulse width modulation(PWM) switching techniques allow switching a terminal between the two available voltages at a high switching frequency so that the average voltage at the terminal can be set anywhere between zero and the full available bus voltage.

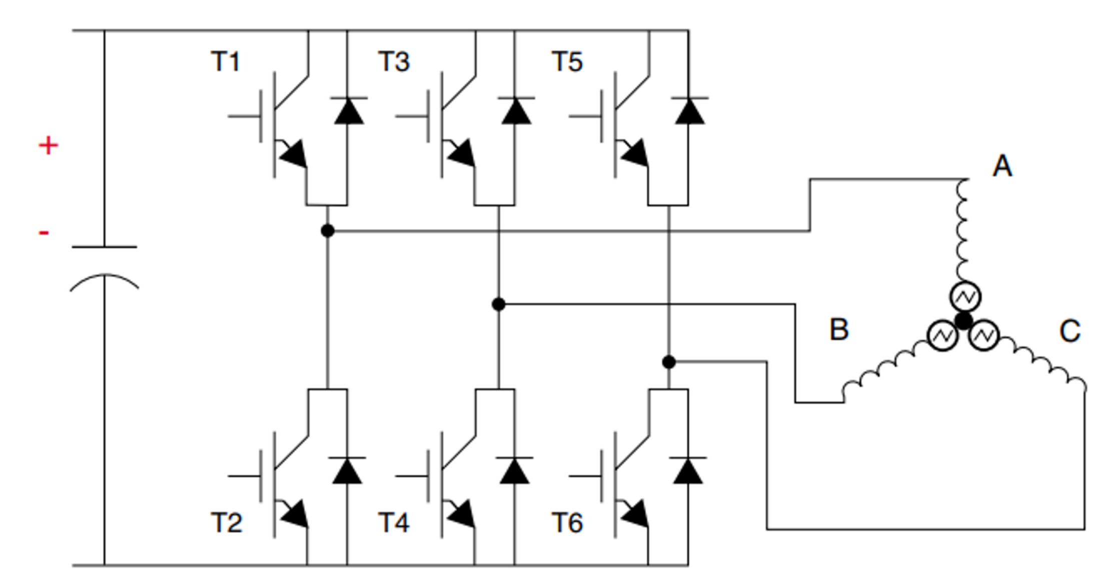

Figure 4: A six step inverter

Control

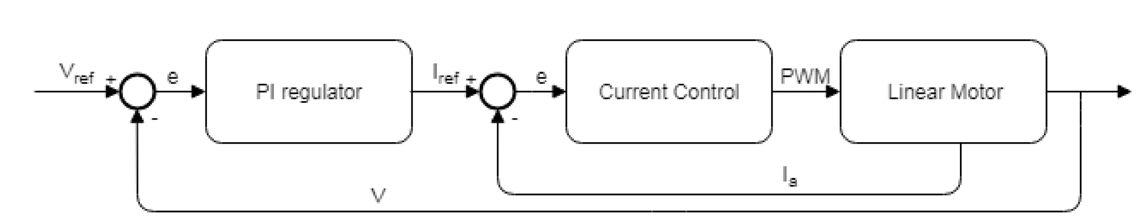

Figure 5: The control loop

There is an outer speed loop cascaded by an inner current loop. The controller takes input from speed feedback and reference, regulates the output torque by controlling the on/off of high-side MOSFETS and hence to maintain the rotor at target speed.

Testing

The test was overall successful. The motor travels very smoothly. However, in reality, the speed control does not show satisfying result. Even though the hall sensors themselves are fixed in absolute positions, they cannot generate absolute position data continuously over an entire electrical cycle.

Future Work

There are several ways to further improve the motor's performance.

- Add a RC filter in parallel with each phase
- Use thicker copper PCB

References

[1] P.-K. Budig.
The application of linear motors.
Third International Power Electronics and Motion Control Conference (IEEE Cat. No.00EX435), 2000.

[2] Mark Dyck.
Magnetically levitated six degree of freedom micro-machining rotary table.
IEEE/ASME Transactions on Mechatronics (Volume: 22, Issue: 1), 2017.

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