DISTRIBUTED CONTROL OF A PM BRUSHLESS MOTOR WITH MULTIPLE MOVING ELEMENTS

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Linear servo motors are becoming increasingly popular in applications requiring high accelerations and velocities and very accurate positioning. In this article a novel technique which combines sinusoidal PM machine drive technology with distributed control systems has been implemented to obtain a linear servo machine which can control multiple moving elements over unlimited linear distances at high position accuracies.

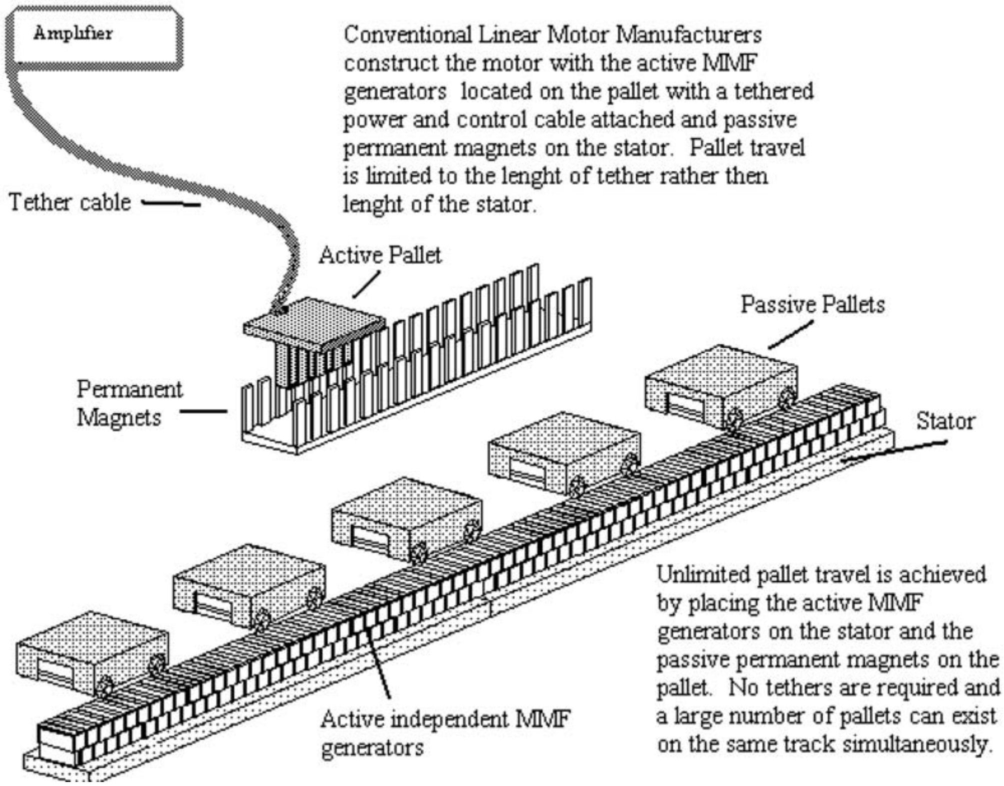

Figure 1: Traditional Linear Motor vs. Modular Linear Motor

INTRODUCTION

Automated assembly systems typically require transportation of a work piece from one assembly cell to the next. Conventional methods for moving the work piece include conveyor belt systems and rotary indexing tables. Typically in these applications, the work piece is moved into a work cell, located precisely to a datum point, then operated on by the cell process, and finally transferred to the next work cell. The throughput of the assembly system is often limited by the transfer time between work cells. Further, many of these automation systems require complex arrays of datum stops, sensors, and programmable logic controllers (PLCs) to manage the transfer of work pieces.

This article describes a modular linear motor (MLM) with precise independent control of high speed multiple moving elements (pallets). This machine can be configured to arbitrary lengths with arbitrary numbers of pallets. As an alternative to material transfer systems currently used in automated manufacturing, the MLM system achieves higher throughput with simpler programming.

The MLM system achieves independent servo control of individual pallets, so that each pallet can follow an independent path. Datum stops are not required to obtain precise location of the work pieces. High acceleration and velocity rates dramatically reduce cycle times. The velocity of a work piece can be reduced and “electronically geared” (synchronized) to a moving operation. In continuous mix operations, where different products are assembled on the same line, individual pallets can have different programs - bypassing operations, or changing destination work cells “on-the-fly”.

A general discussion of linear motor operation will be presented followed by descriptions of the major elements of the MLM: magnetic field synchronization, independent pole control, position feedback, modular motors and network communications.

LINEAR MOTOR OPERATION

A conventional synchronous linear motor consists of a single moving pallet on a stationary magnetic structure called a stator (see Figure 1). Typically, the stator consists of alternating magnetic poles (N-S-N-S-N-S-...) achieved using individual permanent magnets. The moving pallet contains a multi-phase winding which could be energized by a conventional brushless DC motor controller. In this case, the linear motor can be viewed as an "unrolled" rotational synchronous motor, with the permanent magnet stator repeated multiple times to achieve the desired range of motion.

Linear motor technology has improved greatly with the advent of less expensive, more reliable power electronics and faster microcontrollers. Since traditional linear motor designs have the multi-phase windings ("active magnetics") in the moving pallet, and permanent magnets ("passive magnetics") in the stationary linear track, these systems typically include a tether containing a harness to power the active head and to read encoder feedback. The tether limits the practical range of travel for these systems. While multiple active pallets are possible, the practical limit is two or three pallets, again due to the complexity of the tether arrangement.

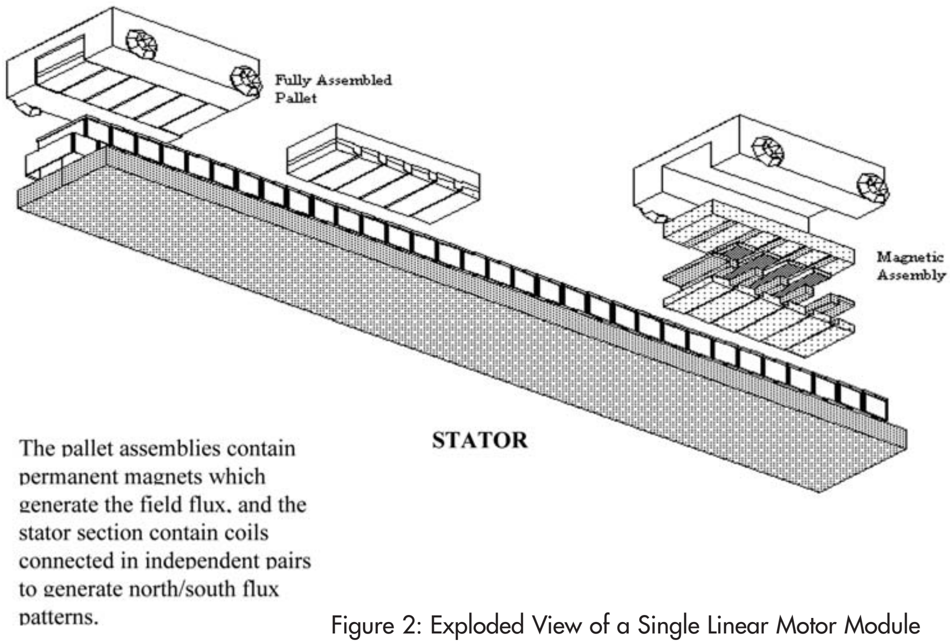

Figure 2: Exploded View of a Single Linear Motor Module

The MLM system eliminates the tether requirement by putting the passive magnetic components (permanent magnets) in the pallet, and the active coils in the stator. The stator control electronics can economically control current in individual coils along the length of a stator module. As a result, the MLM system described here presents a unique method for controlling multiple passive pallets on an active track. An unlimited number of pallets can be controlled over arbitrary distances. The active motor base is assembled using multiple independent sections or "modules".

MAGNETIC FIELD SYNCHRONIZATION

Force generation in a linear motion is a result of the attractive forces between the static magnetic field of the permanent magnets and the moving magnetic field of the energized coil windings. By maintaining a fixed displacement (phase angle) between these two fields, a constant force is produced, with a small amount of ripple force due to the saliency of the stator and pallet. One function of the control electronics is to dynamically adjust the coil winding currents to keep the relative distance between these two magnetic fields constant as the pallet moves. We can visualize the control electronics as producing a traveling wave of magnetomotive force (MMF) in the stator coil windings.

As the pallet moves, the controller "electronically commutates" the stator winding currents to maintain this constant phase angle (self synchronization). By adjusting the magnitude and sign of the stator current, the force on the pallet is controlled. A position control loop can be placed around this current control to achieve servo position control just as in a rotary DC servo motor.

INDEPENDENT POLE CONTROL

To achieve independent motion of multiple pallets, only the stator coil windings immediately beneath a pallet are energized. As the pallet moves, MLM controllers use pallet position information to determine which coils are active. The pole pitch and pallet magnet design are such that individual pallets can be positioned side-by-side without experiencing any stray magnetic effects from the adjacent pallet's active coils.

As the pallet moves from one linear motor module section to another, it will bridge coils on both modules. A high speed network is used to communicate current set point information from one motor module to the next as the pallet moves. Once the pallet leaves a module, control of that pallet is transferred to the next module.

A separate PWM amplifier and drive circuit must be constructed for each coil winding on the stator (see Figure 3). Amplifiers are implemented using MOSFET half-bridges. A high speed DSP processor along with custom gate arrays generates PWM waveforms using a second order compensator for each of 36 coils on the module. Each current control loop outputs a dedicated PWM signal which is used to control one half bridge coil driver specific to one coil winding. While this approach is computationally intensive, it achieves a controller with very low parts count and minimal incremental cost for each winding drive.

Coil current setpoints are determined using a table lookup to reconstruct a sinusoidal MMF.

The table contains unscaled magnitudes for current setpoint. These values are multiplied by a gain factor equal to the output of a PID position control loop to obtain servo control.

Multiple pallets on a single section require multiple indexes into the table. As the pallet passes from one control section to the next, the PID controller state variables must be passed to the next module in the instant that pallet control transfers. Independent S-curve trajectory generation for each pallet allows independent control of velocity and acceleration for each pallet.

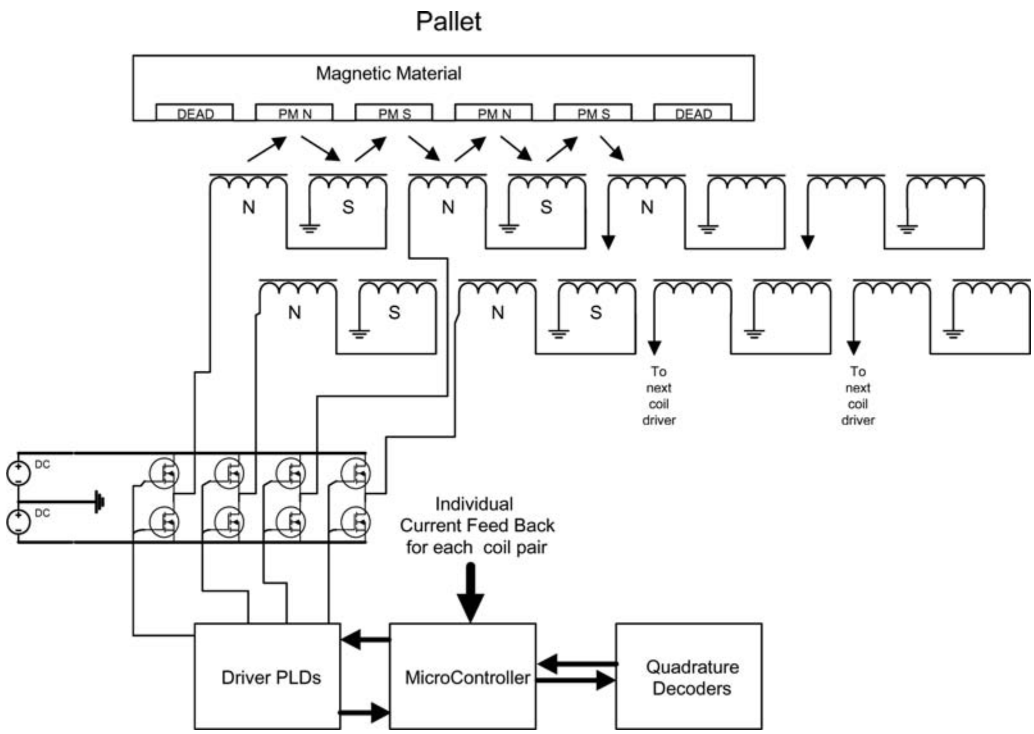

Figure 3: Linear Motor Drive Circuit

POSITION FEEDBACK

The MLM system requires accurate position feedback to achieve position servo control, to synchronize the MMF field to the pallet position, and to determine which group of coils needs to be active for individual pallets. The position feedback system must be capable of tracking multiple pallets. Since no tether is required to power the pallet, it is desirable to have no contact associated with the position feedback system.

A novel configuration of quadrature optical strips and encoders meets these various objectives. Each pallet is fitted with an optical codestrip that contains typically several hundred lines/inch. Multiple quadrature incremental encoders are distributed along the length of the linear motor module. The encoder uses a Light Emitting Diode and a precision photodiode array to convert linear motion of the code strip to a binary count value representing the relative motion of a codestrip. A Digital Signal Processor in the MLM section processes data from the distributed encoder modules to determine which encoders are “active” (contain a codestrip), and to reconstruct accurate absolute positions for each pallet. This system achieves position accuracies of approximately 0.002”. Higher accuracies can be obtained using magnetic strips and encoders.

As pallets pass from one motor section to the adjacent section, the section controller must relinquish control of the position loop.

MODULAR MOTORS

A major objective of this system is to demonstrate modular motor sections that can be configured into automation systems of arbitrary lengths. A simple analysis will show that any control scheme based on a single master controller will quickly run into bandwidth bottlenecks (computational or communication) as more motor sections and more pallets are added to the system.

The distributed control structure used in the MLM system can be broken down into zones tied together by two different communications networks (see Figure 4). A zone contains an independent DSP based microcontroller that is responsible for a fixed number of current loops and encoders. The physical size of the zone is determined by pole pitch and number of current loops. The system uses modules that are one meter in length containing 36 coil loops. It is convenient to have one control zone coincide with the physical length of the motor module.

Two different network types are used to implement three communications links for each zone. An Interzone Network is used for two of the links which transmit and receive state variable information between nearest neighbors. This information follows a pallet as it moves around the MLM system. The Interzone Networks are high speed bi-directional links to allow quick information exchanges when required.

A Supervisory Network establishes a third communications link to a module controller. This multidrop network is used to transfer commands which initiate a pallet motion and to communicate diagnostic and error status information.

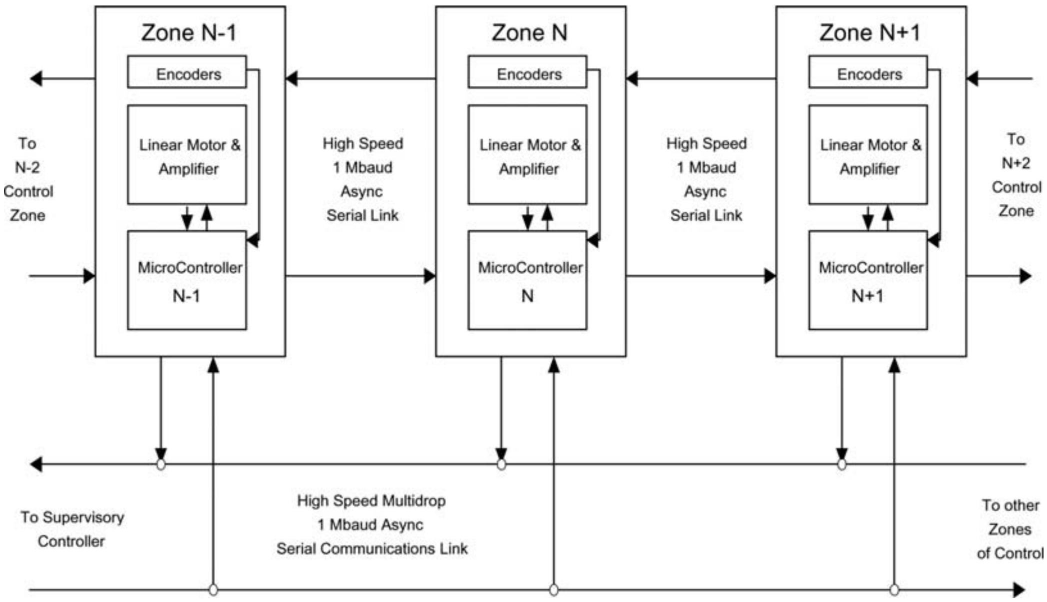

Figure 4: Multiple Module Network Communication Block Diagram

NETWORK COMMUNICATIONS

The Interzone Network is used during pallet zone transitions to allow the smooth transfer of a pallet from one zone to the next, or during servo position operation of a pallet bridging two zones. Interzone Network traffic begins when a pallet reaches a position where a neighbors' coil windings must be energized. Current setpoint data for specified coils in the neighboring zone is transferred directly to the current loop process in the neighboring microcontroller, requiring minimal CPU involvement. During this phase, network communications packets are very short. When the pallet must move completely out of the controlling zone, a larger communication packet is transferred containing state variables for PID position control, pallet ID, and trajectory information. The neighboring zone now takes over control of the pallet. All position control and current control is confined to a local controller. Interzone Network traffic occurs only as a pallet transfers from one zone to the next.

Supervisory Network is limited primarily to messages which initiate a single pallet motion.

Since only one network packet is required to initiate a motion, the Supervisory Network is capable of initiating thousands of pallet motions per second. Additional messages are used to report error conditions such as servo position errors or pallet collisions. The Supervisory Network can also be used to query the specific location of an individual pallet.

CONCLUSION

A modular linear motor system with independent pallet control has been demonstrated. This system is a departure from the conventional approaches used in linear motors. A distributed network scaleable to arbitrary motor lengths and numbers of pallets has been demonstrated.

The ability to assemble motor modules to arbitrary lengths combined with simple, transparent control of multiple moving pallets will form the basis for many advanced automated projects in the future.