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# Design of a new fasten-able linear motor for smart distributed robot system

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**Abstract**—Distributed robot often contains two systems. One is for moving, and another one is for fastening. In this paper, we focus on a new linear motor, in addition to motion function; it can provide suction force, and does not require continuous energy supply for suction. A basic circuit for the new linear motor was designed and tested, which can freely control the length of dead-time. Design guide for initial design are also summed up.

**Keywords**— smart systems; scalability; distributed robot; linear motor; electro-permanent magnet

## I. INTRODUCTION

Conveyors are important part of industry; they are usually designed as monolithic entities solving one problem at a time. They lack flexibility to environment changes and failures that occurs at small scale. To solve this problem, self-reconfigurable distributed modular robot systems are potential solutions, which are also new trends in robotics [1-3]. On the other hand, nowadays many scientists start to research on distributed robots and programmable substances [4-6].

These projects' common feature is using very small robots to combine into a large objects or collaboration to complete a task. In order to achieve these goals, the small robots must contain two systems, one is for moving, and another one is for fastening. Wheel is the basic solution for moving system. And there are also many ways for fastening, the most stable ones are electromagnets and mechanical hooks. Electromagnets act fast and are very easy to control. However, it requires continuous power supply; the energy consumption is huge, not suit for robots in small scale. In spite of stability and strong fastening force, complex structure, difficult to process, high production costs, slow response, limits mechanical hooks' application scope in small robots. Whether electromagnets or mechanical hooks, they are independent systems from the motion system. That is, for the entire robot, both motion system and fastening system are both needed. For the robot miniaturization, it is always a major constraint.

This paper presents a new kind of linear motor [7]. Its structure is simple. There is only one system inside, which can act as both motion system and fastening system. More importantly, the fastening system unlike the electromagnets require continuous power supply or the mechanical hooks have complex structures. It's simple and doesn't need power when fastened. Details on theory and design are discussed in later sections.

## II. ABOUT LINEAR MOTOR

Linear motor was widely used in recent 20 years. It can directly transform electrical energy into linear moving mechanical energy. The mechanical friction and losses can be reduced without transmission mechanisms. Therefore, it is very suitable for direct drive system (e.g. smart conveyor project). Optimal motor design and driving technology are two main developing directions of the linear motor. In addition to reducing energy loss, linear motor can generate great acceleration, and is not bound by the centrifugal force, so it can produce very high straight-line speed in a short stroke and theoretically without speed limit [8-10].

There are many types of linear motors; their structures vary depending on the application, their basic principles are shown in "Fig. 1". It consists of a rail full of magnets (the stator part) and a coil structure (the rotor part), when the coil is energized, rotor can move along with the stator.

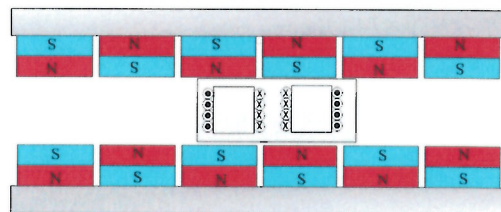


Figure 1. Basic principle of linear motor

Linear motor is mainly used in some special occasion. The design of it depends on its application. It is difficult to form a unified, normalized type. Thus limiting the development of the linear motor; another weakness of linear motor is that it can only move in two directions, and requires a relatively high level of arrangement (positive permanent magnet next to negative one). However, whether it is a linear motor or ordinary motor, for distributed robot systems, the biggest problem is that they can't provide both driving force and fastening force.

## III. THEORY OF THE NEW FASTEN-ABLE LINEAR MOTOR

The new fasten-able linear motor is based on the theory of the Electro-permanent (EP) magnet.

### A. Electro-permanent (EP) magnet

EP magnet is a solid-state device which allows an external magnetic-field to be modulated by an electrical pulse. No



electrical power is required to maintain the field. EP magnet contains two magnetic materials, one magnetically hard (e.g. NdFeB) and one semi-hard (e.g. Alnico), capped at both ends with a magnetically soft material (e.g. Iron) and wrapped with a coil. NdFeB and Alnico are the two most common materials used to make the EP magnet. It is because, NdFeB has a very high coercivity (1000 kA/m), and Alnico has a relatively lower coercivity (48 kA/m). However, both have about the same residual induction (1.28 T and 1.26 T) [11-13].

“Fig. 2” shows the principle of EP magnet; a current pulse of one polarity magnetizes the materials together, increasing the external flow of magnetic flux. A current pulse of the opposite polarity reverses the magnetization of the semi-hard material, while leaving the hard material unchanged. This diverts some or all the flux to circulate inside the device, reducing the external magnetic flux.

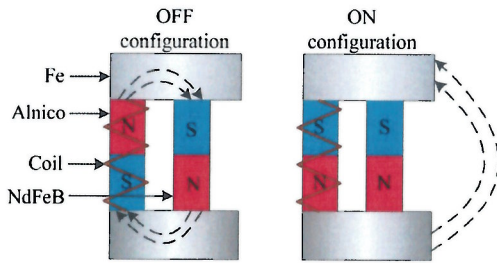


Figure. 2. Principle of EP magnet

### B. Half EP magnet, controllable permanent magnet

Due to the small power consumption, EP magnet is primarily used to provide a force to fasten objects. However, people ignored one of its basic functions. Since the Alnico polarity can be controlled; it could exist independently from the EP magnet. Alnico wrapped by coil is the only part we need for building a fasten-able linear motor, so we call it half EP magnet. The main principle of half EP magnet is shown in “Fig. 3”; it is almost the same as EP magnet but without NdFeB. The Alnico is wrapped by coil; its polarity direction can be changed when adding pulse on a coil.

“Fig. 4” shows the motion mechanism of new linear motor. According to the basic principle of magnet, same polarities repel each other. Different polarities attract each other.

Two Half EP magnets, one produces repulsive force, another one produces attractive force at the same time; they can move another permanent magnet. The direction of movement is controllable. In this new linear motor, Half EP magnet is the stator. The permanent magnet is the rotor. There is only one permanent magnet in “Fig. 4”, but the rotor can be composed by a plurality of permanent magnets.

“Fig. 4” shows the status of 4 half EP magnets in one complete movement process. NdFeB (rotor) moves for right to left. The initialization polarization direction of half EP magnet is N to NdFeB’s N. The system only needs energy at the moment of rotor’s movement. After that, it does not need energy to fasten rotor and stator together. In theory, the new linear motor can be made as tiny as possible.

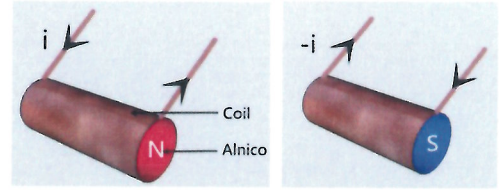


Figure. 3. Principle of Half EP magnet

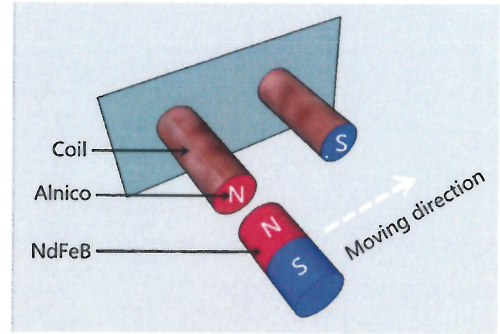


Figure. 4. Motion mechanism of new linear motor

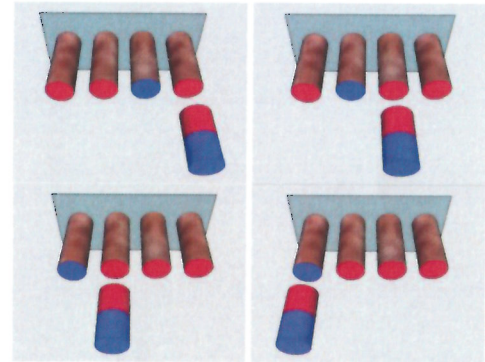


Figure. 5. Motion mechanism of new linear motor

In addition to provide both driving force and fastening force, another advantage of the new linear motor is that, it can move in any direction, with the proper arrangement of permanent magnets in the plane. And the permanent magnets are simple to install, only needs to be placed in the same direction, rather than placed alternately.

## IV. CIRCUIT DESIGN

### A. Pulse magnetizing

As mentioned before, pulse is used to change the magnetization direction of half EP magnet. When the pulse discharges current pass through the solenoid, it generates a pulse magnetic-field in its interior. In general, when the peak value of the pulse magnetic-field reaches 3-5 times the material coercivity, it can be full magnetized [14].

There are two main methods for generating large pulse current, using a strong enough pulse power or capacitance pulse discharge [15]. Since distributed robot systems generally require a smaller volume, so we choose the latter one.

Capacitance pulse discharge also has the advantage of simple structure; it requires low power, and easy to operate. "Fig. 6" is a schematic diagram of it.

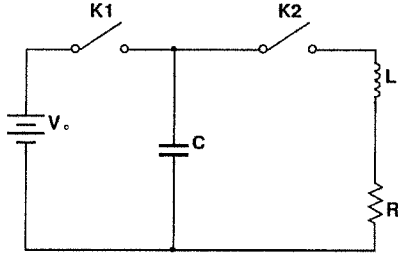


Figure 6. Schematic diagram of Capacitance pulse discharge

As shown in "Fig. 6", when the switch K1 is closed, capacitor C will be charged by power source. Then disconnect K1, close K2; the circuit forms a typical RLC oscillation circuit. In this case, a constant coefficient second order linear homogeneous differential equation can be formed; U is as an unknown quantity. That is,

$$LC \frac{d^2 u_c}{dt^2} + RC \frac{d u_c}{dt} + u_c = 0 \quad (1)$$

$\beta$  is damp coefficient  $\beta = \frac{R}{2} \sqrt{\frac{L}{C}}$ ,  $\omega$  is angular frequency  $\omega = \sqrt{\frac{1}{LC}}$ ,  $i = -C \frac{d u_c}{dt}$ .

The initial conditions is when  $t = 0^+$ ,  $u_c = U_0$ ,  $i = 0$ . Depending on different circuit parameters, the following three conditions are calculated:

- When  $\beta = 1$ ,  $R = 2\sqrt{\frac{L}{C}}$ , the circuit is in critically damped state,

$$LC \frac{d^2 u_c}{dt^2} + RC \frac{d u_c}{dt} + u_c = 0 \quad (2)$$

- When  $\beta > 1$ ,  $R > 2\sqrt{\frac{L}{C}}$ , the circuit is in over-damped state,

$$i(t) = \frac{CU_0 \omega}{\sqrt{\beta^2 - 1}} e^{-\beta \omega t} \operatorname{sh}(w \sqrt{\beta^2 - 1} t) \quad (3)$$

- When  $0 < \beta < 1$ ,  $R < 2\sqrt{\frac{L}{C}}$ , the circuit is in Under-damped ringing state,

$$i(t) = \frac{CU_0 \omega}{\sqrt{1 - \beta^2}} e^{-\beta \omega t} \sin(w \sqrt{1 - \beta^2} t) \quad (4)$$

Waveforms of the three states are shown in "Fig. 7". Intuitive looking, the current peak of second state is too low. The third state has a high-current peak, but the presence of negative pulse, will play the role of degaussing. So the first state is suitable for magnetization.

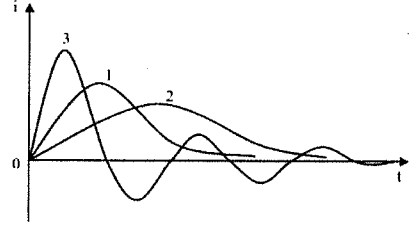


Figure 7. Waveforms of the three states

### B. Magnetization coil fabrication rules

Magnetization coil for generating strong magnetic-field is a typical solenoid.

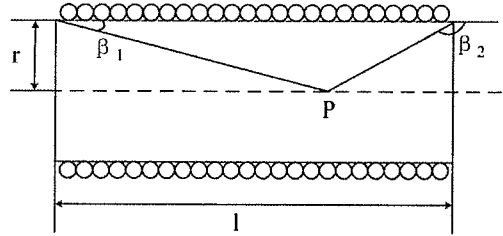


Figure 8. Structure of solenoid

Its structure is shown in "Fig. 8". The radius is r; the length is l; and a single-layer coil is wrapped in N turns on it. When charge with current I, the magnetic-field strength on its axis at P is,

$$H = \frac{NI}{2l} (\cos \beta_1 - \cos \beta_2) \quad (5)$$

The magnetic-field strength of the center is,

$$H_{center} = \frac{NI}{\sqrt{4r^2 + l^2}} \quad (6)$$

Multi-layer wrap solenoid is often used in practical, set length is l, inner and outer radius are r1 and r2. Its magnetic-field strength of the center is,

$$H_{center} = \frac{NI}{2(r_2 - r_1)} \ln \frac{r_2 + \sqrt{r_2^2 + l^2}}{r_2 + \sqrt{r_1^2 + l^2}} \quad (7)$$

If we take the mean radius  $r = \frac{(r_1 + r_2)}{2}$  into count, and still use the formula of a single solenoid to calculate the  $H_{center}$ , then it will be much simpler, and the results of both are very similar. Therefore, we can only use a single-layer solenoid to analyze.

In the process of generating a magnetic-field, due to the non-linear magnetization curve, the coil is also a non-linear inductance element. Its inductance  $L$  is related to current changes. And because of the eddy current and hysteresis, it can't even be seen as a single value. Therefore, the calculation process is very complex, to the best of our knowledge, there are no existing studies explain how to determine the exact number of turns, coil layers, the wire diameter and other parameters. However, we summarized some general selection rules.

Observe the formula (2) and (6), it can be seen, when  $I$  and  $l$  are fixed, if  $r$  getting smaller, the magnetic-field strength of the center will get bigger, and the difference between magnetic-field strength at both ends and center will also get greater. From another perspective, at the premise of big enough to place Alnico,  $r$  is smaller; the required current for saturation magnetization is smaller, and the required storage capacitor discharge voltage is also smaller. That is, solenoid with the single-layer is better than with the multi-layer.

Within a certain range, more turns are better, but when adding turns, the radius and the thickness increases at the same time. The magnetic-field strength is proportional to the current, and the current is proportional to the capacitance, thus the greater the capacitance, the greater the magnetic-field strength. However, due to rising volumes and prices, the capacitance cannot increase indefinitely; the rule is choosing the bigger one in an acceptable range. The wires for making solenoid should be with a large cross-section.

The magnetizing current pulse width is short, pulse rise time is much shorter, only a few microseconds, and thus will generate great potential  $e = -d\psi/dt$  and induced eddy currents in Alnico. These eddy currents in turn generate anti-magnetic-field, which will hinder the magnetizing. This anti-magnetic field is enhancing radially along the outside to the inside of Alnico. So, non-uniform magnetization often occurs when magnetizing the permanent magnet with large cross-section. Its surface is saturation magnetized, but the central portion is not. If possible, better to choose the Alnico with a small cross-section.

### C. H-bridges for controlling the magnetization direction

H-bridge is used in EP magnets to control the magnetization direction as a result of control the electric current direction. "Fig. 9" is the schematic of H-bridge. It contains four MOSFET [16].

#### 1) Dead-time in H-bridges

Dead-time is also called as shoot-through protection or no-overlap PWM. Generally speaking, its presence is a good thing in most instances. When turning one MOSFET off, while turning the other MOSFET on, for a short while both the low and high-side MOSFETs are potentially conducting to a certain degree, creating a relatively low resistance path from the supply to flow to the ground. This results in a current spike which is quite problematic. The main goal of dead-time is to avoid this.

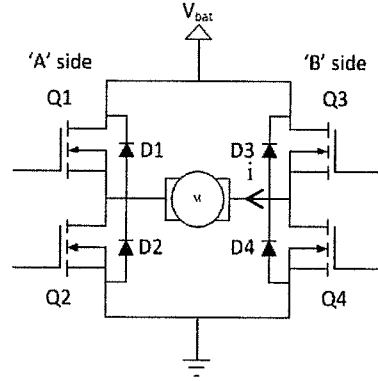


Figure 9. Schematic of H-bridge

Dead-time is an inherent characteristic of MOSFET. It is mainly due to a small amount capacitance in MOSFET. This capacitance information is usually found in the MOSFET data sheet. Table 1 is the capacitance parameters of two transistors that we use. For input capacitance, the 8736 is 2315 pF, the 9310 is 5250pF.

TABLE I. CAPACITANCE PARAMETERS OF TWO MOSFET

Items	MOSFET	
	<i>Irf8736pbf</i>	<i>Irf9310pbf</i>
Input Capacitance	2315 pF	5250 pF
Output Capacitance	449 pF	1300 pF
Reverse Transfer Capacitance	219 pF	880 pF

#### 2) Effect of dead-time on H-bridge output voltage

For half EP magnet, the presence of dead-time is no longer a good thing. A MOSFET is limited in its speed to switch on and off by the amount of time that it takes to charge and discharge the small amount capacitance in its structure. The most direct consequence of dead-time is to cause delay.

In addition to delay, there are other effects of dead-time. Suppose in "Fig. 9", in the beginning, during the dead-time, Q1 is open, Q2, Q3 and Q4 are off. Since the current flows to different direction, the power unit output level will be different. As shown in "Fig. 10", when the current flowing through the power unit is greater than 0, that is  $i > 0$ , the power unit output voltage is  $U_{dc}$ , conversely when  $i < 0$ , the output level is 0. Therefore, during the dead-time, since the current flows to different direction, the actual output voltage of the power unit is as shown in "Fig. 10" (e) and 10 (f). Obviously, when  $i > 0$ ,

the actual output voltage will increase  $\frac{U_{dc} T_d}{T_s}$ , when  $i < 0$ , the

actual output voltage will decrease  $\frac{U_{dc} T_d}{T_s}$ . This will cause the

distortion of the output waveform; generate new harmonic components; reduce the effect of active filtering.



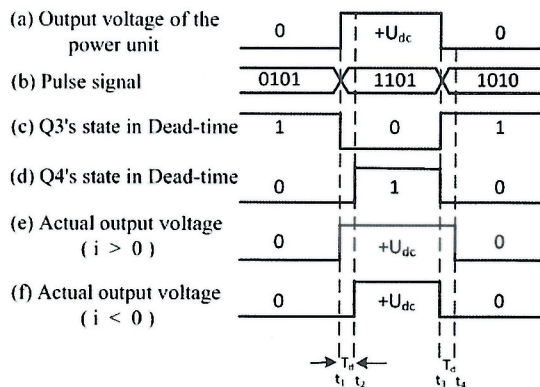


Figure 10. Effect of dead-time

Theoretically, the dead-time can be calculated. The most important parameter is turn-on and turn-off times. Calculating dead-time is a complex process, relatively; Use machine to test is a more direct approach.

### 3) Elimination of dead-time to achieve quick movement

We measured the dead-time with an oscilloscope. It is 130ms. This is longer than charging time of the capacitor (100ms).

“Fig. 11” displays the improved H-bridge, especially for Half EP magnet. We use independent micro-controller’s IO to control each MOSFET, instead of an IO to control a half-bridge. The advantage is, the on and off time of each MOSFET can be precisely calculated and can be directly controlled by program. The dead-time can be added from zero to a large value.

“Fig. 12” shows the actual test board we made. The size of Alnico is 1 mm in diameter and 3 mm in length. It is wrapped with 80 turns of 0.15 mm enameled copper wire in two layers. Experimental results show the circuit is stable, verifies the feasibility of the scheme.

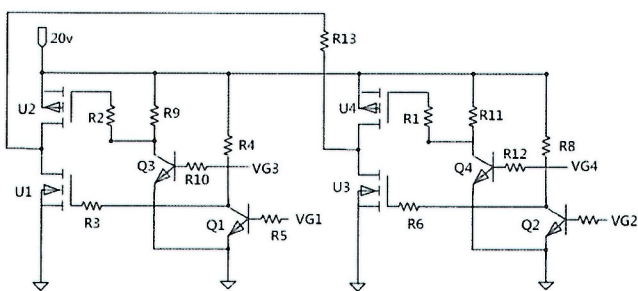


Figure 11. Improved H-bridge for magnetization half EP magnet

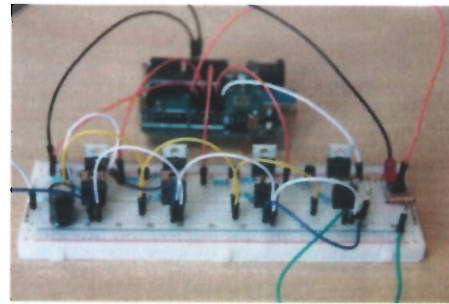


Figure 12. Actual test board of improved H-bridge

## V. CONCLUSION

This paper presents a new type of linear motor, which not only can implement motion but also can provide fastened force. For small distributed robotic systems, it has following advantages:

- One system to realize two functions. It can greatly reduce the complexity of robot systems, and save energy.
- Does not require continuous energy supply for suction.
- The structure is very simple and can be made at small scale.
- As a linear motor, it can move in any direction. Rail is easier to make than normal linear motor.

For this new motor, we analyze its circuit configuration and summed up some rules for initial design. The rules are as follows:

- For magnetizing, single-layer wrapped solenoid is better than multi-layer.
- The greater the capacitance, the greater the magnetic-field strength. So, choose the bigger one in an acceptable range.
- The wires for making solenoid with a large cross-section are better than which with a small cross-section.
- If possible, chose the Alnico with a small cross-section.
- Within a certain range, more coils turns are better. However, too many turns will increase the resistance and the thickness.

At last, the effects of dead-time on H-bridge output voltage are discussed. It will cause delays and the distortion of the output waveform; it generates new harmonic components; reduces the effect of active filtering. A basic circuit for the new linear motor was designed which can freely control the length of dead-time. Its feedback is much faster than common H-bridge.

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