Design of a Small-Scale Prototype for a Stabilized Permanent Magnet Levitated Vehicle

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ABSTRACT: A small-scale proof-of-concept prototype has been designed and built as the next stage in the development of a novel maglev vehicle concept. This prototype demonstrates many of the key advantages of the technology which uses permanent magnets for levitation and does not require any moving parts in a track bifurcation. Key design features and performance characteristics of the prototype are described: the control system for stable levitation, the linear synchronous motor for propulsion and the method of track switching. Alternative system configurations and other applications of the technology are also briefly discussed.

1 INTRODUCTION

The repelling forces resulting from bringing like poles of two magnets together is a commonly experienced phenomenon. The use of this repelling force to levitate a vehicle was considered early in the exploration of maglev vehicle technologies (Pollgreen 1964, Olsen 1965), but was largely discarded due to poor performance of the magnetic materials available at the time. As SmCo materials became available, the approach was revisited but again set aside by most due to the material's high cost (Sinha 1987). In the 1980's and 90's NdFeB materials began to be developed as a low cost alternative and have steadily improved over time. Today, NdFeB magnetic materials offer a very economical option with more than adequate performance for use in maglev vehicles and their tracks.

LaunchPoint Technologies, in collaboration with Applied Levitation and Fastransit Inc., has been developing a permanent magnet maglev vehicle concept which substantially reduces the amount of magnet material required (Fiske, et al. 2004). The reduction of required magnetic material and low cost of NdFeB result in the cost of track magnets being a significant, but by no means dominant, contribution to the total track cost on a per-mile basis. To demonstrate the feasibility of this type of permanent magnet levitation, a large-scale demonstration vehicle was constructed (Figure 1, Fiske 2006).

As is commonly encountered in permanent magnet bearing design (Paden et al. 2003), the levitated body must have at least one unstable coordinate due to the limitations expressed by Earnshaw's theorem (Earnshaw 1842). A method for stabilizing the vehicle in the lateral direction is required and, as will be shown, it can be provided by coils and sensors placed in the levitation gap. This type of stabilized permanent magnet (SPM) suspension is inherently different from electromagnetic suspension (EMS) and electrodynamic suspension (EDS) approaches which have been more common up until now.

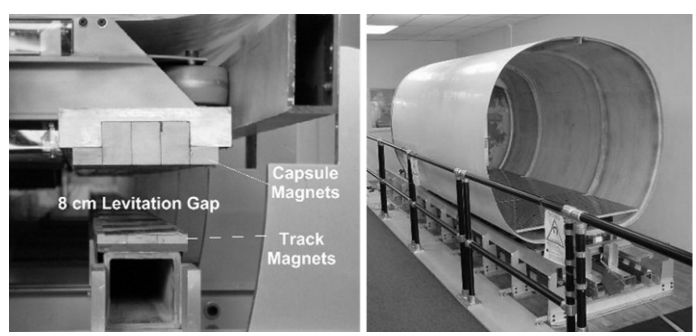

Figure 1. Large-scale permanent magnet demonstration vehicle.

Another key feature of this SPM approach, whose importance cannot be overstated, is the totally passive nature of the track bifurcations. No physical motion or electrical actuation of the track is necessary for vehicle switching. With this SPM technology, switching happens in the vehicle, not in the track. The result is higher reliability and extremely short headways that enable modes of operation that are not possible with any of the alternative maglev vehicle technologies (Fiske 2008).

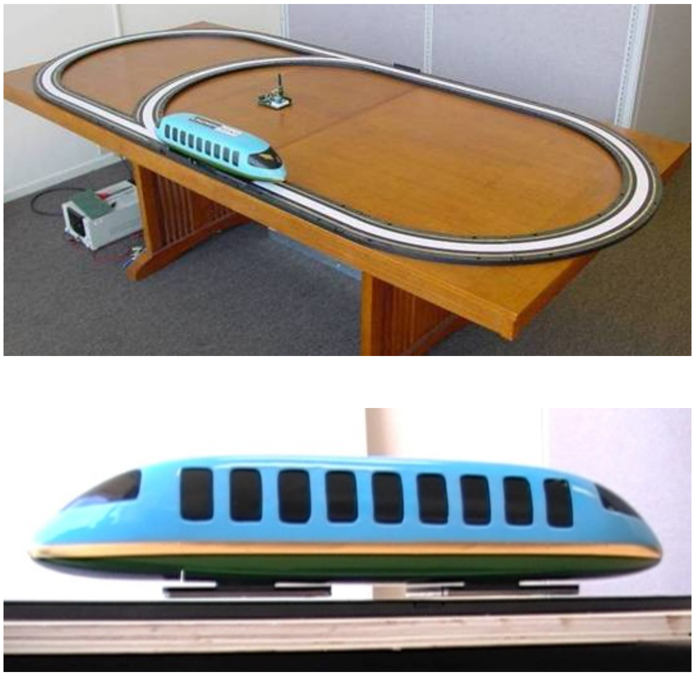

Figure 2. top: The prototype on its track; bottom: A close-up view of the small-scale prototype vehicle levitating.

To demonstrate this novel switching concept and to further develop the SPM technology, a small scale prototype was built and tested (see Figure 2). The remainder of this paper will describe the key features of that prototype and discuss differences and similarities to future full-scale prototypes that are currently being planned.

2 PROTOTYPE DESCRIPTION

The purpose of the prototype is to demonstrate the lateral stabilization and switching concept. In order to achieve that goal in the fastest and most economical way, a small scale was selected and commercially available components were used whenever possible. The prototype is a little over 0.5 meters long and weighs about 1.5 kilograms. The track gauge is 60 mm which is wide enough for the track magnets to fit on the outside of a standard G scale model railroad track.

Most of the electronics and batteries are housed on the main chassis. Two freely rotatable bogies house the levitation and propulsion actuators and sensors. These bogies allow the actuators and sensors to conform to very tight turn radii and are directly analogous to the bogies found on railroad cars. A cosmetic shell hides the inner workings of the vehicle and can easily be removed (see Figure 3).

The vehicle's speed and switching direction are controlled via analog voltage signals generated by a Basic Stamp II microcontroller which receives digital commands over a radio frequency communications link from a hand held controller.

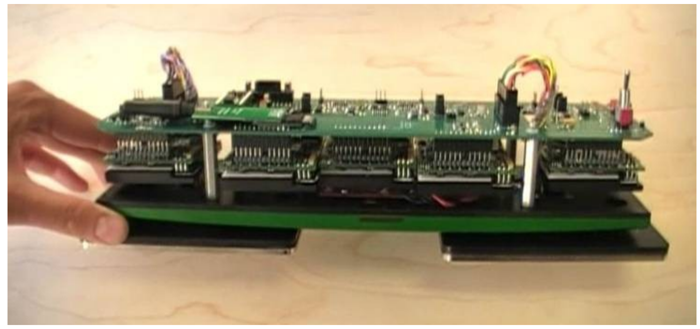

Figure 3. The prototype with the cosmetic cover removed.

Many of the key components are identified in the vehicle cross-section and bottom views shown in Figure 4. The small-scale prototype consists of several subsystems which will each be discussed in more detail:

1. Vertical Levitation
2. Lateral Stabilization
3. Switching
4. Vertical Damping
5. Propulsion
6. Energy

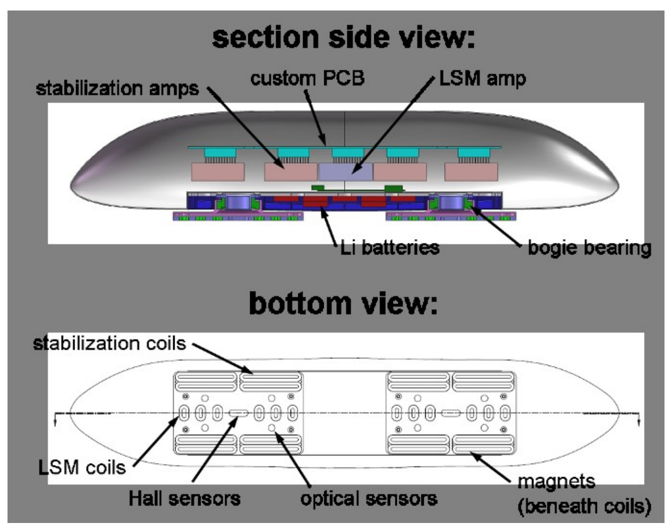

Figure 4. Two views showing several key components.

2.1 *Vertical Levitation*

The track levitation magnets were selected from those commercially available in standard sizes. While the use of a Halbach array configuration would minimize the magnet material required (Fiske, et al.

2004), it would also introduce design constraints that would make manufacturing at a small scale difficult and the use of standard magnets infeasible. Because the Halbach array track configuration was already validated in the large-scale prototype (Fiske 2006), a much simpler arrangement of dipole magnets was used in the track and in the vehicle for the small-scale prototype (see Figure 5).

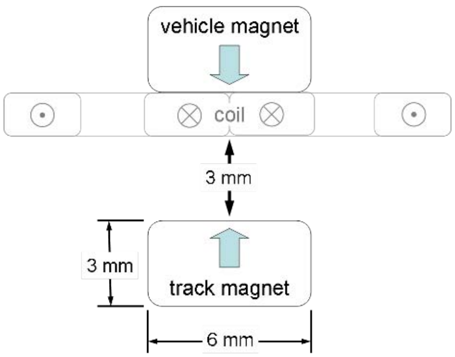

Figure 5. The track and vehicle magnet configuration.

The magnets in the track are sintered NdFeB, while those in the vehicle are made from a much weaker bonded NdFeB magnet material that was readily available and easy to machine into the desired shape. Despite the less efficient magnet arrangement and the relatively weak materials used, the levitation gap is 3 millimeters, which is large for a vehicle of this size. As is shown in Figure 1, the levitation gap at full-scale with sintered NdFeB levitation magnets arranged in a Halbach array without any payload and without stabilization coils is about 8 cm with very modest sized magnets in the track. When the full payload is applied and stabilization coils are added, the levitation gap will shrink to about 3 cm. This is large compared to typical levitation gaps of many other maglev technologies.

2.2 Lateral Stabilization

The large levitation gaps afforded by permanent magnet Halbach arrays (Halbach 1982) are sufficient to allow part of this valuable real estate to be filled with coils which interact with the track magnets to provide forces in the lateral and vertical directions. The lateral stabilization coils carry current in the longitudinal direction and interact with the parts of the track magnetic field which is oriented in the vertical direction (see Figure 5). Lorentz' law dictates that a force orthogonal to the magnetic field and current will be generated with the force's sign being determined by the direction of current.

Lateral position is sensed with an LED/photodetector optical sensor which measures the deviation from the edge of a line on the track (see Figure 6). These optical sensors are very simple and inexpensive with low noise and high bandwidth, and proved to be a great solution for the small scale prototype. However, real-world conditions such as dust, ice and other opaque contaminants that will be present in the final application will likely preclude the use of this type of optical sensor. In future full-scale prototypes, these optical sensors will be replaced with electromagnetically based sensors such as a variable reluctance sensor.

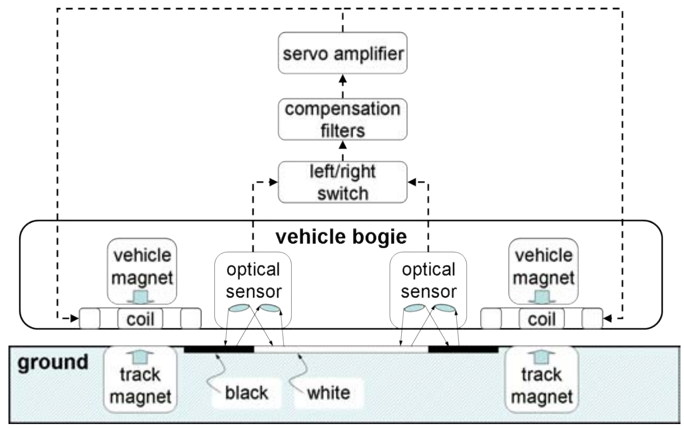

Figure 6. The elements of the lateral stabilization loop.

The optical sensor signal is filtered with a simple lead compensator implemented with low-cost analog operational amplifiers. The filtered sensor signal is provided to a commercially available PWM servo amplifier which controls the current in the coils.

The elements of each lateral stabilization loop are shown in Figure 6. Each bogie contains two of these loops in order to stabilize the lateral and yaw motions of the bogie. Because there are two bogies per vehicle, there are a total of four stabilization loops (see Figure 7).

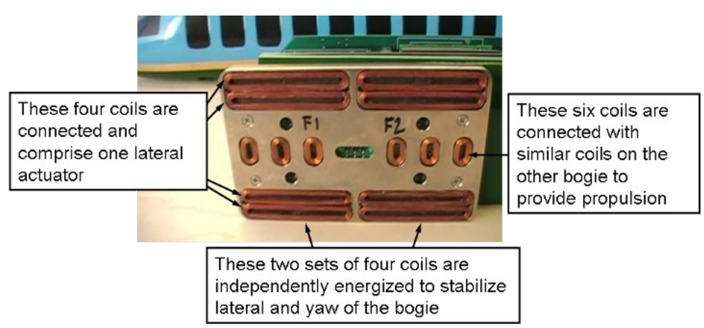

Figure 7. The bottom of the bogie houses the actuator coils and sensors.

2.3 Switching

Each lateral stabilization control loop has two sensors that both measure the lateral displacement when the vehicle is in a straight section of track (see Figure 6). If the leftward path is to be followed when traversing a bifurcation in the track, the left sensor is used and the right sensor is ignored. If the rightward path is to be followed, the right sensor is used and the left sensor is ignored. The track is totally passive in this switching process – all of the action happens in the vehicle electronics.

Details of the track bifurcation magnetic design are currently being held as proprietary and may be covered in future publications once pending patents are processed.

2.4 Vertical Damping

Permanent magnet levitation is inherently lightly damped as is commonly discovered by those who have researched permanent magnet levitation and bearing design (Jayawant 1981). In order to control ride quality, oscillations in the vertical, roll and pitch coordinates need to be controlled. On future prototypes, coils will be added in quadrature to the lateral stabilization coils to allow for the application of forces in the vertical, roll and pitch directions.

These vertical coils can be part of a closed loop control system with levitation gap displacement feedback. This approach is very versatile and allows for feedforward compensation of known track variations (Wang and Nagurka 1997). Much simpler sensorless approaches can also be used provide adequate damping from these coils, but don't provide as much versatility.

The large levitation gap afforded by the SPM approach makes it possible to leave out the secondary mechanical suspension that is found on many other maglev technologies. As a result, overall system complexity and weight will be reduced while providing excellent ride quality and maintaining track manufacturing and settling tolerances at a reasonable level.

On the small-scale prototype, vertical damping was not a high priority. However, for cosmetic reasons it was important to keep these oscillations at a reasonable level. To accomplish this, the bottom of the bogies was made from nickel plated copper. The high conductivity of the copper provides enough eddy current damping to allow cosmetically pleasing operation over magnetic variations in the track and when poked with a finger during demonstrations.

2.5 Propulsion

The large levitation gaps make permanent magnet linear synchronous motor (LSM) propulsion more suitable than a linear induction motor (LIM) which typically requires a very small air gap. In the small-scale prototype, the magnets for the LSM are placed in a Halbach array along the middle of the track, between the levitation magnets. There are many advantages of putting the LSM magnets in the track including reduced cost, higher reliability and arbitrarily small headways. This configuration is expected to be maintained in future full-scale prototypes.

The coils of the LSM are placed along the middle of the bogies (see Figure 7). Those familiar with LSM design will probably recognize that this coil arrangement is not as efficient as it could be. This is due to the fact that expeditious design, simplicity and ease of manufacture were favored over performance and efficiency on the small-scale prototype. Future full-scale prototypes will include a highly optimized coil design.

The LSM coils are connected in a three phase wye configuration and are energized with a commercial PWM amplifier. The commutation signals are provided by three hall-effect sensors that measure the fluctuations of the LSM magnets in the track as it passes beneath the vehicle.

2.6 Energy

The energy required to operate the vehicle is stored on the vehicle using seven Li-polymer batteries. In order to maintain a balanced state of charge between the batteries, a commercially available balancing circuit was also included. The steady state quiescent power draw is about 10 W, most of which is dissipated in idling losses of the significantly oversized commercial amplifiers and in the numerous LEDs on the vehicle which are used in the optical sensors and to communicate the state of the vehicle to the user. The batteries are sufficient to operate the vehicle for about 15 minutes under normal operation.

For future full-scale prototypes, the LSM coils will likely be kept on the vehicle and power will be transferred to the vehicle via an inductive coupling system similar to the one demonstrated by California PATH for roadway powered electric vehicles (Systems Control Technology 1994, 1996). Even when taking into account the cost of the inductive coupling, this configuration is more cost effective than an equivalent system with commutated coils in the track and magnets in the vehicle.

3 OTHER APPLICATIONS

In addition to the mass transportation application focused on in this paper, the SPM technology discussed is well suited to several other applications where a high reliability and low cost network of vehicles are needed, such as freight transport and industrial processes.

The SPM technology discussed throughout this paper is similar to the magnetic suspensions that are being developed on other active projects at LaunchPoint Technologies (see Figures 8 and 9 for two examples).

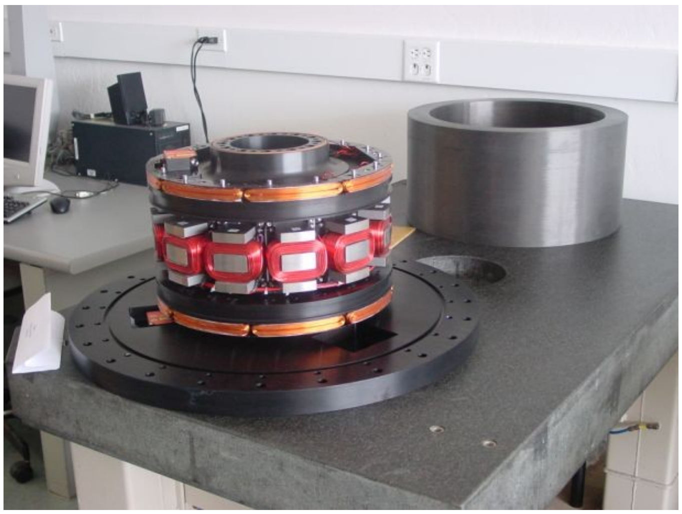

Figure 8. A magnetically suspended high speed flywheel being developed at LaunchPoint Technologies.

Figure 9. One example of the many maglev blood pumps developed at LaunchPoint Technologies.

4 SUMMARY AND CONCLUSIONS

The SPM maglev technology discussed in this paper offers the capability to vastly increase the utilization of infrastructure due to its fast switching, short headways and high reliability. In addition, capital and maintenance costs are lower than the alternative maglev technologies. A small-scale prototype of the system was discussed and expectations for future directions of development were included throughout. A full-scale prototype is in the planning stages and funding is being sought to develop the SPM technology further. More information, including videos of the small-scale prototype going around the track and through the switches, can be found on the LaunchPoint Technologies website: www.launchpnt.com.

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