23-24 Hyperloop Global Propulsion White Paper

Nikita Dolgopolov
Sibley School of MAE
Cornell University
nd287@cornell.edu

Mahika Goel
Sibley School of MAE
Cornell University
@cornell.edu

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1 Abstract

The use of linear induction motor for propulsion system of a Hyperloop pod is essential to the mission of the pod - long-distance travel with virtually zero friction. By virtue of magnetic levitation, any form of drive propulsion is eliminated, as contact with the track is zero, so a linear induction motor must be used in order to provide translational force to accelerate the pod.

2 Introduction

The benefits from the usage of a linear induction motor range from efficiency, better power-to-mass ratio, long distance travel capability, and easy manufacturing/assembly/maintenance. The main components of a linear induction motor are the primary and secondary, the **primary** being the magnetic core + windings that create a variable magnetic field that induces interfacing eddy currents in the **secondary**.

There are two general types of linear induction motors:

- **Single Sided LIM** - a LIM configuration in which a single primary and a single secondary is used.
- **Double Sided LIM** - a LIM configuration in which 2 primaries surround the secondary.

In either configuration, either the primary or secondary is fixed in order to induce translational motion in the other. For the purposes of our application, our primary is an already purchased Linear Induction Motor - iron core with copper windings mounted to the chassis of our pod, and our (fixed) secondary is the aluminium T6-6061 track provided by most student Hyperloop competitions. The geometry of the I-beam track makes a double sided LIM configuration undesirable when considering space constraints imposed by other subsystems on our pod (particularly braking and guidance), so we intend to utilize a single-sided LIM. This year's propulsion system design builds upon the progress that was made last year and involves a range of major improvements.

3 System Design Specifications

3.1 Functionality and Requirements

The dimensions of our system are primarily constrained by the size/weight limitations of our pod, since the LIM will be the most mass-concentrated part on the pod. System constraints include:

- **Full Pod System Mass Constraint:** 236 kg, to prevent track damage and allow for robust levitation
- **Dimensional Constraint:** Must fit in 12" horizontal chassis width, and 10" vertical pod height

The major constraint that played role in the LIM selection process is the power available on the pod. The battery pack design was fixed to provide up to 325VDC at up to 22A in a normal mode of operation - these values dictate the maximum power available to LIM and its drive.

3.2 Equipment

Using the mechanical size and electrical supply constraints of our system, we were able to identify a manufacturer that could provide us a LIM that would meet our desired specifications. We bought an adapted model of LMAC1607C23B60 from H2W Technologies, as shown in the table below.

Mechanical Dimensions		**General Configurations**	
Height	76 mm	Voltage	230 VAC
Width	178 mm	Current	20 A
Length	412 mm	Phase Input	3-Phase
Air-Gap	3.175 mm		

The LIM is mounted inside the chassis at the height of 0.125in from the track via aluminum tube and angle brackets. The mounting is designed for a safety factor of 10+, and the hand calculations were confirmed via FEA Ansys Structural Simulations.

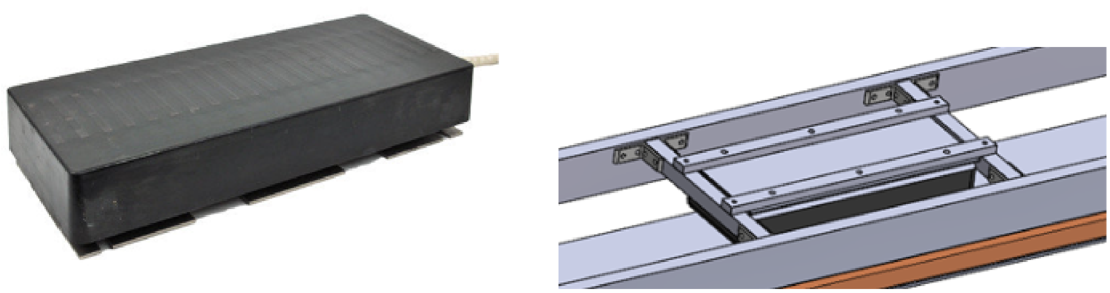

Figure 1: LIM and LIM Mounting

The drive was selected in accordance with the battery pack output values and the LIM input values: 325VDC at 22A to 3-phase 230VAC at 20A and a frequency of up to 120Hz. Such a VFD was found and purchased. There are some concerns with the reliability of this product, so additional testing will be performed to ensure that the device operates as desired. A cheaper VFD was selected due to significant budget constraints and current lack of experience in working with high-voltage electronics: cheaper products allow us to experiment and have minimal losses in the case our design does not work out. This makes it that the main propulsion system components are the battery pack, the VFD, and the linear induction motor as described above.

3.3 Circuitry

The following circuit was designed to integrate the key elements of the propulsion system and to implement protection in case of failure of one or more devices, overcurrent protection, overheating protection, and manual start and stop switches. The VFD is connected to Battery pack via two DC lines through a fuse, Ground Fault Circuit Interruptor (GFCI) and a contactor (C). VFD feeds the LIM via 3-phase AC lines and 3 fuses for overcurrent protection. Both VFD and LIM are grounded to the chassis similar to what is done in the cars. Since the pod's guidance system contacts the track, any current running into the chassis will run into the Earth ground. The contactor C is controlled via an additional contactor and a 12V power supply. The circuit integrates the start, stop, EPO button, LIM's thermal switch and a buzzer to include manual switches and a latching circuit for the thermal switch. The thermal switch would cut off the power to the C contactor and effectively the LIM in the case LIM gets too hot: the temperature inside the LIM reaches 120 degrees Celcius, the switch opens. The latching circuit ensures that, when the LIM cools back down and the switch closes, the power to contactor is not supplied - a manual intervention is required from the team engineer. The exact equipment for the circuit has not yet been selected, besides the battery pack, the VFD, the LIM, and the chassis.

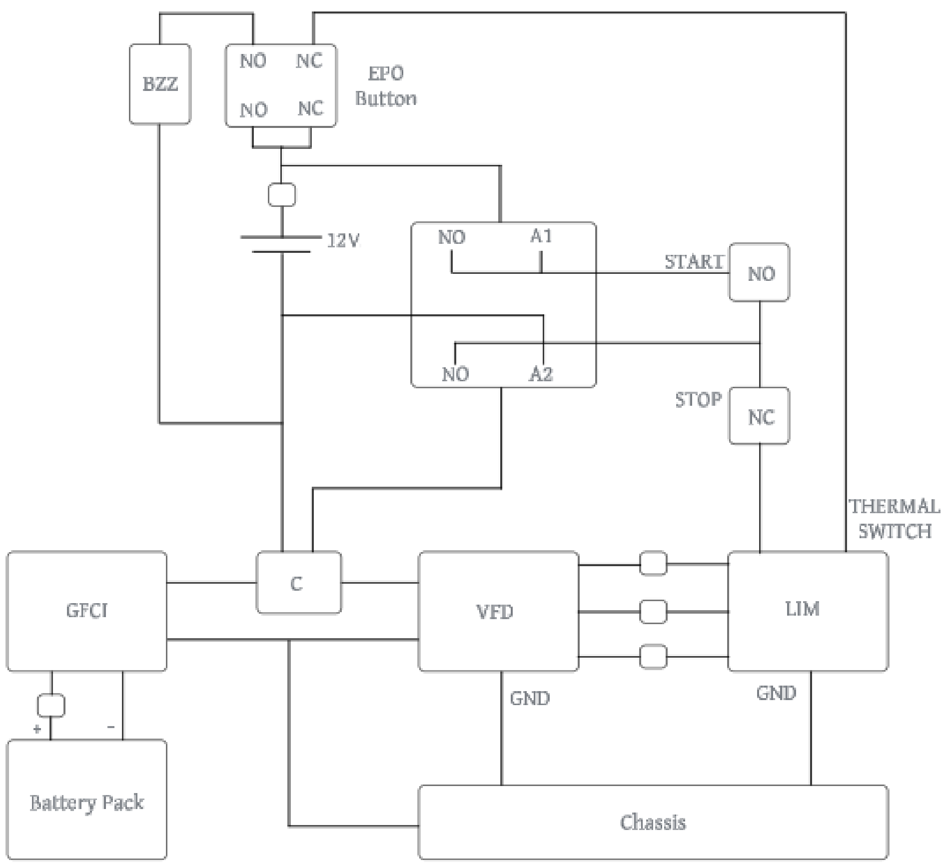

Figure 2: Electric Circuit

3.4 Cooling System Design

The cooling system designed for this year's propulsion system is the liquid cooling system. The system utilizes water as the coolant due to a range of reasons, such as easy and cheap availability, simple storage requirements, and no risk of chemical pollution in the case of a spill. It is designed to prevent the LIM from heating up to 120 degrees Celsius. The cooling system includes 4 pumps, 4 tanks for refill, and 16 heat sinks - 8 to cover the sides of the LIM and 8 to cover the chassis. This forms 4 independent modules of double heat exchangers between the LIM and the chassis. The Heat dissipated in the hollow chassis is carried away by the air coming through the chassis tubes. There are dedicated inlets and outlets at the front and end of the chassis to allow for this natural cooling via ambient air.

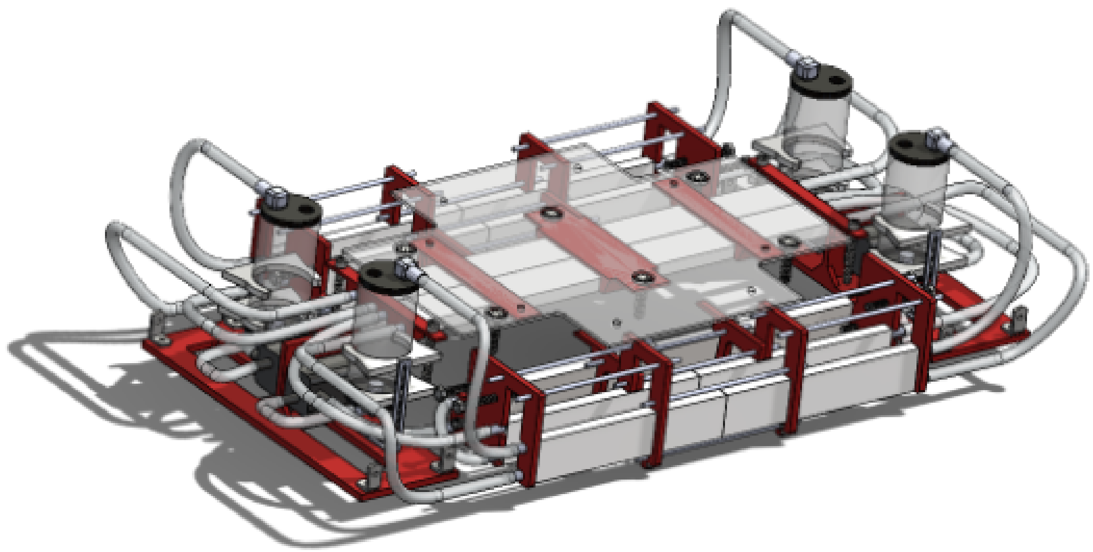

Figure 3: Cooling System Design

3.5 EMI Shielding

Due to a possibility of electromagnetic interference from the LIM, an additional shielding might be required. The ares of particularly strong fields are the top and the front and back faces of the LIM due to end-effects. As a result, it was decided to attach 0.19in thick steel plates on the front and back of the LIM. Though the risk of significant problems due to interference is low and the shielding may not be needed, the cost of this option is under 30 USD, which makes it viable. The front plate will provide additional protection for the LIM in the case it hits the bump in the track - the tolerance of 5mm is very big and placing the LIM farther than 0.125in from the track would diminish its performance by a high factor. The EMI plates are directly attached onto the cooling system and don't take any extra space on the pod.

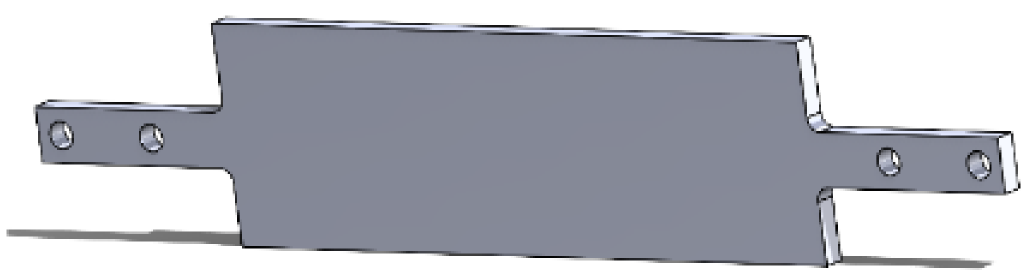

Figure 4: CAD of the EMI Shielding Plate

3.6 Hardware Mounting

The whole system is designed to be modular, so it is possible to assemble the whole unit and place it onto the chassis. There are additional features like support hook, fillets for slide fits, cutouts in the top sheet for handles and sensor placements, and etc. The format of this submission does not allow to list them all. The cooling equipment is attached to the LIM support structure and rests on the chassis - this was designed to utilize 3D printed supports while avoiding the use of big 3D printed pieces which take a lot of material and time to be printed. The electrical equipment will be mounted above the LIM in a location that is water proof. It will be positioned within special electrical enclosures supported by DIN-rails or otherwise. Additional cord grips and wire supporting structures will be implemented. The complete system CAD is in Appendix A.

4 System Readiness Level

While the designs are almost finalized, there is still additional work needed for verification and safety guarantee. The machining of some metal parts of the system has started and additional 6-8 hours of machining are needed. The cooling system prototypes had been made to ensure fitting of all components and sufficiently good performance under higher temperature - affordable pumps used in the design may under perform at higher temperatures. Current work lies in developing and conducting safe LIM testing procedures for characterization. This has likely been the most complex part of the project, as it is important to ensure complete safety of our team members when working with such high voltages as 320V. Consequently, we are currently being consulted by the college safety engineers to ensure that a set of very specific guidelines is created for pod testing and operation.

Next steps also include developing a controller for the linear induction motor. It will utilize at DQ/ABC transform and a PID controller on the voltage - it will be fed into the VFD via a digital input to set the voltage and frequency (which are coupled). Before the controller is tuned, the dynamics of the pod needs to be characterized along with the magnetic circuit of the LIM. The magnetic circuit is depicted in Appendix B.

5 Conclusion

The process of designing the complete propulsion system has been quite challenging due to current inexperience with the process of designing such systems. It had proved to be difficult to find certain electrical components that fit the desired characteristics at the affordable price. Nonetheless, a significant progress has already been made and it is possible to finalize the designs and implement the propulsion system before the competition. The VFD was selected in August 2023, and the rest of the design was completed in the fall at quite high pace; if we are able to keep this pace, the characterization testing of the LIM will be completed in late February and the pod might be ready for a test run on the competition track in March. The battery pack is expected to be assembled in late January, so the battery pack and VFD verification testing will likely be done in late February.

In the next iterations, it would be helpful to investigate more expensive yet powerful cooling solutions as well as industrial inverters from more reliable manufacturers. However, this may not be necessary if the VFD performs as described. There are also aspirations of building our own Linear Induction Motor to suit our specific goals. From the Virtual Showcase event we learned that many other teams use longer slimmer LIMs that operate at higher currents and voltages. In 2-3 years, we might take steps in that direction.

A Appendix A

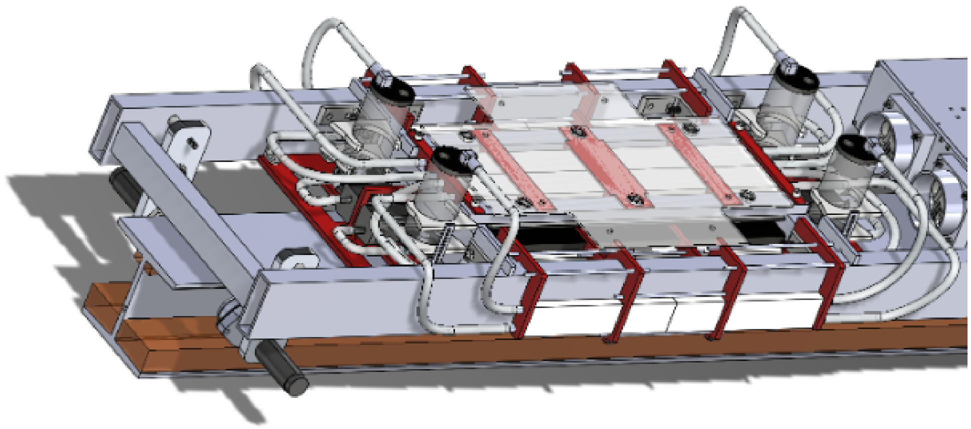

Figure 5: Complete System CAD

B Appendix B

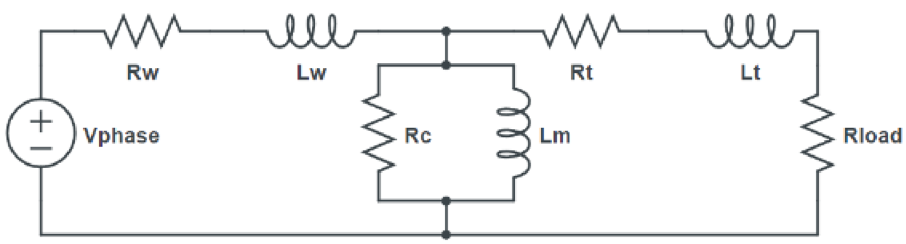

Figure 6: LIM Magnetic Circuit

Rc - resistance of the core, core Lm - magnetizing inductance, Rw and Lw - resistance and reactance of the windings, Rt and Lt - resistance and reactance of the track, Rload - mechanical load. The procedure for determination of their values is not covered in this paper.

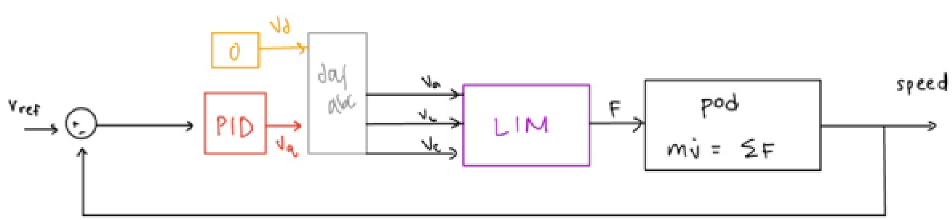

Figure 7: LIM Control Circuit Diagram