GA Urban Maglev – Stable Levitation, Propulsion and Guidance

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ABSTRACT: A full scale test track and vehicle was designed and constructed at General Atomics facility in San Diego, California. The purpose of the facility is to demonstrate stable levitation, propulsion and guidance of the maglev vehicle as it navigates the track. This paper reviews the latest progress in an effort to upgrade the controller systems in preparation for the deployment of a Maglev demonstration system. Also, included is a discussion of the hardware, software and instrumentation elements of the controller and related systems.

1 CONTROL SYSTEM

1.1 General System Description

The Control System must control the voltage vector magnitude and angle imposed on the LSM track through an inverter. It performs the required operational commands using internally programmed or generated algorithms and feedback from the vehicle position sensor and inverter output.

The control system is required to provide stable operation of the vehicle as the magnetic gap changes through the normal operating range, preventing oscillatory instabilities caused by coupling between the horizontal motor thrust force and the vertical levitation forces, and smoothly accelerate the vehicle through the drag peak to cruising speed. Providing stability and smooth acceleration with changing gap provides a controls challenge since the force applied to the vehicle for a given LSM current angle and magnitude varies with magnetic gap.

The control system provides the track motor stator with the appropriate voltage and frequency that propels the vehicle at the desired speed while controlling acceleration and the active lift due to motor current and angle. This requirement is complicated by the fact that the required thrust force is largest at low speed when the vehicle is first levitating. This is called the drag peak and is significantly higher than the normally required thrust force during cruising speed depending on the initial levitation gap.

The overall system can be depicted schematically as shown in Figure 1.

Power is derived from a 3-phase 60-cycle source stepped down from a high voltage 15 kV transformer. The selected tap on the transformer supplies 600 VAC 3-phases to the rectifier, which converts it to ~1600 VDC. The inverter converts this DC power into 3-phase variable voltage, variable frequency (VVVF) by pulse width modulation (PWM) of IGBT based half-bridges housed within a single cabinet. This is transmitted from the inverter to the LSM as three-phase frequency and magnitude controlled voltage/current.

Since the Urban Maglev draws high current at start-up, a voltage option was selected that gives the most current practicable. Ultimately, the vehicle is driven by the LSM, which itself is designed as an air-core/iron core (~50/50) motor. General Atomics specifically built the propulsion system inverter for the test track. It is based on advanced power electronics using insulated gated bi-polar transistor (IGBT) technology.
Control starts at the control computer which serves as a user interface allowing the various run parameters such as speed, acceleration, jerk, direction and distance to be set. The control computer communicates with the controller box via a fiber optic serial port. The controller in turn communicates (again via a fiber optic serial link) to the Power Width-Modulation (PWM) card located inside the inverter cabinet. Enable and ready states are exchanged from the rectifier through the inverter control boards. Sensor cards located along side the PWM card measure current and voltages used as feedback signals in the control algorithm. The use of optical isolator communications between the inverter and the controller box ensure high voltage separation from the operating computers.

The Maglev control system is designed to provide currents that are synchronous with the position of the magnets attached to the vehicle. The phase and amplitude of the currents are adjusted to provide the thrust required while minimizing disturbances in the vertical force created by the motor. The method adopted is a type of AC motor control known as vector control using a position sensor to detect the position of the vehicle. The position information is transmitted to the inverter on the wayside, which then provides the desired thrust, and normal force commanded.

The inverter output is a three phase voltage applied to the linear synchronous motor (LSM) in the guideway. The amplitude, phase, and frequency of the ac voltage are adjusted to produce the desired current. The inverter current is measured and compared to the current commands. The error is used to vary the voltage to obtain the desired current. The position sensor is used to provide a reference position to the inverter to which the voltage and current signals are compared.

The current commands are created by the vehicle control system using the commanded speed, estimates of the drag, and (optionally) predictions of the magnetic gap based on vehicle mass and velocity.

The command inputs to the control are the desired thrust and a value of “Id”, which is used to control the attraction of the LSM to the vehicle magnets. This value is adjusted for the loaded weight of the vehicle.

The thrust control consists of a velocity regulator, which adjusts the thrust to maintain smooth acceleration through the drag peak. To aid the velocity regulator, an estimate of the vehicle drag is made using the speed signal and the estimated drag added to the output of the velocity regulator.

The feedback signals used by the control to establish the motor operating point consist of:

- AC current at the inverter terminals
- A position sensor signal, which is processed to yield position, velocity, and acceleration
- DC link voltage at the inverter
- AC power output of the inverter

The control software to provide the necessary inputs to the vector control, process these feedback signals. Additionally, the feedback signals allow the operation of the system to be monitored and documented during test runs. This information is used to refine the vehicle operation and to document the test results.

1.2 Control System Upgrade

The current hardware and control firmware used in the existing General Atomics test platform is being upgraded to a more modern system before deployment of a demonstration urban Maglev system. While the current control system has served as a good first step in demonstrating the potential of the General Atomics Maglev system, upgrade to more modern hardware and software is important to continue the evolution to a more robust control system.

1.2.1 Control System Background

The current controller hardware and software was an evolution from the development and control of high power inverters using insulated gated bi-polar transistor (IGBT) technology. GA has developed AC motor drive inverters at power levels up to 4475 kW for various applications.

The controller hardware and software for the AC propulsion system used in Unit Rig MT 5500 Lectra Haul mining trucks was adapted to control the GA urban Maglev system.

The control hardware consists of the central control box which contains an Intel 80C196KD processor with analog, digital, and serial inputs (figure 2). The outputs are serial, digital, and analog. This control box is the same as that used on the mining trucks to control the inverter.

![Figure 2: Central Control Box](image-url)

For the Maglev application there are separate hardware units for the inverter PWM control and the
position sensor. There is a user interface provided by which the user can control the operation of the system, change control parameters, create digital scope like debug files, and reload the code. This interface is a copper RS232 cable to a separate PC. The analog inputs are copper. The serial signals are fiber optic isolated for safety.

The advantage of adopting this hardware and software was its availability and the ease of adapting it to control the inverter system. While this approach allowed the system to demonstrate stable levitation, propulsion and guidance in a cost effective and timely manner, an upgrade to a more modern system is necessary to prepare for the deployment of the demonstration system at California University of Pennsylvania.

1.2.2 Simulation
Control system simulations are the key to developing a working control system. Dynamic interaction of the algorithms describing each component identifies instabilities and transient peak values before they are discovered in the hardware where corrections are costly. Control of the Urban Maglev involves the interaction of nonlinear magnetics and dynamic motion of the vehicle. Simulink, a preprocessor of Matlab, was selected to build the model. Simulink lends its self well to the overall approach taken to analyze the interaction between the magnetics and vehicle dynamics. Simulations were run iteratively as the models were developed. In each case, the "scopes" of particular interest were observed in order to follow the effects of modifying the model or changing gains. Once the model produced satisfactory results, cases were run to determine if the control system could maintain stable operation over the range of vehicle masses and velocities.

All runs were limited to the GA test track operational parameters. The test cases for the single chassis unit mass ranged from a low of 7170 kg to a maximum of 11500 kg (a full vehicle has two chassis units). Because of the 120 m track length, the velocity was limited to 10 m/s with a maximum acceleration of 1.6 m/s². The velocity profile was blended at each transition in acceleration in order to limit jerk.

The results of the Simulink modeling provided excellent simulated control of the Urban Maglev test vehicle. This model as compared to other proven General Atomics' Simulink models (which matched the experimental data with a high level of accuracy) is similar in design and the level of sophistication. Therefore, this model is very likely a good predictor of what can be achieved, and would be a good model for a Simulink-based embedded hardware controller.

1.2.3 Next Revision Controller hardware selection.
Due to the capabilities of the platform as well as the level of support available from the manufacturer, we have chosen the National Instruments Compact RIO system for the controller hardware (see figure 3).

Figure 3: National Instruments cRIO

This controller has several key advantages over the existing controller:

- The cRIO is capable of floating point arithmetic in hardware where the current controller is not.
- Modern compilers have built in support for trigonometric functions. Limitation with the current controller requires a lookup table with a course level of accuracy.
- Modern processors are much faster and have more memory.
- The cRIO is 100% compatible with full MathWorks Simulink modeling and simulation. This will allow for the rapid development of control code since a working model of the controller already exists.
- Currently available in-circuit-emulators and debug tools allow for real time communication allowing debugging operations to be more streamlined.

The core functionality of the controller model will be implemented in the cRIO. This will include linking the cRIO with the Simulink model and implementation of the low level functions such as the vector rotations, jerk to velocity calculations, and setup for debug and data acquisition.

1.3 Speed and Location System.
One of the key components of the control system is an accurate and reliable position and speed detection system. An optical position system with a laser sensor and target tape is currently being used for the test track (see figure 4).
While this optical system was not a long term solution, it allowed the test track to become operational within the constraints of cost and schedule. However, it became apparent that this optical system had a number of issues that were causing problems for the control system.

Position Latency and Jitter. Control system components, such as the position data receiver and the Power with Modulation (PWM) inverter card are currently not synchronized with the control system controller (Gold Box). Each of the control components operate at different frequencies. The PWM card operates at 1000 Hz, the position receiver operates at 500 Hz and the controller operates at 200 Hz. Latency jitter results when frequency of the external components are not an integer multiple of the controller frequency loop rate (200 Hz).

Position pulse anomalies. The optical system can have data skips or anomalies due to dirt or water on the optical tape, or data loss due to interference with the wireless data transmission between the vehicle modem and the data receiver.

In order to resolve these issues a new position sensor receiver with hardware that eliminates the variable latency and lack of synchronization needed to be developed.

1.3.1 Helical winding and coil design optimization

Double helical coil manufacturing. The double helical coil was manufactured by winding two conductors simultaneously (two in hand winding) on an aluminum mandrel. Then the coil was stretched on a smaller size rod to an accurate helical pitch and installed on the test track.

The double helical coil is manufactured from two 12 gage solid conductors. Solid conductor was chosen so that the wire would have some memory and spring rate.

Next, two conductor reels were installed on a winding machine tensioning device (see figure 5). This tensioning set-up insures that a uniform coil can be wound.

The winding mandrel size was calculated to be 21.08 mm to result in an inner diameter of 15.875 mm when each conductor is stretched to a coil pitch of 54 mm. In figure 6, the winding mandrel is shown installed on a winding machine where the two in hand coils were wound. The two conductors, one with black insulation and the other with red insulation, were tightly wound with no clearance between turns.

The coils were installed on a 15.875 mm diameter fiberglass rod and stretched to actual LSM pitch positions previously marked on the rod. A gauge is used to check the distribution of the winding between the LSM pitch positions, and wire ties are used to secure each conductor (see figure 7).

Figure 4: Existing Optical Position Detection System

Figure 5: Winding tensioning device

Figure 6: Winding of double conductors

Figure 7: Coil Stretching.
Finally a heat shrink tube is installed over each helical coil wavelength to both protect the conductors and stabilize the winding spacing. The finished cable is shown installed on the test track in figure 8.

When the charged coil is positioned as shown in figure 11, the induced voltage is at or near zero.

Principle of Operation. The helical coil positioning system operates by detecting the voltage induced in a double-helical pick-up line mounted on the track from a charged coil mounted on the vehicle. The charged coil is shown mounted on the Maglev vehicle in figure 9, above the double-helical line mounted on the Guideway Module.

As the charged coil passes over the helical winding, varying voltages are induced in the helical wire as a function of the position of the charged coil. When the charged coil is positioned as shown in figure 10, the induced voltage is at its maximum. In this position the charged coil is aligned with the maximum cross-sectional area of each wire without cancellation from the other.

Each zero crossing represents the fixed pitch of the helical coil, which is 28 mm. To increase the resolution of the position sensor the peaks of the voltage plot are also determined, which increases the resolution to 14 mm. The large peaks at the end are due to helical winding where the 28 mm pitch is no longer maintained (on this short sample).

By counting these voltage pulses, accounting for time and knowing the pitch of the helical winding, one can determine the speed and position of the vehicle anywhere along the test track.

Filtering Noise from Position Data. In order for this approach to work with these small induced voltage pulses in an environment with many noise sources, including the LSM motor, filtering is required.

First, a spectrum analysis of the LSM motor noise was performed to locate low noise frequency candidates. After some investigation a frequency of 24.9 kHz was selected for the position sensor.

Figure 13 is a plot of raw data from the helical coil as the vehicle traveled along the track. The area marked “Vehicle over helix” is the area of a short length of helical winding, the remaining area of the track was not covered by the coil. It is clear that the helical signal is above the background noise, but there is a lot of noise in the raw data. After filtering around the target 24.9 kHz induced signal, the noise is greatly reduced and the signal appears as
figure 12 data. Now the peaks and zero crossings can be used to determine the vehicle position with respect to the helical coil.

![Figure 13: Helical Coil Raw Data](image)

Signal generator assembly for race-track coil. The signal generator assembly is designed to supply a 22 kHz to 26 kHz adjustable sine wave signal to the emitter coil mounted on the vehicle. The signal generator assembly provides the modulation carrier signal that will induce a varying voltage on the helical coil based on its position with respect to the helical windings.

The signal generator assembly receives its power from the 120 volts AC vehicle inverter. This provides the power for a DC supply with +/-15 volts and +/-5 volts DC used for a sine wave generator. The AC is also driving a 28 volts DC supply, which in turn is supplying two 200 volt DC/DC converters for the signal amplifier. One 200 volt DC supply provides positive voltage and the other supplies negative voltage. All supplies have external load resistors mounted to meet minimum load requirements. The power indicator LED mounted above the ON/OFF switch is connected to the AC input.

Shown in figure 14 is a photograph of the signal generator assembly with the enclosure open. This assembly will be mounted on the Maglev test vehicle.

![Figure 14: Helical coil positioning system signal generator assembly](image)

**Position Sensor: Signal Conditioning Board.** The position sensor signal conditioning board takes the noisy AM modulated position signal from the track position sensor helix and converts it to a digital pulse train which is transmitted from the track to the Maglev control system located over 100 meters away in the control room via a fiber-optic cable to eliminate electrical noise pickup.

Since the position sensor generates output by inducing a 25 kHz signal on a pair of helically mounted wires on the track, peaks in the helix will produce large 25 kHz signals at the output and nulls will produce smaller amplitude signals. This amounts to an AM modulation where the message signal corresponds to position of the vehicle on the track and the carrier wave is the induced 25 kHz signal. Also included in the output is strong interference signals induced by high energy sources in the Maglev track and associated nearby wiring.

The current implementation of the controller requires vehicle position to be in the form of digital pulses. Therefore, a signal conditioning board is required to filter out noise in the sensor signal and convert it into a digital pulse train which is usable by the control system. An overall block diagram of the position sensor system is shown in Figure 15.

![Figure 1.3.1-11: The overall position sensor system block diagram](image)

A noisy AM modulated position signal is fed into the signal conditioner board and is then amplified by a pre-amplifier. The amplified signal is then tightly band-pass filtered to remove noise induced by other sources. The filtered amplitude modulated signal is then amplified. The amplified signal is then AM demodulated removing the 25 kHz carrier signal and leaving an amplitude equivalent to the vehicle’s position relative to the helical wires on the track.

While the vehicle is moving, this signal will appear as a sine wave with frequency proportional to vehicle velocity. The demodulated sine wave position signal is then sent through a comparator which produces a digital pulse train with period equivalent to the sine wave position signal. Finally these digital pulses are converted directly into optical pulses by a fiber-optic driver. The optical signal is transmitted through an underground fiber-optic cable directly to the control room approximately 100 yards away.

Before trackside installation of the position sensor signal conditioner, the entire circuit will be tested using bench-top test equipment. Next, the signal conditioning board will be installed full track testing. Figure 16 shows the position signal conditioner board nearing completion.
System integration has included the installation of the wound helix position sensing wire, the development of the vehicle mounted coil and excitation source, the track side signal processing hardware, and the position processing unit in the inverter room.

The new helical coil positioning system is replacing the existing optical laser system. When fully integrated into the General Atomics Urban Maglev test track, it will provide the follow enhancements as outlined in table 1 over the old optical system.

Table 1: Position observer system comparisons.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Optical Position System</th>
<th>Helical Coil Position System</th>
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<tr>
<td>Position observer processing speed</td>
<td>500 Hz</td>
<td>500,000 Hz</td>
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<tr>
<td>Functional vehicle speed limit</td>
<td>9 m/s</td>
<td>No practical limit</td>
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<tr>
<td>Position observer data transmission</td>
<td>Wireless</td>
<td>Direct fiber-optic</td>
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<td>Synchronization with controller</td>
<td>No</td>
<td>Yes</td>
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<td>All weather reliable operation</td>
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<td>Yes</td>
</tr>
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REFERENCES