Development of a Maglev Space Transport System

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Abstract

Access to space is becoming both more in demand and increasingly more expensive. In order to lower the cost of getting to space, maglev space launch assist is considered as one of the options for a space transport system. Maglev as a zero stage is viewed as a safe, reliable, and inexpensive launch assist for sending payloads into orbit. This paper presents an application of maglev technology for a space transport system by developing a Maglev Launch Facility (MLF) for the Super-Loki sounding rocket. It provides technical analysis and trade-off studies to develop an inexpensive, reliable and reusable Maglev launch assist system. The main result is a computer simulation framework to derive an optimal configuration of a MLF that provides necessary initial state vectors for various launch scenarios. This computer simulation was then applied to a Super Loki Rocket launch scenario and specific optimal parameters for launch were obtained. The results can also be extended to design a MLF of a full-scale expendable launch vehicle and a space shuttle replacement vehicle through scalability.

1. Introduction

While major application of Maglev is currently focused on public transportation [1, 2], its application to space launch has been of great interest in space society [3, 4]. The development of advanced propulsion systems for space vehicles is becoming a necessity not only for economic reasons but also for mission requirements beyond those of past space launch systems. Research objectives in advanced propulsion include significantly improving safety, reducing the cost of space transportation, eliminating turn around time to next launch for in-space missions, as well as enabling special new missions. By using a Maglev assisted launch (MAL) system, the launch vehicle would be accelerated up to speeds of 600 mph (965 kph) without depleting any on-board fuel. When the vehicle nears the end of the track, it would take off like an airplane and then switch to more conventional rocket, scramjet, or ramjet engines to continue to orbit. The weight of propellant is a major culprit in the high cost of conventional rocket launches. As a direct result of the fact that Maglev uses off-board electricity for launch assist, the weight of the vehicle at liftoff is much less than that of a typical rocket. This makes access to space less expensive. It is estimated that each launch using a full-scale Maglev track would consume only less than $100 for the cost of electricity in USA [5].

Florida Space Institute has focused on a feasibility study of a Maglev system for a rocket launching system using the Super-Loki sounding rocket. The approach has been empirical and robust demonstrating the potential scalability of the magnetic launch facility to a full-scale expendable launch facility and ultimately a space shuttle launch assist system. The Super Loki was chosen for this research due to its availability, cost and ease of operation. Its research has determined the general specifications of the Maglev Launch Facility (MLF) that in turn is the first major milestone toward the development of a space shuttle replacement aerospace vehicle that is launched by a Maglev track. The Super Loki MLF will be a research test bed to address a feasible design space for the full-scale MLF. In order to investigate the design space, the initial goal was defined as an increase of the Super Loki's apogee by 32% with the use of the Microstar II motor. As the result of this percent increase, the Super Loki can carry heavier payloads than when it uses the Microstar III motor to achieve the same apogee since it can save 34.7% propellant mass.

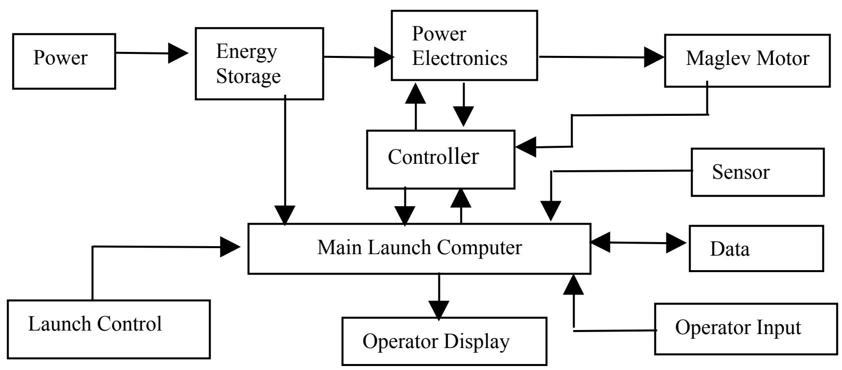


Figure 1. Maglev Assisted Launch System

Figure 1 shows the overall system configuration for the MLF. There are two control elements required to achieve successful operation. One element would govern the launch procedure in itself while the second element controls the overall supporting functions for the launch. As shown in Figure 1 the Main Launch Computer is the central module for the system. At its core a high speed digital processor will assume responsibility for actual launch duties. All other key modules possess their own dedicated diagnostic systems, and to ensure continuity and reliability of operations, the system will be designed as a network of distributed processors capable of uninterrupted operation in case of any single processor failure [6].

2. Super Loki Sounding Rocket

Super Loki sounding rockets have been used for nearly 50 years to make routine observations of the earth's atmosphere. These rockets provide one of the best forms for probing the "middle atmosphere". The Super Loki, otherwise named Microstar system, consist of an inert second stage or Dart, the interstage, and a rocket motor and igniter. The different configurations for the Dart are LX-1, LX-2 and LX-3. There can be three different types of rocket motors used in this system named Microstar I, Microstar II, and Microstar III depending on what your designated altitude is. All of the Darts can be combined with any of the three different Microstar motors. The specifications for Microstar II and Microstar III using LX-3 Dart are listed in Table 1.

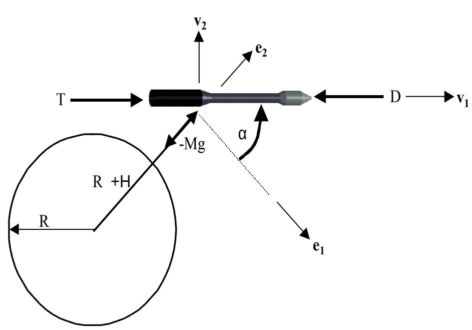
The LX-1 Dart is designated to measure vertical profiles of atmospheric temperature and winds between 80,000 and 240,000 feet altitudes with a transponder instrument (sonde). The LX-3 meteorological payload, under consideration in our research, is designed to measure vertical profiles of atmospheric density and winds between 100,000 and 300,000 feet altitudes using a radar reflective inflatable sphere. The rocket motors consists of a propellant grain, forward closure, motor case, nozzle assembly and igniter. The propellant used is polysulfide and ammonium perchlorate oxidizer. The propellant grain is cast-in-case and bonded to the motor case interior surface. The payload sections are equipped with telemetry transmitters. These transmitters have carrier frequency of 1680 MHz. The telemetry package has four channels for data available. The LX I system is also equipped with a receiver for transponder operations. This receiver accepts a 400/405 carrier at the frequency of 75 MHz. In a traditional Super Loki launch the rocket is launched from a LAU-99A launcher. The LAU-99A launcher is an elevation mount with spiraling rails inside of which the rocket is loaded. The rails impart spin to the rocket, which stabilizes it during flight. This rifling effect ensures that the rocket will not nutate or tumble. If either effect were to occur the mission would most likely fail or not achieve the desired mission altitude [7].

Specifications	**Microstar II/LX-I**	**Microstar III/LX-I**
Apogee Altitude [m]	73150	94500
Propellant Weight [kg]	16.87	25.85
Max Acceleration $[m/s]^2$	1470	1667
Length [m]	1.8	2.4
Diameter [m]	0.1016	0.1143
Inert Weight [kg]	5.26	8.35
Velocity [m/s]	1691.64	1990.30

Table 1. Specifications for Microstar II and Microstar III motors using LX-I

To model the Super Loki the assumption that it would launch into a gravity turn trajectory was made [8]. Most rockets are not capable of flying through the atmosphere at an angle of attack. If they do the aerodynamic loads generated could result in serious damage to the structure of the booster. Therefore, the thrust vector must be aligned with the velocity vector of the vehicle through out the trajectory. The vehicle must be rotated from its original vertical position to a horizontal one. The spin stability of the Super Loki helps to assure the rockets' thrust vector remains aligned with its velocity vector. The gravity turn effect rotates the rocket velocity vector much like a well-thrown football turns along its flight path. There are four equations describing this phenomenon.

The free body diagram of the Super Loki and the gravity turn equations are given by



$$\frac{dX}{dt} = V\cos\theta \tag{1}$$

$$\frac{dH}{dt} = V\sin\theta \tag{2}$$

$$m\frac{dV}{dt} = T - D - \left(mg - \frac{mX^2}{R+H}\right)\sin\theta \tag{3}$$

$$mV\frac{d\theta}{dt} = -\left(mg - \frac{mX^2}{R+H}\right)\cos\theta \tag{4}$$

Figure 2. Free Body Diagram of Super Loki Rocket

In Figure 2, the gravity turn variables are as follows: *m* defines rocket mass, *V* is the velocity, *T* is the thrust, *D* is the drag, g is the gravitational acceleration, *X* is the position, *R* is the radius, *H* is the Altitude and θ is the flight angle. Drag is given by

$$D = 0.5 C_d A \rho V^2 \tag{5}$$

Where _ is the density of air, C_d is the drag coefficient of air, A is the area of the Super Loki, and V is the velocity.

The mass flow rate of the Super Loki is modeled as a ramp function and the thrust is modeled as a step function. Drag effects and air density as a function of scale height are modeled for increased fidelity.

3. Modeling of Maglev Track

The Maglev track under consideration has a linear synchronous motor (LSM) for producing thrust required to launch the Super Loki rocket. The Lagrange's method is used to model the maglev track. Then, the Lagrangian is modified to include other terms to describe more complex effects on the system, which includes more degrees of freedom to capture effects such as the suspension effects. Figure 3 shows a free body diagram of the forces acting on the carriage going down the track.

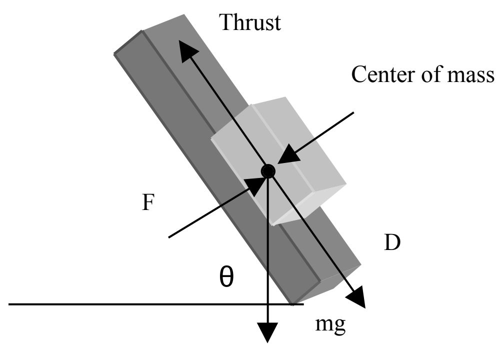


Figure 3. Maglev Track

It is followed that energy equation describing the maglev is given by

$$Tx - Fx - Dx - mg\sin\theta = \frac{1}{2} m x^{2} \tag{6}$$

Where *T* is the thrust (N), *F* is the levitation force (N), *D* is the drag force (N), *m* is the mass (kg), *x* is the length of track (m), and _ is the launch angle (deg).

The magnitude of the drag force in (6) is given by

$$D = \frac{1}{2}\rho C_d A V^2 = \frac{1}{2} S V^2 \tag{7}$$

Where S is the shape factor of the maglev vehicle, which is expressed by the density of the medium _, drag coefficient C_d, area of the Maglev vehicle A multiplied by each other, and V is the velocity of the maglev carriage.

The Lagrange equation (6), with the assumption that the levitation force is small compared to that of the thrust force that we do not include it in the Lagrange equation, becomes

$$L = \frac{1}{2} m x - Tx + \frac{1}{2} S x^{2} x + mg \sin\theta \tag{8}$$

Where m defines the carriage mass, S is a shape factor for computing aerodynamic drag force on the carriage, T is the thrust generated by the LSM motor, and θ is the elevation angle of the track, and x is the position of the carriage on the track.

Using the Lagrangian mechanics defined by

$$\frac{f}{ft}\left(\frac{fL}{fx}\right) - \frac{fL}{fx} = 0 \tag{9}$$

Then the Lagrangian equation for the maglev is derived as

$$m x + S x x + S x^{2} + T - \frac{1}{2} S x^{2} - mg \sin\theta = 0 \tag{10}$$

Rearranging (10) for x, the equation is as follows

$$x = \frac{1}{m + Sx}\left(T - \frac{1}{2} S x^{2} - mg \sin\theta\right) \tag{11}$$

Rewriting (11) in a state model, the maglev track is given by

$$x_1 = x_2 \tag{12}$$

$$x_2 = \frac{1}{m + Sx_1}\left(T - \frac{1}{2} Sx_2^{2} - mg \sin\theta\right) \tag{13}$$

Using (13) and Simulink™, a mathematical model was created for the maglev track to produce the initial velocity the Super Loki Microstar II needed for a 32% increase in apogee altitude. The selected values represent each of the free variable system inputs in the acceleration equation—T, m, and x. The end velocity (system output) of the carriage is also chosen as the most significant quality of the track. In order to have a realistic model of the track, the shape factor (S) is assumed to be 0.0633 [9]. The magnetic drag that is associated with the maglev track is neglected since it is so minimal at the speeds under consideration [10].

4. Design Approach for the MLF

In order to investigate a feasible design space for the Super Loki maglev launch facility (MLF), the design goal in this research was defined as the increase of the Super Loki's apogee by 32% with the Microstar II motor, which is the same altitude that the rocket can reach with the Microstar III motor. Hence, heavier payloads can be carried in comparison to those allowed by the Microstar III motor to achieve the same apogee, which results from savings of 34.7% in propellant mass.

Before creating the design space for the system, it is required to derive the optimal launch elevation angle for the highest apogee while it provides a proper safety range for the launch. Figure 4 shows the apogee altitude and the rocket's safety range with respect to launch elevation angles.

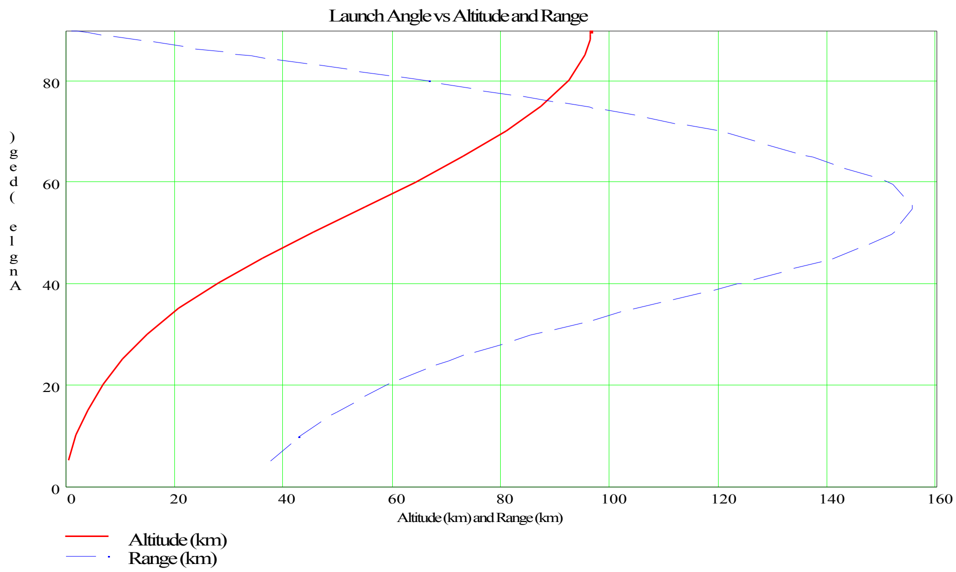


Figure 4. The apogee and the safety range with respect to the elevation angle

The highest apogee will be achieved at 90^0 elevation angle, but the launch angle of 83^0 is chosen to have a safety range of 25 miles, which is required as the minimum safety range for any launch.

Since the maglev track under consideration has an LSM motor for the propulsion, the magnets are placed on the carriage in a certain pattern. To estimate the mass of the carriage, an assumption was made on the carriage length as equal to that of the Super Loki Microstar II rocket (78 in). By having 2 by 2 NdFeB permanent magnets each 1.5 [in] apart down the carriage length and each magnet weighing 0.25 [kg], the estimate weight of the total weight of the magnets are 26 [kg]. The carriage itself will weigh 23 [kg], incorporating the sensor system, safety system, and the essential systems that will be needed on the carriage. The total weight of the carriage will be 49 [kg], and the total weight of the system of the Super Loki Microstar II and the carriage will be 80 [kg].

knowing the launch angle and carriage weight, the desired initial velocity needed to augment by the maglev track can be calculated using the gravity turn equation given by (1) – (4), which is need for the Super Loki rocket with the Microstar II motor to increase its apogee by 32%. The initial velocity calculated is 189 [m/s] that the rocket with Microstar II requires to increase its apogee by 32%. Consequently, this is the target carriage velocity for the maglev track design space of the Super Loki rocket.

Based on the elevation angle and the initial velocity required, different candidate systems have been produced to derive an optimal configuration of the MLF. The candidate systems use different combinations of carriage mass, thrust, and track length to produce the desired velocities. The different candidate systems will create the design space of the MLF. The design space of the MLF is a significant feature that will shape the initial design of the track.

5. Simulation of the MLF Design Space

Since the design goal is defined to increase the Super Loki's apogee by 32%, simulations focus on its major design spaces how an optimal MLF configuration can be derived in various scenarios. Simulations were carried out using Matlab™ to drive an optimal configuration of the MLF. The simulation results used a wide range of different combination of thrust required and track length needed for producing 189 [m/s] at the end of the track. The simulation results in an optimal configuration of a maglev assisted launch among various system configurations.

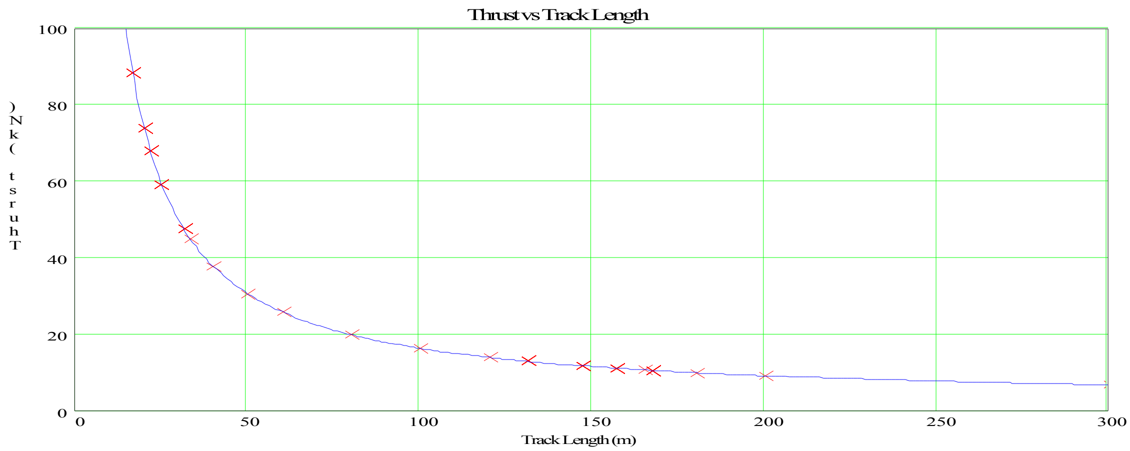


Figure 5. Thrust [kN] Vs. Track Length [m] combinations for required velocity of 189 [m/s]

Figure 5 shows the different combinations of thrust and track length needed to produce 189 [m/s]. The equation of the curve, by using power regression curve fitting method, is

$$1462 \cdot TrackL^{-1.006} + 2.045 = Thrust \tag{14}$$

To have a more detail analysis of the design space of the system, Figure 6 shows the power required for a end velocity of 189 [m/s] for thrust and track length.

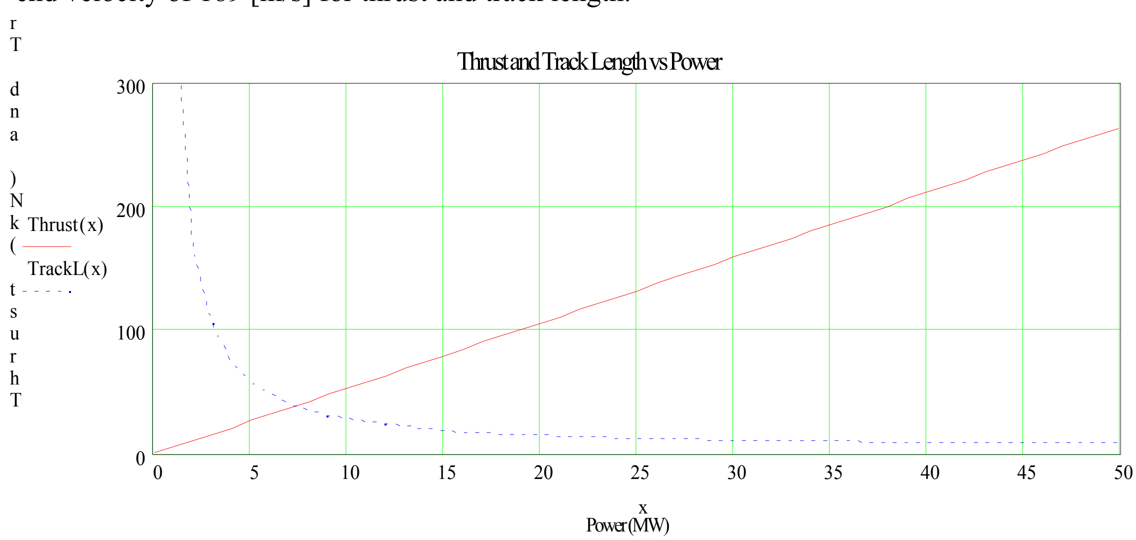


Figure 6. Thrust [kN] and Track Length [m] Vs. Power [MW] required for end velocity of 189 [m/s]

Figure 6 illustrates a trade-off between the required power and the track length to produce the initial velocity of 189 [m/s] for the rocket to achieve the design goal.

The simulations above concern just the altitude augmentation of the Super Loki rocket. In Figures 7 and 8, the graphs show how various payload masses can effect thrust and track length required to achieve the design goal. The simulation results still achieve the 32% increase in the Super Loki altitude, but the payload mass is increased resulting in higher thrust and longer track length needed for the achievement of the 32% increase in altitude.

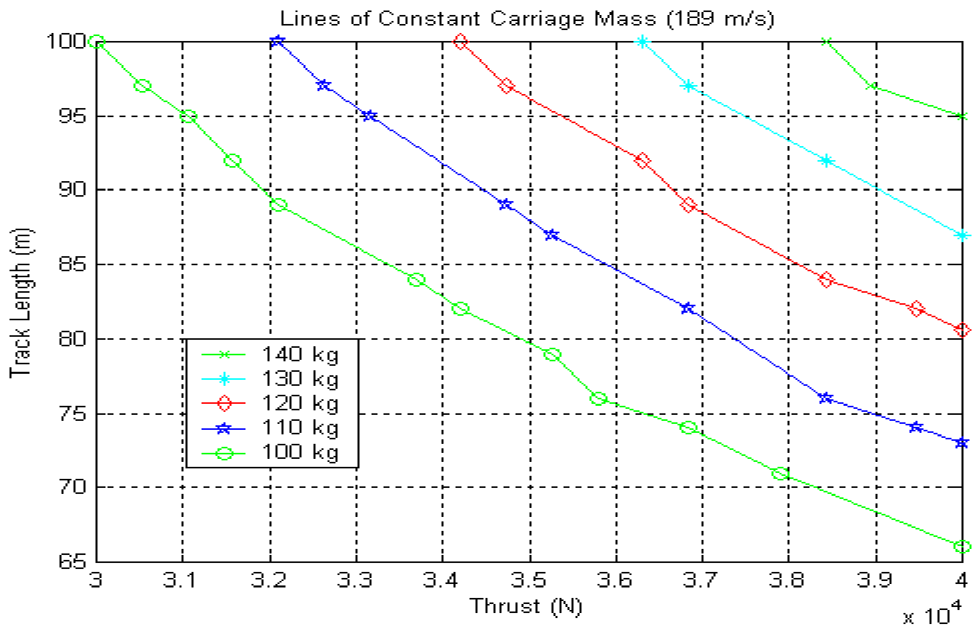


Figure 7. Constant Lines of Increased Payload Mass

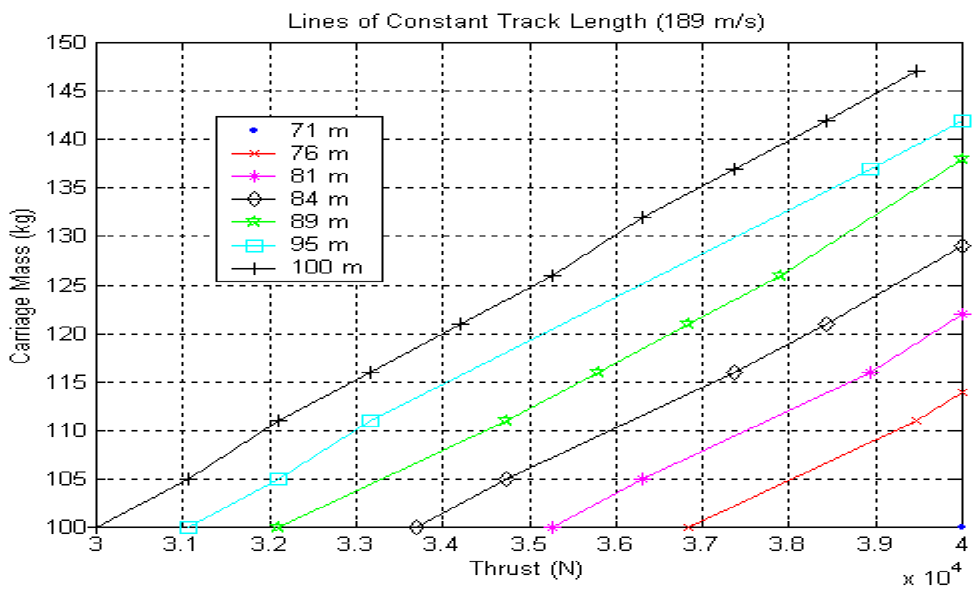


Figure 8. Constant Lines of Increased Payload Mass

Since a MLF of the Super Loki sounding rocket has the capability to provide an initial velocity up to Mach 1, Figure 9 shows the design space of thrust and track length at the maximum velocity. Based on simulation results, the rocket can reach an altitude with a system mass of 80 [kg] of 110 [km] with an initial velocity of Mach 1.

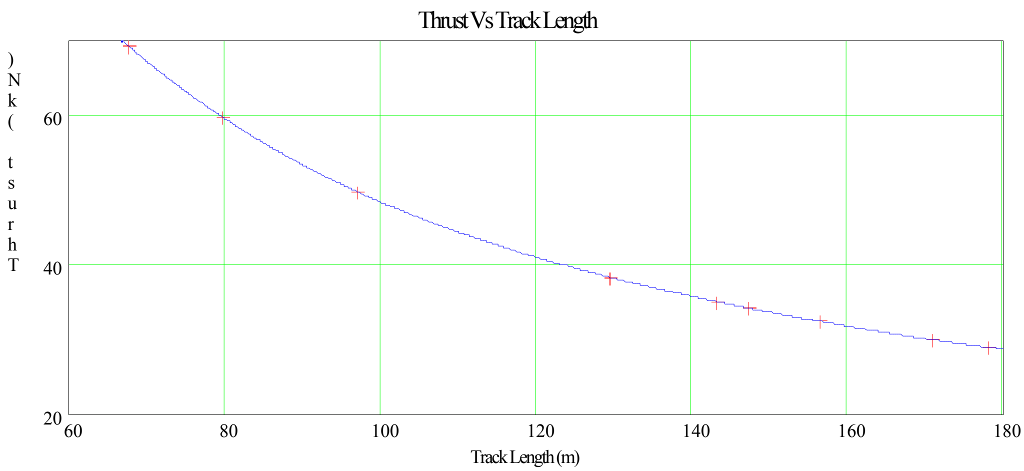


Figure 9. Design Space for an initial velocity of Mach 1

The simulation results in Figures 1 through 9 provide a design space for various MLF configurations to derive an optimal one among many possible combinations of the design parameters.

In the design of a MLF for the Super Loki Sounding Rocket, the optimal configuration is selected based on simulation results shown in Figure 6, which is shown by the intersection point between thrust, track length and power required. This selection indicates that the optimal MLF is defined as follows: 7.3 [MW] total power, 38.6 [kN] thrust and track length of 38.6 [m].

6. Conclusion

The focus of this paper is the research of possible applications of Maglev technology for a space transport system and the development of a Maglev launch facility for the Super Loki sounding rocket. Using the Super Loki as the target vehicle a test bed was devised that can be easily scaled up to a full-scaled space launch vehicle. The initial results in this study show that a Maglev space launch system can improve the overall space transport system resulting in smaller motor requirement, which results in low cost and larger payload capability. The developed simulation framework provides a visual tool to derive an optimal configuration of the MLF from several design trade-offs. Subsequently, an optimal configuration of the Super Loki MLF is derived that provides necessary initial state vectors to achieve the design goal of a 32% increase in its apogee. Future study is needed to consider other potential technical hurdles on how the system can be optimized under real operating environments such as air resistance, and electromagnetic field effects on ignition and electrical system. The dynamic stability of the rocket also needs to be carefully investigated so that the spin-up and separation mechanisms of the carriage can be correctly designed.

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