Maglifter: A Ground-Based Next Generation Reusable Launch Assist for a Low-Cost and Highly Reliable Space Access

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Abstract

Major difficulties in a space missions are the launch cost and the inability of using the launch vehicle consecutive times. A maglev launch system, Maglifter, uses magnetic fields to levitate and accelerate a vehicle along a track at speeds up to 600 [mph]. It is a feasible and revolutionary first stage propulsion system that gives an initial velocity and altitude, reducing dramatically on-board fuel. Furthermore, the Maglifter is inexpensive, costing less than an estimated $100 per full-scale launch, and environmentally clean, using only electrical power from ground sources. It also reduces turn-around time to next launch in quick succession space missions. This paper provides feasibility studies conducted for realization of the Maglifter for a sounding rocket, which can be utilized as a small satellite launch system. It introduces a feasible system configuration of the Maglifter and also develops a computer simulation framework that derives an optimal configuration according to the required thrust, launch mass, track length, and elevation angle of track to provide a desirable initial state vector (velocity, altitude, and angle). Preliminary study results show that the Maglifter is capable to augment a sounding rocket's apogee by 30% or to achieve the same apogee with 53% less propellant for the same weight of the payload. Therefore, the Maglifter can extend various small satellite missions utilizing a sounding rocket.

1. Introduction

With advances in technology, modern society's dependence on artificial satellites has been on an ever-increasing rise. Satellites are used for a variety of uses including telecommunications, weather, global positioning, and military to name a few. This has contributed to unprecedented growth in commerce, provided real time access to news and weather information, and allows tracking and positioning information that is not only used by the military, but by various municipalities, businesses, and even private citizens. With the advances that have already been realized, it is expected that the trend to use artificial satellites will continue to increase in the future. However, these benefits have come at a cost. The cost of placing the satellite used for these applications into space has been ever increasing. Currently the cost of placing a satellite in orbit can easily exceed $11 million [1]. It is therefore desirable to reduce the cost of placing satellites into space, with the eventual goal of placing a manned vehicle into space. Currently a typical Shuttle mission costs more than $400 million per flight [2]. The National Aeronautics and Space Administration (NASA) is currently working on developing technologies with the goal of reducing the cost for space access by a factor of 100, while improving reliability and safety by a factor of 10,000. These technologies are being developed through a program call Advanced Space Transportation Program (ASTP) [2].

A Magnetic levitation and propulsion system (Maglifter) is viewed as a promising technology to provide a safe and reliable system of launch assist. It can also be the key complementary component to Rocket Based Combined Cycle (RBCC) engines, which NASA currently focuses on as the next generation space launcher. The main advantage to launch assist is that the initial velocity of 600 [mph] is obtained using a source of energy external to the space vehicle. As the vehicle approaches this velocity, the main engines are started and the vehicle is released from the track. By using this track for the initial velocity, a savings of over 20% in onboard fuel, resulting in decreased vehicle weight and size, and increased payload [2]. By providing an initial velocity without the use of onboard fuel, a single stage to orbit vehicle becomes a possibility. Also by using a horizontal take-off versus a vertical take-off, further cost advantages can be realized through the reduction of the required thrust to weight ratio [3]. There already exists extensive research information on the Maglifter; 1) design trade studies on all the key system elements of a full-scale Maglifter, 2) preliminary analyses on potential costs and economic impacts, and 3) three proof-of-concept subscale tracks. The technology requirements for the system are significant, but not beyond a reasonable extension of the state-of-the-art.

Florida Space Institute (FSI) has performed cutting edge research on the Maglifter system in order to demonstrate its full feasibility leading to eventual use as an integral part of the next generation space launch system. FSI has established a Maglifter research team jointly with NASA at the Kennedy Space Center (KSC) based on the Space Act Agreement between KSC and FSI. The agreement with NASA provides the framework for cooperation and sharing of resources, facilities, and personnel between the Institute and NASA. Based on the agreement, we are currently performing research with the Foster Miller Maglev track and will acquire the Lawrence Livermore National Lab Maglev track, in the summer of 2003. This unique organizational structure and our location at KSC facilitates close collaboration and integration of expertise, between academia, industry, and government sources to carry out joint research efforts of Maglifter technology. It is based on 1) utilizing the unique test facilities and technical support provided by NASA; 2) the synergetic extension of the FSI and KSC partnership for combining expertise and sharing resources; and 3) enabling technical readiness for supporting NASA's leadership role in development of next generation launch technology. Our goal is to perform critical research required to extend the state-of-art of current Maglifter research from a simple proof-of-concept to demonstration of the full-scale feasibility. This can be demonstrated through a combination of computer simulations and actual experiments using the existing tracks.

FSI also has developed a program for student involvement using sounding rockets to launch payloads into space. This program involves the students developing payloads for the rockets, consisting of instruments that can measure engineering parameters during flight, atmospheric sounding instruments, global positioning system (GPS) payloads for tracking and vehicle acquisition, science payloads to measure natural phenomena, and cameras to record images of earth or other bodies from space. This program uses the Super-Loki sounding rocket as its main vehicle. This is a 2-stage rocket, utilizing the Super-Loki first stage motor as a booster, and a dart as the inert second stage. Once the booster burns out after 2.5 seconds, the dart drag-separates and coasts ballistically to maximum altitude. Upon reaching apogee, payloads can remain attached to the dart or be ejected and float back to earth on a parachute, giving a long measurement time for the payload. The rocket is launched from fixed launchers at SLC-47 at CCAFS, and from mobile launch equipment. The rockets reach altitudes of about 180,000 [ft] with launch velocities of Mach 5. The payloads are small diameter of less than 3 [cm], and can be no more than 1 [kg] in weight.

Currently FSI has focused on a feasibility study of a Maglifter for 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 launch facility. We emphasize bridging the identified gaps and also attempting to identify, as early as possible, items of concern that might have been overlooked. The Super Loki was chosen for this research due to its availability, cost and ease of operation in order to determine the general specifications of the Maglev Launch Facility (MLF). The Super Loki MLF will be a research test bed to address a feasible design space for the full-scale MLF. In this paper, we define a Maglifter system configuration for the Super Loki sounding rocket and also develop a computer simulation framework for the rocket's Maglev Launch Facility (MLF) that provides a tool to define the launch motor, energy storage system, total power requirements, and other properties of the system for various launch scenarios. In order to investigate the design space of MLF, the initial goal is defining how the MLF can increase of the Super Loki's apogee by 30% with the use of the Microstar II motor. We also investigate how much heavier the payloads can be using the Super Loki sounding rocket with the Microstar II motor for reaching the same apogee when the Maglifter is used.

This paper is organized as follows. In section 2 a Maglifter system configuration is introduced. The Super Loki sounding rocket is modeled in section 3. The design of the Super Loki rocket Maglifter system, which provides the optimal system configuration according to the required thrust, total launch mass and track length, will be in section 4. Finally the conclusion of this paper is made in section 5.

2. Maglifter System Configuration

The Maglifter system consists of the space vehicle, the electromagnetic carrier and levitation and propulsion track, and the power supply and storage systems. The general system configuration of the Super Loki rocket MLF is shown in figure 1.

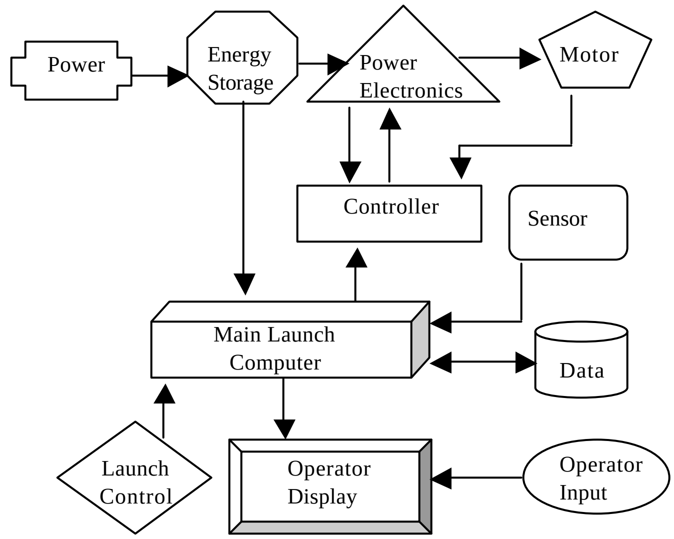


Figure 1. Maglifter System Configuration

The full-scale vehicle will utilize a minimum of major consumable components in order to reduce costs. One method is to use a single stage air-space plane. With the utilization of a horizontal take-off, the thrust to weight ratio required to achieve orbit will be reduced from approximately 1.3 to 0.8. This allows a reduction in the number of engines required. Based on experience from the commercial airline industry, the optimal number of engines will be two. This reduces the total cost of the engines even though the engines are bigger [3]. The use of two engines still allows for flight after an engine failure. The vehicle, like a commercial airliner, will be able to fly on one engine to a safe landing. In addition, the vehicle should also carry the least amount of oxidizer as possible. One method is to utilize supersonic and hypersonic ramjets, which use external oxidant from the ambient air, thus reducing the oxidant that is required on board [4]. Using a winged space plane would reduce the thrust required as the wing generates part of the lift. The wing is sized for landing the unloaded vehicle in order to reduce the aerodynamic drag. The use of the smaller wing however requires a higher take-off speed [3].

The maglev track will require mainly three sections, an acceleration section to bring the fully loaded vehicle up to speed, a separation section that would allow for engine power-up, and a deceleration section to bring the carriage and fully loaded vehicle to a stop. The ability to bring the fully loaded vehicle to a stop is made necessary in the event of an aborted launch. Depending on the final acceleration and deceleration rate, the deceleration section would therefore be at most approximately the same length as the acceleration section [4]. While there is some concern about the launch direction, studies have shown that a launch direction within 45° of the desired direction is acceptable. This means that it is acceptable to launch both polar orbital and due east using the same track [3].

The carriage needs to be capable of supporting itself and the fully loaded vehicle during launch at maximum acceleration and deceleration. It will contain the vehicle support structure and release mechanism as well as all of the drive, lift, stabilization and control systems. It will also need to contain support wheels, capable of supporting its own weight and the fully loaded vehicle. These wheels are utilized when the carriage speed is below the critical speed for levitation. There are several methods under investigation to provide levitation of the cradle. The most promising of these are the concepts developed using the Foster-Miller (FM) and Lawrence Livermore National Laboratory (LLNL) test tracks. The Foster-Miller track uses a Linear Synchronous Motor (LSM) for propulsion and null flux coils acting against a magnetic field for levitation. Currently the carrier for this system utilizes rare earth magnets. In the final design it is anticipated that these will be replaced with super conducting coils in order to achieve greater flux densities [2]. The Lawrence Livermore track on the other hand uses rare earth magnets mounted on the carrier that are arranged in a special arrangement called a Halbach array. This array combines the flux densities on one side and cancels them on the other. It is anticipated that this system will still utilize rare earth magnets in a full size system. Propulsion is achieved by inserting drive coils between the levitation coils. These drive coils act on the magnet arrays and are powered sequentially down the track based on the speed of the carrier [2].

In order to prove the concept of the Maglifter to provide initial launch velocity, the Super Loki rocket will be used as the space vehicle. In this research this will provide us with information concerning the vehicle release mechanism, dynamic stability and controls and aerodynamics.

3. Super Loki Sounding Rocket

Super Loki rocket, otherwise known as the Microstar system, have been used for nearly 50 years, providing routine observations of the earth's atmosphere. These rockets provide one of the best methods for probing the middle atmosphere. The Super Loki rocket consists of two parts – a dart which houses the payload and the rocket motor. Three darts can be used in these rockets, the LX-1, LX-2 and LX –3 dart. Each dart produces its own unique measurements. For example the LX-1 darts are used to measure vertical profiles of atmospheric temperature and winds between 80,000 and 240,000 feet altitudes with a transponder instrument called a sonde. The LX-3 dart 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 Super Loki rocket has three different types of motors named Microstar I, Microstar II and Microstar III motor. Each rocket motor consists of a propellant grain, forward closure, motor case, nozzle assembly and igniter. The propellant used is polysulfide and ammonium perchlorate oxidizer. The motors vary in size and weight depending on the target altitude. All of the darts, mentioned above can be combined with the three Microstar motors. Table 1 shows the two Super Loki configurations discussed in this paper. In a traditional Super Loki launch, the rocket is launched from a LAU-99A launcher. The LAU-99A is an elevation mount with spiraling rails inside of which the rocket is loaded. The rails impart spin to the rocket stabilizing its flight. This spinning

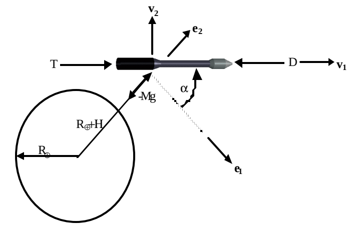
Effect ensures that the rocket will not mutate or tumble. Because of the rocket is spin stabilized, an active guidance system is unnecessary. This greatly simplifies the operation of the rocket and enhances its safety [5].

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-1 dart

In order to study the benefits of launching Super Loki rockets by using a magnetic levitation system, an accurate model of the rocket is essential. The simulation will provide useful information like the initial velocity provided by a maglev system to reach a certain altitude. This information will give useful insight to make decisions on designs. In the effort of this paper a simulation of a Super Loki rocket is conducted by the use of the computer software Matlab™. To model the Super Loki the assumption that it would launch into a gravity turn trajectory was made [6]. 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. This rotation happens naturally and is defined by the gravity-turn trajectory dynamic equations.

The Super Loki free body diagram and the gravity turn equation are given below:



$$\frac{dh}{dt} = V \sin\gamma \quad (1)$$

$$\frac{dx}{dt} = V \cos\gamma \quad (2)$$

$$m\frac{dV}{dt} = F - D - \left(mg - \frac{m\dot{x}^2}{R+h} \right) \sin\gamma \quad (3)$$

$$mV\frac{d\gamma}{dt} = -\left(mg - \frac{m\dot{x}^2}{R+h} \right) \cos\gamma \quad (4)$$

Figure 2. Free body diagram of Super Loki Rocket and Gravity Turn Equations

In Figure 2, the gravity turn variables are as follows: *m* [kg] defines rocket mass, *V* [m/s] is the velocity, *F* [N] is the thrust, *D* [N] is the drag, g $[m/s^2]$ is the gravitational acceleration, *x* [m] is the position, *R* [rad] is the radius, *h* [m] is the altitude and γ [ang] is the flight angle. Drag is given by:

$$D = 0.5\, C_d\, A\, r\, V^2 \quad (5)$$

Where ρ [kg/m^3] is the density of air, C_d is the drag coefficient of air, *A* $[m^2]$ is the area of the Super Loki, and *V* [m/s] is the velocity.

In order to use these equations to simulate the Super Loki rocket, the mass flow was calculated by a series of step functions. These step functions were useful in accounting for the loss of propellant and the separation of the motor and dart at burnout. Also the density as a function of ambient pressure and altitude was feed into the drag equation. The position and altitude where calculated by integrating over the product of the velocity and the fight path angle. Once the variables where calculated they were inputs to the gravity-turn equations. After algebraically manipulating these equations and feeding them to the software, we were able to integrate over them to obtain real time position, velocity and acceleration outputs, also flight path angle. Once an accurate model was designed, the velocities to reach the desired altitudes can be obtained from the output of the simulation. These initial velocities describe the target final velocities, which will need to be produced by the maglev track to meet our altitude goal and have a successful launch. This leads to the design of a maglev track model to provide the best track configuration that would give us this initial velocity necessary to reach the altitude desired.

4. Design of the Super-Loki Rocket Maglifter

4.1 Modeling the Maglifter

The Maglifter under consideration has a linear synchronous motor (LSM) for producing thrust required to launch the Super Loki rocket. To model the Maglifter, the Lagrange's method was used. For a more realistic model, the Lagrangian equation is modified to include other terms to describe more complex effects on the system. The free body diagram of the Maglifter is given in figure 3.

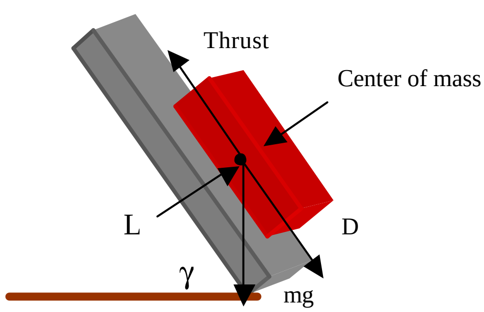


Figure 3. Super Loki Rocket Maglifter

By using energy equations and applying the Lagrangian method, the Super Loki Maglifter model is described by the acceleration equation, shown in equation (6). For equation (6), an assumption was made that the levitation force (L) is small compared to that of the thrust force (F), that we do not include it in the Lagrange equation.

$$\ddot{x} = \frac{1}{m + Sx}\left(F - \frac{1}{2} S \dot{x}^{2} - mg \sin \gamma \right) \qquad (6)$$

The variables for equation (6) are found to be: m is the mass [kg], F is the thrust [N], g is gravity, γ is the launch angle [deg], x is the length of the track [m] and S is defined as the shape factor of the Maglifter vehicle, which is expressed by the density of the medium, drag coefficient and area of the Maglifter vehicle.

Rewriting equation (6) in a state model, the Maglifter is modeled by:

$$\dot{x}_1 = x_2 \qquad (7)$$

$$\dot{x}_2 = \frac{1}{m + Sx_1}\left(F - \frac{1}{2} S x_2^{2} - mg \sin \gamma \right) \qquad (8)$$

Using equation (8) and Simulink™, a mathematical model was created for the Maglifter track to produce the initial velocity the Super Loki Microstar II needed for a 30% increase in apogee altitude. Thrust (*F*), mass (*m*) and track length (*x*) where chosen as the free variable system inputs for the acceleration equation. The end velocity is chosen as the most significant system output of the model. In order to have a realistic model of the track, the shape factor (*S*) is assumed to be 0.0633 [7]. Another assumption is that the magnetic drag that is associated with the Maglifter track is neglected since it is so minimal at the speeds under consideration [8].

4.2 Maglifter Design Based on a Computer Simulation Framework

In order to investigate a feasible design space for the Super Loki Maglifter system, an initial goal was defined to augment the Super Loki's Microstar II/LX-I apogee by 30%. This increase of apogee was chosen because a comparison was made between two different types of motors used by the Super Loki rocket (Microstar II and Microstar III). As shown in table 1, Microstar III motor has a

30% higher apogee altitude then the Microstar II motor, but the Microstar III motor needs 53% more fuel then the Microstar II motor. By using the Maglifter as a zero stage for the Microstar II Super Loki, a 30% increase of apogee can be met (Microstar III apogee) and at the same time 53% less fuel can be saved. Hence, higher altitudes and heavier payloads can be achieved using the Maglifter and launch cost will be decreased because of the reduction in fuel required to reach target altitudes.

Before creating the design space for the system, it is required to find the optimal launch elevation angle, which will produce the highest apogee while providing a proper safety range for the launch, and find the total weight of the Maglifter carriage/Super Loki system at launch. Past research has found that the Super Loki Maglifter system's optimal launch angle will be 83^o, which will provide a safety range of 25 miles. An assumption of 100 [kg] total weight of the Maglifter carriage/Super Loki system is made [8]. Knowing that the Super Loki rocket will launch at 83^0, the initial velocity to increase the Super Loki Microstar III/LX-3 apogee by 30% can be found using the Super Loki model. The target velocity is found to be 189 m/s. The initial velocity of 189 [m/s] will be the target carriage velocity that the Maglifter will need to produce. Based on a launch elevation angle of 83^0 and target velocity of 189 [m/s], different candidate systems have been produced to derive an optimal configuration of the Super Loki Rocket Maglifter system. The candidate system use different combinations of total system weight, thrust, and track length to produce the target velocity of 189 [m/s].

4.3 Simulation

The simulations created throughout this paper generate the design space of the Super Loki Maglifter system. The design space of the system is a significant feature that will shape the initial design of the Maglifter track. The simulations produced focus on finding optimal Super Loki Maglifter system configurations from various scenarios. The simulation results use wide ranges of different combinations of thrust, track length and total mass need to produce 189 [m/s] final velocity. Simulations were carried out using Matlab™.

The simulation results shown below have a constant total weight of 100 [kg].

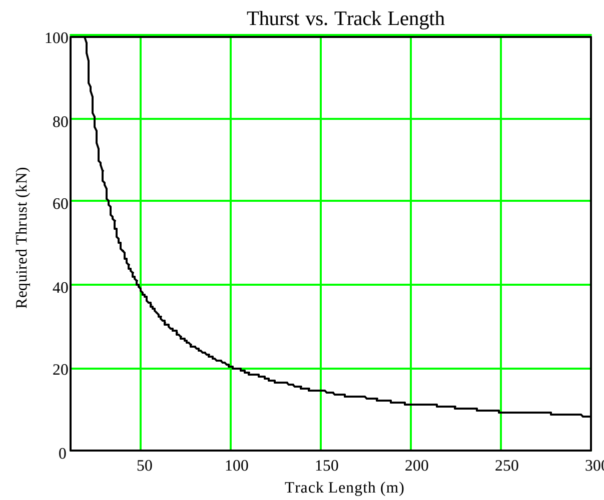


Figure 4. Thrust [kN] vs. Track Length [m] combinations for require velocity of 189 [m]

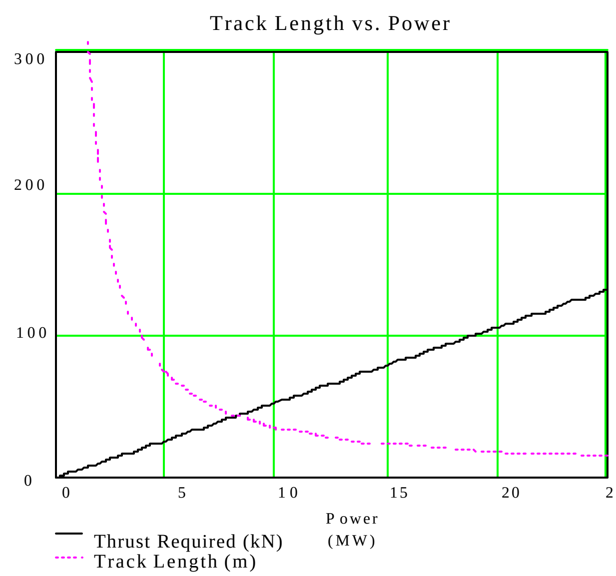


Figure 5. Track Length [m] vs. Power [MW] required for end velocity of 189 [m/s]

Figure 5 illustrates a trade-off between the required power and the different combinations of thrust and track length to produce the end velocity of 189 [m/s]. The trade off is to have a low power system, a large track with a low thrust value will need to be constructed.

The simulations above concern just the altitude augmentation of the Super Loki rocket. In Figure 6, the graph show how various payload masses can effect thrust and track length required to achieve the design goal. The simulation results still achieve the 30% 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 30% increase in altitude.

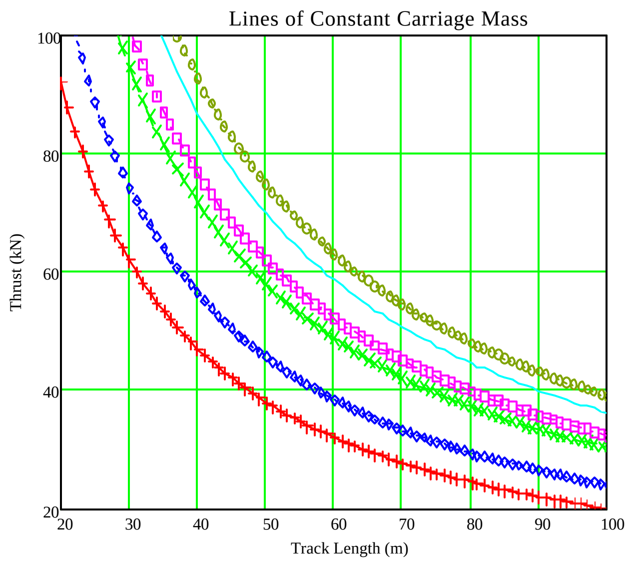


Figure 6. Constant lines of increased payload mass

The simulation results in Figures 4 through 6 provide a design space for various Super Loki Maglifter system configurations to derive an optimal one among many possible combinations of the design parameters.

The next figures show the Maglifter propulsion system [9]. The magnets that are used are NdFe35 permanent magnets. In this system there will be a total of 24 magnets. The total weight of the magnets is 36.715 [kg]. Figure 7 shows a schematic of the magnet array. The total length of the magnets is 1.11125 [m] shown in Figure 8. As seen in table 1, the length of the Super Loki Microstar II is 1.8 [m]. Therefore the total length of the propulsion system fits the Super Loki. By using EM simulation software, a thrust value of 11436 [N] is produced by the propulsion system. By using figure 4 and a thrust value of 11436 [N], a track length of approximately 200 [m] will need to be constructed. This simulation basically shows that a propulsion system for the Super Loki Maglifter system is feasible.

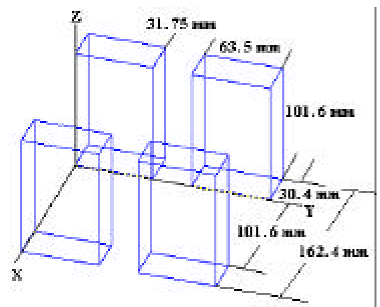


Figure 7. Schematic of magnet array

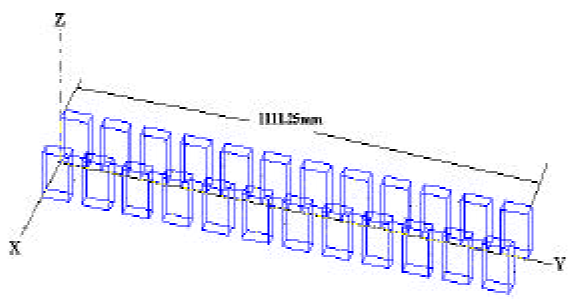


Figure 8. Schematic of the magnets of the Maglifter propulsion system

4.3 Maglifter Proposed

In the design of a Super Loki Maglifter system, the optimal configuration is selected based on simulation results shown in Figure 5, which is shown by the intersection point between thrust, track length and power required. This selection indicates that the optimal Super Loki Maglifter system is defined as follows: 8.2 [MW] total power and track length of 43.35 [m].

5. Conclusion

This paper provides feasibility studies for the realization of the Maglifter for a Super Loki rocket. Each of the Super Loki Maglifter system configurations, such as the levitation and propulsion, has been thoroughly explained. A computer simulation framework was developed to produce an optimal system configuration according to the required thrust, launch mass and track length. The computer framework provides a visual tool to derive an optimal configuration of the Super Loki Maglifter system from several trade-offs. The results in this study show that the Maglifter system can improve the Super Loki rocket's apogee by 30%, resulting in smaller motor requirement, which results in lower costs and larger payload capability because 55% propellant weight can be saved. By using the Super Loki Maglifter system as a test bed, essential research can be done for the realization of a space launch utilizing a Maglifter. Future studies are needed to consider other potential technical hurdles such as air resistance, electromagnetic field effects on ignition and electrical system, dynamic stability of the rocket, and the rocket's carriage design.

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