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# Comrehensive Design of Electro Magnetic Actuator

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**ABSTRACT**

This article presents the design, implementation and validation of the linear tubular actuator considering different physical constraints, an algorithm is developed to get optimal geometric dimensions. A condensed but an extensive design guidelines are presented to improve the speed propelling requirements for objects, with improved efficiency of a multi-stage (sectioned) models. The effect of coil length, coil diameter, power supply on the muzzle velocity is studied for comparison. An interface is developed that allows users to interact with the algorithm through graphical icons and visual indicators.

***Keywords:*** Electromagnetic actuator,plunger, Design, Coil parameters, Velocity, GUI model.

## 1. INTRODUCTION

In early 1980's, extensive research activities have been started and carried out to explore the utilization of electromagnetic technology for high propulsion and moving applications. The desire for linear electrical machines, for controlled motions and electrical power generation has increased steadily in recent years. Chemical and hydraulic systems have mature and reliable operations, but unfortunately they require many technical improvements and maintenance efforts. This increases the cost and reduces the efficiency of the conventional systems, for this reason they cannot satisfy all the requirements in the modern world. The electromagnetic linear actuators are attracting more attention as they are an alternative for chemical and hydraulic propulsion with their performances of high strokes/movements, silent operation and less manufacturing cost. The use of electromagnetic field to produce the force is beneficial to overcome the velocity and hazardous limitations of chemical systems.

These linear electromagnetic machines are used in the aeronautics, medical devices, industry sector for packaging and manufacturing, transportation, defense and military applications, as they provide thrust force directly to a payload without the need of conventional rotary machines. They can offer significant advantages in terms of simplicity, efficiency, positioning accuracy, and dynamic performance in acceleration capability. Various types and configurations of linear motors evaluated in the present day in numerous applications in actuators, energy harvest systems, coil guns since they have a high thrust force density and high efficiency. Several researchers have focused on developing tools to model, design and analyze the linear electric drives, with a majority upon permanent-magnet (PM)-based devices.

The electromagnetic actuator is one of the most important research aspects in today world as it makes a damage free acceleration. The electromagnetic actuator uses the Lorentz forces created by the magnetic field generated by the precise timing of the coil currents, to accelerate any object in the stator housing with a plunger [2]. The principle of an electromagnetic actuator is explained pictorially in fig.1 and fig.2.

The design and analysis of electric machines in general is a very complex approach and requires a simple design and implementation for the designer. There are several design tools available for commercial and research applications but most of them are confined to the design of a particular type of machine.

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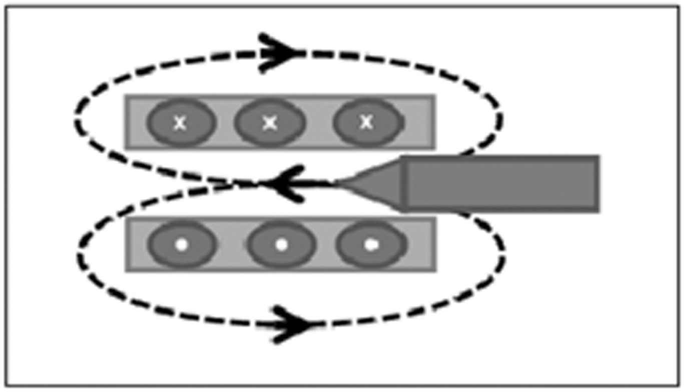

**Figure 1: Current in the coil are been established and the black line indicates the cumulative magnetic field around the coil.**

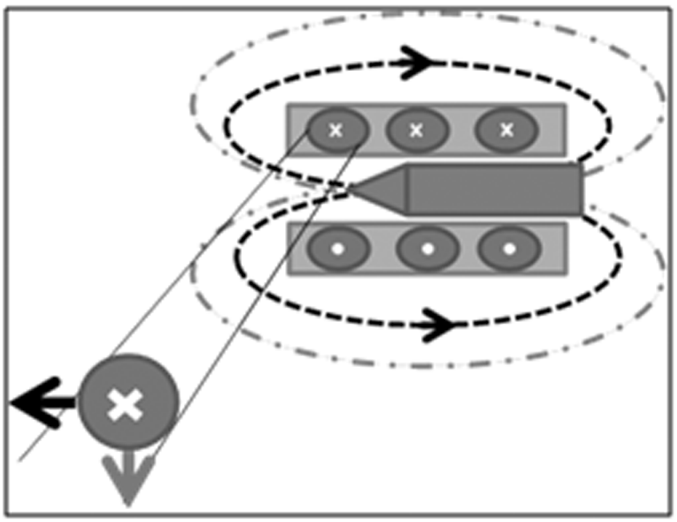

**Figure 2: Object magnetic field shown in blue color dotted lines produces Lorentz force F on charges moving at velocity v in coil.As the coil is fixed, object moves. In the zoomed in part, the black arrow is the Lorentz force acting on the coil and Blue arrow is the magnetic field in the object.**

Ahmasdali khatibzadeh and M.R.Besmi had investigated on how the coil design parameters are affecting the object dimensions using finite element technique in [1]. They concluded that reducing the air gap between the object and the internal frame of the barrel can increase the velocity of the object and best efficiency is achieved with equal lengths of object and coil.

Tao Zhang et al. has built and tested a 4-stage synchronous induction coil gun to accelerate two types of projectiles likely a 0.65 kg sleeve projectile with a speed of 125m/s through a 0.8m actuator and a 1kg sleeve projectile with a velocity of 92m/s using a computer simulation model in finite element analysis software in [2]. G.William Slade presented an illustrative, physically unified model for the study of a solenoidal reluctance linear accelerator in [3].

A three-phase slot less tubular permanent-magnet actuator is selected for accelerating 20g mass in a pick and pack application in [4]. The stator contains coils and the translator is a moving-magnet where the force is calculated using the Lorentz force equation. A method of calculating the force and dynamic characteristics of the linear dc motor (LDM) screen door system was suggested using three-dimensional data of flux density in air gap from finite element analysis for each position in [5]. A novel type of cylindrical, non-overlapping, transverse-flux, and permanent-magnet linear motor(TFPLM) is investigated in [6] used in a free-piston stirling generator system. The TFPLM configuration has a stator laminations overlap in the axial direction with armature winding wound and the mover includes permanent magnets, a core, and a shaft.

The design of air-core tubular linear electric drives was established in [7]. The system considered includes a linear multi pole magnet, a full-bridge rectifier, and an energy storage capacitor. The article includes a comprehensive derivation of inductance, testing of hardware prototype. The expression for inductance calculation was derived from lumping algorithm. The use of the models in automated design was demonstrated on an energy harvester that is intended for use in bovine health monitoring [7].

A tubular permanent magnet linear drive concept was developed for industrial applications up to 3000N thrust force to fulfill safety standards in [8]. The design is made for easy production and assembly of a few hundred units per year. The design concept of this linear drive consists of a stator which is build with discrete coils mounted on poles in radial direction, a permanent magnet armature and an internal position sensor based on the hall-effect. The cogging force is calculated with the change of the magnetic Co-Energies in the air gap. They suggested that the cogging force can be controlled by variation of the magnetic permanence, with constant magnetic reluctance in the air gap and with an optimal arrangement between slots and permanent magnets.

A general framework for the analysis and design of a class of tubular linear permanent magnet machines is described in [9]. The open-circuit and armature reaction magnetic field distributions were established analytically in terms of a magnetic vector potential and cylindrical coordinate formulation, and the results are validated extensively by comparison with finite element analyses. The thrust force, winding emf, self and mutual inductances were predicted with analytical field solutions.

In the past literatures, many designs were assembled and analyzed with permanent magnet stator or mover configurations and vice versa. Few articles discussed on the functionality and application of solenoid actuators but no article highlighted on the detailed designs with the basic constraints of the coil parameters with user interactive procedures to develop the models. To facilitate the design optimization and accurate dynamic modeling of linear actuator, a wide variety of techniques have been employed to predict the magnetic field distribution, the most common approach being used is an equivalent circuit model. This method allows the relationship between critical design parameters and machine performance to be established analytically. The equivalent circuit models suffer from problems associated with model inaccuracy, particularly when flux leakage is significant and the flux paths are complex. With the availability of software tools, analysis of the field distribution and their performance has become common practice.

This paper attempts to provide a unified framework for the analysis and design of electromagnetic actuator which embraces the topologies shown in Fig.3. The analytical solutions allow the prediction of the thrust force, winding inductances and winding parameters. In turn, this facilitates for the characterization of the actuator and provides a basis for comparative studies, design optimization, dynamic modeling and simulations. To obtain a comparison facility of the stator coil design and plunger performances, various coil lengths and input power supply are examined for the required acceleration based on the application. A step by step design approach is developed which includes coil dimensions and performance of actuator. The paper is organized as follows: Section II gives the brief description of Electromagnetic actuator. Section III explains the design topology of the actuator adopted, Section IV covers the view of user interactive algorithm developed, Section V gives the analysis on the design during simulation, Section VI gives a description of Graphical User Interface model of the electromagnetic actuator designed and Section VII demonstrates the discussion of results obtained. The last section provides the concluding remarks.

## 2. ELECTROMAGNETIC ACTUATOR

An Electromagnetic actuator is a device which converts the electrical energy in a system to mechanical energy on a moving body with the help of plunger. The new intelligent electromagnetic actuator includes:

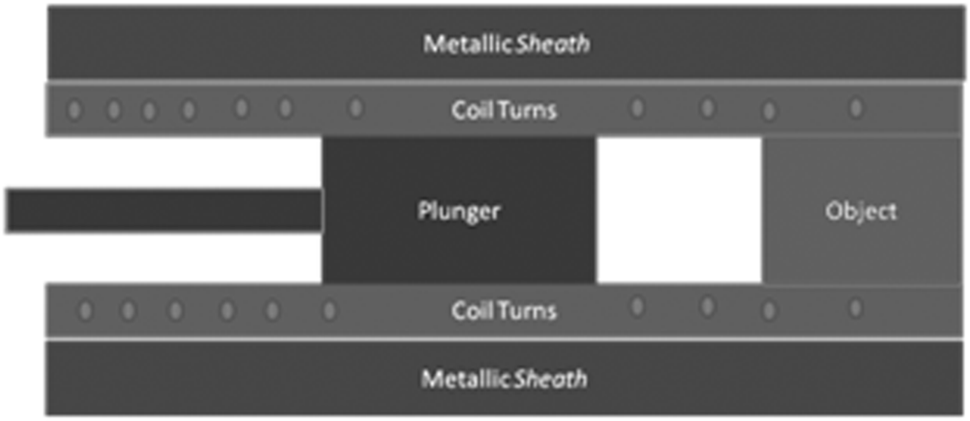


**Figure 3: Basic geometry of electromagnetic actuator**

a primary/stator with main transmission mechanism with several windings mounted on the housing energized by a power supply and a secondary with ferromagnetic plunger to propel/move objects as shown in fig 3. Back irons are attached on primary to reduce flux leakage and magnetic energy loss.

The actuator primary can be provided with Single coil or a number of single coils positioned along the housing which makes the actuator design a Multi stage topology for the required size and propelling range. A single stage actuator consists of a single drive coil energized by a power supply and a plunger to move object inside the housing or a sleeve, where as a multi stage actuator has a series of drive coils connected to a power supply bank and a control unit to switch off the supply every stage relative to the position of the plunger. Multi stage actuators can propel the objects with relatively high velocities, with summation (addition) of velocities gained in each stage. The schematic of a multistage actuator is shown in fig.4. Usage of non ferromagnetic plunger materials with flux densities higher than one Tesla, high voltage in KV range for short time of operation leads to specific hyper velocity application of these actuators. The major factor in designing an electromagnetic actuator is to have a minimum size of the actuator primary/stator to achieve the given velocity on the propelling object, for the given object dimensions. The next section gives the design dimensions of multistage actuator for the designer required velocities.

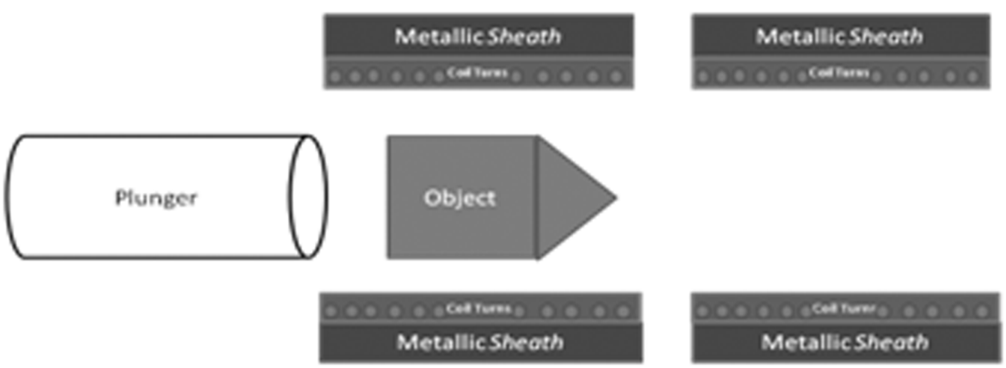


**Figure 4: Geometry of a multi stage actuator**

## 3. DESIGN TOPOLOGY

### 3.1. Stator Coil Dimensions

The major consideration in designing the Electromagnetic actuator is to minimize the size of the stator needed to propel the object within the specified velocity using the available range of the supply bank. It can be summarized that, for achieving a given velocity, the designer should derive the stator coil dimensions with a specified available input supply. In this article, the design is carried out based on the user specified dimensions of the object such as: object weight *($M_p$)*, object length *($l_p$)*, Object diameter *($D_p$)* and also on the required velocity *($V_m$)*.

The inner diameter ($D_i$) of the stator coil is calculated as

$$D_i = f(D_p, g) \tag{1}$$

The air-gap *(g)* between the object and the coil inner diameter shows an impact on the movement of the object. Minimum air-gap length is chosen to avoid the magnetic flux leakages. The outer diameter of the coil *($D_o$)* mainly depends on the number of layers of coil turns *(N)* and also on the diameter *($D_w$)* and area of cross section of the conducting wire *($A_w$)*.

$$D_o = D_i + f(D_w, A_w, layers) \tag{2}$$

$$N = f(constrain, D_w) \tag{3}$$

In the design algorithm used in this article, two parameters are influencing the propelling object speed:

1) Coil length
2) Coil diameter

Three different stator coil lengths are chosen such as length equal to/ twice / half of the propelling object length for a given constraint by the designer. The number of layers in a stator coil is limited for diameter constraint.

### 3.2. Performance Equations

To calculate the accelerating forces, the inductance gradient between the actuator coils, every position of the plunger in the housing needs to be calculated. The electrical parameters of the actuator system are derived from

$$R_{coil} = f(l_w, A_w, \rho_w) \tag{4}$$

$$l_w = f(l_c, d_i, d_o, N) \tag{5}$$

$$[L(x)^-, L(x)^+] = f(l_c, l_p, N, x, \mu_r) \tag{6}$$

The performance of any electromagnetic actuator is predicted from its accelerating force acting on the object and the final velocity with which it is propelled. Hence they are represented as

$$F = f(I, \frac{dL(x)}{dx}) \tag{7}$$

$$a = f(F, M_p) \tag{8}$$

$$v = f(a, t) \tag{9}$$

A design algorithm has been developed by electrical and mechanical motion equations in MATLAB environment.

## 4. INTERACTIVE ALGORITHM

There are various design programs to develop electromechanical devices and analyze their performances. This article presents a new approach for the critical design of tubular actuator with a user interactive algorithm presented in fig 5.

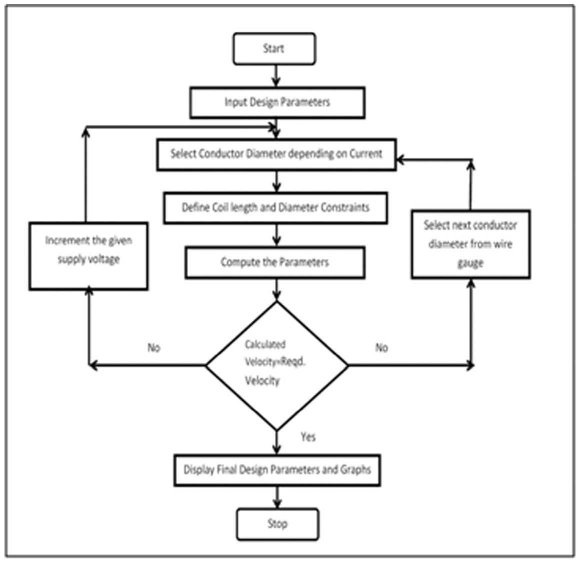


**Figure 5: Flow chart of basic algorithm**

**Table 2**

| | $l_c = l_p$<br>Case B | $l_c < l_p$<br>Case B | $l_c > l_p$<br>Case B |
|---|---|---|---|
| lc | 1.06 | 0.53 | 2.12 |
| do | 0.1196 | 0.1092 | 0.0884 |
| di | 0.078 | 0.078 | 0.078 |
| N | 102 | 51 | 204 |
| stage | 1 | 1 | 2 |
| nol | 4 | 4 | 4 |
| Rcoil | 0.00976 | 0.0042 | 0.0114 |
| Lmin | 0.00221 | 0.00051 | 0.00015 |
| Lmax | 0.010555 | 0.00247 | 0.00072 |
| v | 110.938 | 107.414 | 158.224 |
| Thrust | 861.499 | 807.644 | 445.495 |
| t | 0.9014 | 0.9309 | 1.253 |

**Table 3**

| | $l_c < l_p$<br>Case A | $l_c = l_p$<br>Case A | $l_c > l_p$<br>Case A |
|---|---|---|---|
| lc | 0.53 | 1.06 | 2.12 |
| do | 0.0884 | 0.0988 | 0.0884 |
| di | 0.078 | 0.078 | 0.078 |
| N | 51 | 102 | 204 |
| stage | 2 | 2 | 3 |
| nol | 2 | 2 | 2 |
| Rcoil | 0.00286 | 0.00707 | 0.0114 |
| Lmin | 0.0000377 | 0.000377 | 0.00015 |
| Lmax | 0.00018 | 0.0018 | 0.00072 |
| v | 135.764 | 110.6 | 126.284 |
| Thrust | 352.626 | 293.929 | 161.685 |
| t | 1.408 | 1.543 | 2.08 |

## 5. SIMULATION ANALYSIS

According to the iterative algorithm proposed in section IV, a simulation code is developed to bring out various design dimensions of the tubular actuator with the constraints stated. In this paper, the influence of the coil length and diameter on the design and performance of the actuator are simulated.

From Table II and Table III, we can observe that the influence of the stator coil length and diameter have the desired effect on the coil geometry and its performance. Three models of coil lengths are anticipated with respect to the given designer object length such as $l_c = l_p$, $l_c < l_p$, $l_c > l_p$. Table II displays the simulation results of the propel system with diameter as a constraint. From the analysis, choosing a coil length more than the object length, the number of turns increases raising the coil resistance and inductances, resulting with high propel time.

The methodology is carried out with various current injections to observe the legitimacy on the propel time considering the coil constraints is shown in Table IV. It is observed that with improved input to the drive coil from 30A to 300A, the time of propelling has been forced to reduce by approximately 1.5 sec.

**TABLE 4**
**Case A: Diameter Constraint**
**Case B: Diameter not a Constraint**

| *I* | *Time of Propel for different conditions* | | | | | |
|---|---|---|---|---|---|---|
| | $l_c = l_p$ | | $l_c > l_p$ | | $l_c < l_p$ | |
| | *Case A* | *Case B* | *Case A* | *Case B* | *Case A* | *Case B* |
| 30 | 3.9172 | 2.6122 | 3.1702 | 1.84745 | 5.0958 | 3.0284 |
| 47 | 3.0916 | 2.0276 | 2.5024 | 1.86654 | 4.0197 | 2.3686 |
| 60 | 3.0776 | 1.7467 | 2.2565 | 1.72785 | 3.8023 | 2.4702 |
| 75 | 2.7303 | 1.7874 | 2.3253 | 1.51755 | 3.3729 | 2.1688 |
| 94 | 2.4126 | 1.8755 | 2.0551 | 1.32642 | 3.0604 | 1.8949 |
| 119 | 2.5391 | 1.6192 | 1.7957 | 1.14519 | 2.9805 | 1.6521 |
| 150 | 2.2243 | 1.4003 | 1.6543 | 0.990389 | 2.6103 | 1.9803 |
| 190 | 1.936 | 1.2021 | 1.8510 | 0.866081 | 2.3489 | 1.7 |
| 239 | 1.6932 | 1.0360 | 1.6201 | 0.745813 | 2.3945 | 1.4651 |
| 300 | 1.543 | 0.9014 | 1.408 | 0.9309 | 2.08 | 1.253 |

## 6. GRAPHICAL USER INTERFACE MODEL

A Graphical User Interface (GUI) is a pictorial interface with a program. A GUI is easier to use which provides a familiar environment with controls like pushbuttons, list boxes, object etc; for entering designer input parameter values. In GUI program, it can simulate the equations which describe mechanical as well as electrical transients. The principal elements required to create a GUI are equations, program, components, figures and call backs. With GUI simulation a theoretical knowledge acquired can be implemented, viewed for a real time application and response of physical quantities can be monitored and analyzed. Geometrical dimensions of. Fig 6 shows the GUI model of Electromagnetic actuator design program screen shot. From the algorithm stated in section IV, a simulation code is developed in GUI environment to calculate the design parameters of the stator for the required velocity with coil length and coil diameter as constraints. The designer can enter the input parameters such as: object dimensions, required propel velocity, required propel distance as shown in Fig.6 screen shot. The GUI window is completed by basic designer specified parameters with given constraints using drop boxes and push buttons.

## 7. SUMMARY OF RESULTS

In this article, a design methodology has been proposed and discussed for the complete experimental setup of electromagnetic actuator which can propel the objects with the required velocity. The results obtained are on the basis of two different constraints considered such as coil length and coil diameter. When the coil length is a condition and diameter not a constraint, the number of stages required will be very less to achieve the speed, as the number of turns and turn layer in a single stage can be increased to achieve the desired speed. If the coil length is not a condition and diameter a constraint, the number of stages in an actuator has to be upgraded as the number of turn layers are limited.

The input parameters considered in simulation for propelling an object of mass 7.0 Kg are presented in input parameters block of GUI model in fig 6. The final design values along with the given designer requirements considering various constraints mentioned above are displayed in GUI based electromagnetic tubular coil actuator design program screen shot in fig 6. The time taken for propelling the object with numerous input currents for constraints mentioned in the GUI window can be observed in fig 6. The propel time is almost reduced by 1.5 sec to 2 sec when the coil (outer) diameter has no limitations.

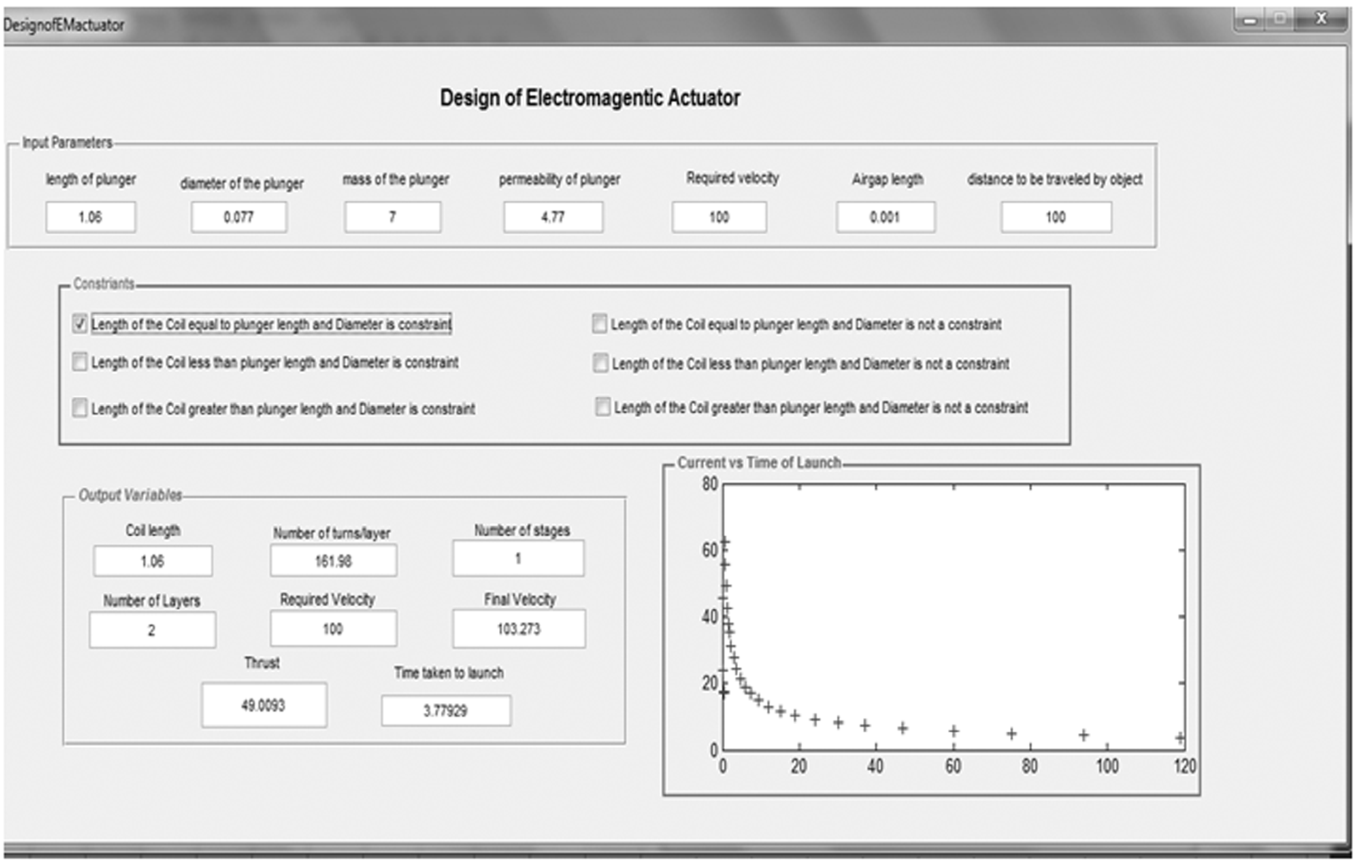


**Figure 6: GUI based electromagnetic coil actuator design program screen shot**

## 8. CONCLUSIONS

The present scenario shows that the EML research is towards the acceleration systems and in attainment of maximum velocity. The design and analysis of electrical machines in general is a very complex approach and requires a design and implementation. At present, each type of actuator is designed primarily by the required velocity, for which this actuator is most effective and reliable. There are several design tools available for commercial and research applications but most of them are confined to the design of a particular type of machine. In this paper, the design and analysis of the electromagnetic actuator is proposed and discussed. An algorithm has been developed and a Graphical User Interface (GUI) was built with program to get the geometrical dimensions of the actuator. It is a user friendly technique for the designer to enter the input values in the GUI window and can get the output parameters and the actuator performance curves in the same window after the execution. The effect of change in input to the actuator on the velocity and propelling time is analyzed. It is observed that with the change in supply voltage to the stator coil, the muzzle velocity of the object is improved and propel time for a given weight of the object is minimized. In view of the compatibility of the space to place the barrel, required velocity and switching conditions, the electromagnetic actuator designs can be extended to multi stage operations to achieve the hyper velocities with reliable and efficient operations. This methodology can further be extended to achieve an optimal design of the electromagnetic actuator.

## REFERENCES

[1] Ahmadali Khatibzadeh, M.R. Besmi , "Improve Dimension of Object For Increasing Efficiency of Electromagnetic Motor," 4th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2013), Feb 13-14, 2013, Tehran, Iran. 78-1-4673-4484-5/13 ©20I3 IEEE

[2] G. William Slade, "A Simple Unified Physical Model for a Reluctance Accelerator," IEEE Transactions On Magnetics, Vol. 41, No. 11, November 2005.

[3] Ali Mosallanejad, Abbas Shoulaie, "Calculation of Coil Inductance in Tubular Linear Reluctance Motor using Three Dimensional FEM", PRZEGLĄD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R. 87 NR 11/2011.

[4] Koen J. Meessen, Johannes J. H. Paulides, Elena A. Lomonova, "Modeling and Experimental Verification of a Tubular Actuator for 20g acceleration in a pick and pack application", IEEE Transactions On Industry Applications, Vol. 46, No. 5, September/October 2010.

[5] Sung-Hong Won, Joon-Seon Ahn and Ju Lee, "Dynamic Characteristics analysis of linear dc motor for the electric screen door," JOURNAL OF APPLIED PHYSICS 99, 08R311 ,2006.

[6] ZHENG Jigui1, HUANG Yuping, WU Hongxing, ZHENG Ping, "Design of a transverse flux permanant magnet linear generator and controller for use with a free piston stirling engine", CHINESE JOURNAL OF MECHANICAL ENGINEERING, April 16.

[7] Ross A.Howard *et al.*, "Modeling and design of air-core tubular linear electric drives", IEEE Transactions On Energy Conversion, Vol. 28, No. 4, December 2013.

[8] Sebastian Gruber *et al.*, "Optimization of a high force tubular linear drive concept with discrete wound coils to fulfill safety standards in inductrial applications." IEEE Transactions, 2009.

[9] Jiabin Wang, Geraint W. Jewell and David Howe ," A general framework for the analysis and design of tubular permanant magnet machines, " IEEE Transactions On Magnetics, Vol. 35, No. 3, May 1999.

[10] F.W. Grover, Inductance calculation working formulas and tables.New York, NY, USA.