From the depths of our hearts

To our families,

who have quietly cheered us on with such strength and courage, that they enabling us to stretch boundaries, embrace the new and face challenges with verve.

Dear amazing team at JOiiNT LAB,

We cannot thank you enough for your guidance generosity an endless willingness to give of your time and knowledge to us.

Your support made this journey not only possible, but truly meaningful.

Contents

Abstract

This thesis describes the study, design, and control of a novel linear magnetic-actuated conveyor system for assembly lines, developed at JOiiNT LAB in collaboration with industrial partners operating in the field of automated production systems. The project proposes an intelligent, modular transport solution based on linear electric machines (LEMs), particularly linear synchronous motors (LSMs), aiming to overcome limitations of traditional belt conveyors—namely, mechanical complexity, limited configurability, and poor adaptability to dynamic production needs.

In the context of Industry 4.0, manufacturing systems must increasingly meet demands for high flexibility, modularity, and smart connectivity. Traditional conveyor solutions are often rigid, subject to wear, and difficult to reconfigure in real time. These constraints hinder individual workpiece tracking, efficient energy use, and scalability—key capabilities for modern high-mix, low-volume production environments. To remain competitive, companies in this sector are rethinking conveyor architectures to deliver transport systems that are accurate, programmable, modular, and easy to maintain.

Electromagnetic actuation enables smooth and precise motion, essential for applications involving variable speed, adjustable pitch, and accurate position control—core requirements in many modern assembly lines.

The research begins with an overview of electromagnetic principles and a state-of-the-art review of LEM technologies. Analytical models were developed to estimate magnetic forces based on key design parameters, guiding the selection of components such as solenoids, permanent magnets, air gaps, and low-friction guidance systems. The mechanical structure was modeled using Creo Parametric CAD tools for modularity and manufacturing feasibility, while the prototype was produced using fused deposition modeling (FDM).

Experimental validation focused on mechanical stability, motion precision, and integration with the control system. Results demonstrated the functional viability of the

concept, though some limitations were observed, particularly related to friction, solenoid control, and material properties inherent to rapid prototyping.

In conclusion, this thesis offers practical insights into the development of smart linear actuation systems for next-generation industrial transport. By integrating magnetic propulsion, modular mechanical design, and embedded control, the work contributes to the evolution of flexible, efficient conveyor platforms tailored to the demands of advanced manufacturing. As a case study, the collaboration with Cosberg SpA served to contextualize and validate the approach within a real-world industrial framework.

1 Introduction

1.1 Challenges and trends of conveyor systems for automatic assembly lines

Industrial automation has advanced increasingly over the last decades due to the demand for more efficiency, precision, and flexibility in manufacturing processes. One inherent component of automated systems is the transport and actuation mechanism; traditionally, these components relied on existing solutions such as belt conveyors, cam mechanisms, and pneumatic actuators. Despite their unidirectional nature, these systems have proven useful and successful when applied because they all have several limitations. These include mechanical wear, restrictions on speed and acceleration caused by inertia, energy inefficiency resulting from the complexity of mechanical transmissions, and high maintenance necessity, to mention just a few. They are also said to be quite redid because most being mostly configured do not allow "free" integration into increasingly flexible and reconfigurable production systems.

Their shortcomings would be addressed by the increasing consideration of Linear Electric Motors (LEMs) otherwise known as Linear Magnetic Actuators (LMAs). As opposed to a rotary actuator associated with a mechanical coupling, direct drive motion was made possible with an LEM since no media was utilized for connections. The power and ability of speed, high position control and exertion of forces in terms of maintenance and frictionless zipping are all attractive for applications demanding fast accurate transports such as in automated assembly, semiconductor fabrication, and intelligent logistics.

This thesis examines the implementation of LEM-based systems as a replacement for conventional conveyor-used transport mechanisms within the industrial production references. The approach is to utilize the advantages of linear actuation to enhance the performance, flexibility, and sustainability of automated manufacturing systems. This study is conducted in collaboration with JOiiNT LAB and Cosberg, focusing on the integration of Linear Magnetic Actuator into the automation industry. Specifically, it explores the application of its technology in Cosberg's production systems (Figure 1.1,

Figure 1.2), replacing traditional belt conveyors with electric linear actuation systems to enhance productivity and operational efficiency.

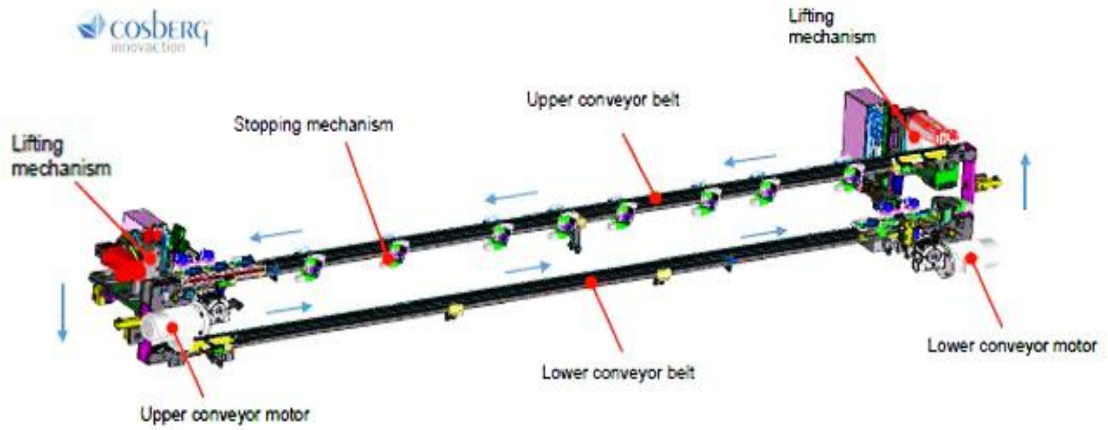


Figure 1.1: Front view of Cosberg's assembly machine highlighting the main components. The figure represents the general architecture of an automated assembly system of Cosberg, including the main conveyor, workstations, and overall mechanical subsystems to be replaced by Linear Magnetic Actuators (LMAs), which would add precision, efficiency, and flexibility in transporting parts around and manipulating their handling.

As you can see in Figure 1.2, for example, the three highlighted stations represent key points along the conveyor path where precise positioning and controlled stop and release operations are required. These critical areas demonstrate the limitations of the current conveyor system in achieving reliable and flexible motion control, creating the need for a new solution for linear magnetic conveyors.

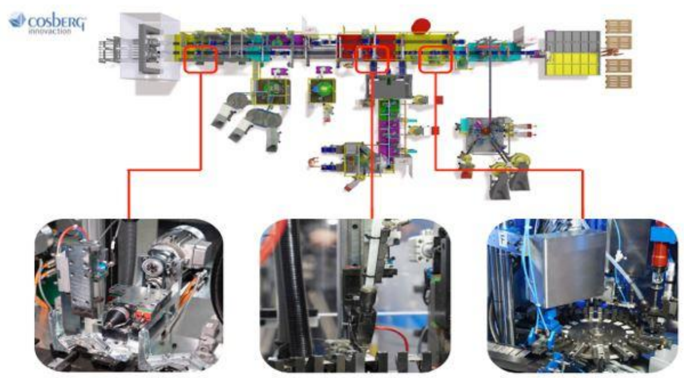


Figure 1.2: Top view of Cosberg's assembly machine

1.2 Cosberg's linear magnetic conveyor requirements

Current conveyor system implementations by Cosberg, which mainly support automated assembly lines, employ purely traditional mechanical actuation technologies like belt conveyors and chain-driven mechanisms. The systems have been accepted by the industries due to their simplicity and cost-effectiveness; however, they would not be ideal for modern flexible manufacturing scenarios in many aspects. For example, complex mechanical systems are required to generate curved trajectories or feed into multiple workstations on belt conveyors, which involves space consumption and mechanical wear.

In addition, conventional conveyor systems have indecisive precision in positioning over their large and bulky mechanical transmission elements difficult to be reconfigured without the long periods of downtime and manual intervention. All of these factors make such a conveyor system unsuitable when it comes to an Industry 4.0 context. With industrial production always calling for constant adaptability and then going into increased traceability and positional accuracy, then limitations are there to make it inefficient and call for better maintenance overhead. It is within this thinking that Cosberg has decided to put forth solutions for replacing or supplementing traditional conveyor systems with entirely new actuation technology solutions based on linear magnetic technology enablement.

Such systems promise modularity, less mechanical complexity, contactless propulsion, and carrier-level control, which are of great value in flexible assembly lines. The next sections delve into the technical requirements set for the development of the next-generation linear magnetic conveyor at Cosberg, with the aim of allowing accurate, scalable, and smart transport platforms for automated production.

Cosberg clearly outlined the project requirements with a well-structured cadence that ensures efficiency and reliability. The requirements of the system must have a stop-and-release time of less than 0.2 seconds so that response delays are decreased and performance is enhanced. To perform best under changing conditions, it should maintain a linear speed of 1 m/s. Besides, the system will also require these properties to support a vertical load of 500 N, which will guarantee structural integrity against the acting load and forces during operation. Also having a metal chip management system implies that one can greatly avoid work stoppages and destruction to the machine.

Figure 1.3 shows the current conveyor layout implemented in Cosberg's assembly lines. This representation illustrates the conventional conveyor belt configuration and the associated spatial and mechanical constraints that motivate the shift toward more advanced transport technologies.

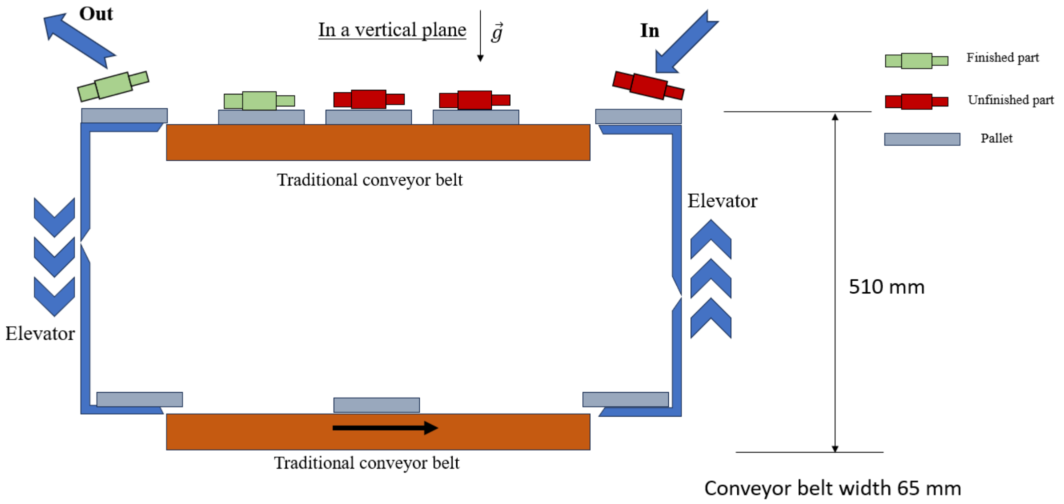


Figure 1.3: Layout of Cosberg's current conveyor system based on traditional belt conveyors. The system relies on mechanical motion transmission and fixed paths, which limits flexibility, positioning precision, and reconfigurability in advanced manufacturing environments.

1.3 Importance and Applications of LEMs

1.3.1 Benefits of LEMs in Industrial Automation

Linear induction motor works upon basic electromagnetic theory that states that magnetic force produces motion [1]. Linear Electric motors (LEMs) are advantageous over traditional actuation systems and can be suitably used for industrial automation applications. One of their advantages is high dynamic performance. The direct electromagnetic drive prevents mechanical backlash, providing a very fast-acting, highly precise motion control system [2]. Further, LEMs present improved flexibility as programmable motions allow adaptable and reconfigurable production processes [3]. Its wear-free operation gives an extended lifetime and lower maintenance requirement, ensuring a much higher reliability and lower operational cost [4]. In addition, LEMs will have a higher energy efficiency because they entail lower energy losses compared to a classical mechanical actuator, maximally optimizing energy consumption for the industrial application [4].

1.3.2 Industrial Applications

The frontiers of application for LEMs are broad in the manufacturing industry owing to their precision, speed, and reliability. These features make them suitable for precision assembly applications, whereby they enable high speed and accurate placing of components on automated production lines [2]. They allow ultra-precise motion control in semiconductor fabrication, which is crucial for microchip production [3]. Their use in the medical device sector extends to controlled and high-precision actuation, which is essential for operation in sterile environments where accuracy becomes the prime concern [4]. In the automobile industry, they are used to automate motion systems, thereby simplifying the assembly process of vehicle components [3]. Automated high-speed sorting and automated material handling systems also utilize them in warehousing and logistics to enhance efficiency [2]. More broadly, this makes LEMs a pivotal technology in industrial automation across several domains.

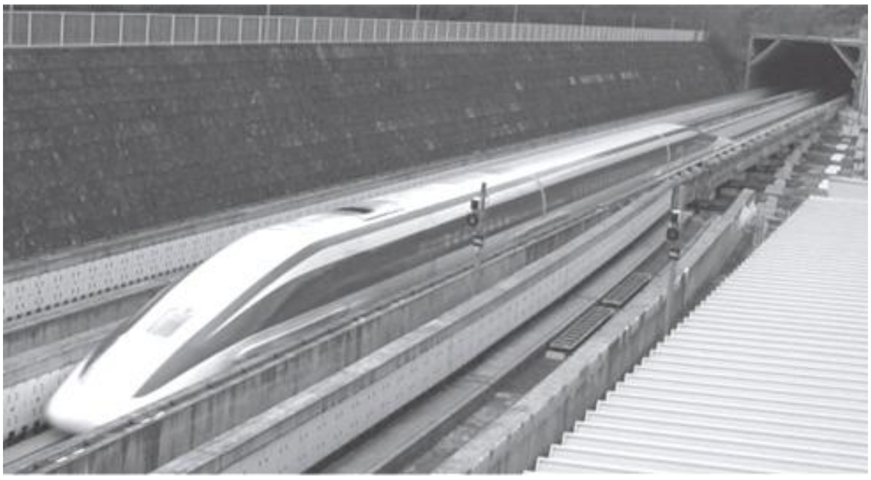


Figure 1.4: On board of vehicle JR-MAGLEV, Japan [4]

1.3.3 Implementation Challenges

Although linear magnetic actuators have numerous advantages, using them for industrial automation comes with problems. Among these problems is electromagnetic interference (EMI), as high-speed electromagnetic actuators can disturb adjacent machines. Excessive heating can cause a reduction in reliability and performance. Motion control needs advanced algorithms for smooth and stable operation. High initial costs for the technology and infrastructure may also cap their use. Finally, reliability and safety must be ensured by introducing fail-safe mechanisms to maintain consistent and secure operation. Addressing these issues will allow linear magnetic actuators to be used successfully in automation. It is important to highlight that, despite the technical advantages of linear electric machines, one of the major challenges remains their high initial costs.

1.4 Objective of thesis

The main goal of this thesis is to research, develop, and validate the application of a linear magnetic actuated conveyor into Cosberg's production systems from the perspective of industrial automation. This study aims to improve the characteristics of motion control mechanisms concerning efficiency, precision, speed, and reliability through the use of new advanced technology electromagnetic solutions in place of traditional actuation methods.

On this basis, the entire thesis is arranged around several key aspects. The first involves the development of a comprehensive mathematical model to describe the force generation and dynamic behavior of linear magnetic actuators, since this model would be the foundation for understanding the performance characteristics of the system under various operational conditions. Later on, the electromagnetic structure will undergo simulations and optimizations for efficiency and force output improvement, allowing the machine to meet the demanding requirements of industrial automation.

Implementing the system and experimental validation are other important purposes for this study. It plans to create, manufacture, and test a linear magnetic actuator prototype at the JOiiNT LAB, which will allow a comprehensive analysis of theoretical predictions and real-world behavior. The experimental results will be analyzed for feasibility in integrating a linear magnetic actuator into an industrial setting and looking into further improvements in system design.

In addition, this thesis discusses analyzing potential advantages granted by linear magnetic actuators against traditional transport and actuation systems. Common mechanisms like belt conveyors sometimes suffer from mechanical wear and are energy inefficient, besides being adaptable. In contrast, linear magnetic actuators offer direct-drive motion, require less maintenance, and have higher precision, making them a promising alternative for modern manufacturing applications. This study intends to quantify these advantages on operation speed, accuracy, energy consumption, and reliability over time.

The research is assessing the extent to which linear magnetic actuators can integrate into the existing field automation infrastructure investigated by the study. Other elements addressed are response time, load characteristics, and environmental conditions that will determine whether or not these machines become potential substitutes for traditional systems in Cosberg's automation solutions. In this way, the path has been cleared for an easy transition to modern actuation technologies while still keeping the levels of existing motion control methods.

With such state-of-the-art innovations, this thesis will try to show how academic research can effectively bridge into industrial applications. Linear magnetic actuator technology will be analyzed and highlighted as having merit in the future revolution of manufacturing automation. The results, therefore, will feed into developments concerning the efficient and adaptable future of linear electric actuation and automated solutions.

2 State of the Art

2.1 Electromagnetic Theory

The operation of linear electric machines is grounded on the classical electromagnetic principles. Faraday's Law of Electromagnetic Induction, Ampère's Circuital Law, and the Lorentz Force Law form the intimate physical foundations for the conversion of electrical energy into motion lines in the context of linear machines. All these laws significantly affect the interaction of electric currents with magnetic fields within the structure of linear motors; therefore, they find a considerable application in thrust generation in synchronous as well as asynchronous configurations.

In Faraday's Law, a changing magnetic flux through a closed loop induces an electromotive force (EMF) in the conductor. This is an important law in understanding the current generation by induced phenomenon in linear machines, especially in linear induction motors (LIMs), where induced currents developed in the reaction rail bring about movement.

$$\text{EMF} = -\frac{d\Phi_B}{dt}$$

Equation 1 - Faraday's Law of Electromagnetic Induction

Where:

- $\mathcal{E}$ is the induced electromotive force (EMF),
- Φ_B Is the magnetic flux.

This creates a time-varying magnetic field due to alternating current in the stator windings. This magnetic field intersects with a conductive secondary element (for example, aluminum or copper sheets), inducing an EMF and thus generating circulating eddy currents. Such currents interact with the primary field, generating force through the Lorentz mechanism.

Ampere's Law relates the integrated magnetic field around a closed circuit to the electric current that penetrates the area enclosed. The law in its differential form, incorporating Maxwell's corrections for time-varying electric fields, the law is expressed as:

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Equation 2 - Ampere's Law

Where:

- $\vec{B}$ Is the magnetic field,
- μ_0 Is the permeability of free space,
- $\vec{J}$ Is the current density,
- ϵ_0 Is the permittivity of free space,
- $\vec{E}$ Is the electric field.

When considering linear electric machines, the Ampère law governs the determination of the distribution of the magnetic field due to the action of stator windings. This is particularly important for the design of optimized magnetic circuits intended for high thrust density and low losses.

Lorentz Force is one of the basic laws relating to electromagnetism. The law states that a charged particle moving through a magnetic and electric field experiences this force. The mathematical expression for the force is as follows:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Equation 3 - Lorentz Force

where:

- $\vec{F}$ Is the Lorentz force,
- q Is the charge of the particle,

- $\vec{E}$ Is the electric field,
- $\vec{v}$ is the velocity of the charged particle,
- $\vec{B}$ Is the magnetic field

In a LEM, when the current-carrying conductors (that is coils) are placed in a magnetic field, this force comes into play. Thus, the force generated is transferred to the moving part of the machine, enabling the conversion of electrical energy into mechanical motion. This is very important for high-performance actuation in industry applications [1].

2.1.1 Solenoids Magnetic Fields

The motion of electric charge produces magnetic fields, which are vital for the working of LEMs. It is common knowledge that a current through a conductor generates a magnetic field according to Ampere's Law. The following considerations will determine the direction of the magnetic field concerning the strength and the magnitude of the current. Electricity sets charged particles in motion within straight wires. The third principle states that a current in a solenoid produces a magnetic field in that solenoid, as is mostly done in LEMs. This magnetic field generates the force that makes the system move. The magnetic field strength of a solenoid is directly related to the current and number of turns:

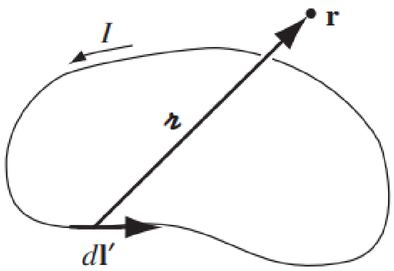


Figure 2.1: Magnetic field produced by a current-carrying wire based on Ampère's Law [1]. It illustrates the relationship between the current direction and the resulting magnetic field.

$$B = \mu_0 \frac{NI}{l}$$

Equation 4 - Magnetic Fields

Where:

- B is the magnetic field strength,
- μ_0 is the permeability of free space,
- N is the number of turns,
- I is the current, and
- l is the length of the solenoid [1].

This magnetic field makes it possible to create a precise control interface for the actuation system in LEMs, thus ensuring high efficiency and reliability, both of which are indispensable to industrial automation.

2.1.2 Magnetic Forces and Efficiency in LEMs

In the case of LEMs, efficiency of the system is highly dependent on the pairing of the magnetic field and coils: the mutual interaction resulting in the forces is therefore directly proportional to the strength of the magnetic fields and the currents in the coils; thus, an improved magnetic circuit can prevent all avenues of loss and preferably maximizes the general efficiency of the system. The recent developments made in the design of complete magnetic fields, coupled with that of permanent magnets into electromagnetism, increase force density with less power loss in LEMs; thus, translating to energy-efficient systems that will perform best in demand-driven industry applications needing high precision and low energy consumption [2].

2.2 Literature Review of Linear Electric Motors

2.2.1 General Overview of LEM Research and Trends

Recently, there has been growing interest in research on linear electric machines (LEMs), which are devices capable of producing their motion linearly without the need for intermediate mechanical transmission systems such as screws, gears, or belts. This feature simplifies the system architecture, eliminates many mechanical losses, and improves the performance of the device in terms of the dynamic response and positional accuracy. This means LEMs are essential in applications that demand a linear actuation system running at high speeds and precision, such as in semiconductor production, magnetic levitation (maglev) transport, robotic actuators, and high-speed elevators [2].

The development of LEMs in academia and industry has received accelerated impetus by the significant advances in power electronics, control theory, and magnetic materials. This evolution of LEMs has engaged improvements in energy efficiency, thermal management, thrust-to-weight ratio, and force smoothness, from early prototypes to their commercial application. The research trends are gradually inclined toward the development of low-cost designs, modularity, sensorless control, and integration with advanced materials such as soft magnetic composites [3].

Rather dramatically, advances in power electronics, control theory, and magnetic materials have finally given the impetus for the development of LEMs in both academic and industrial circles. Energy efficiency, thermal management, thrust-to-weight ratio, and force smoothness contribute to the LEM's evolutionary program from early prototypes for commercial applications. The other trend of research is towards cost-effective designs, modularity, sensorless control, and integrating advanced materials such as soft magnetic composites [3].

The literature contains multiple journal articles, conference proceedings, and patents dealing with improvements of design topologies, control strategies, and electromagnetic performance. In one of the most exhaustive treatises on the subject, Boldea and Nasar (2018) provide detailed classification schemes, design methodologies, and case studies of applications [4].

2.2.2 Classification by Geometry

Linear electric machines (LEMs) can be classified according to many criteria, depending on the analysis being performed. Most commonly and considered to be technically relevant, the classification methods are based upon machine geometry and operating principle. The following subsections will give insight into these classification types.

They can be classified according to the configuration of their components, most commonly the stator and mover configuration. Among the most widely recognized types are flat type, U-shaped, and tubular linear machines.

Flat Linear Machines

Flat-type linear machines can be defined as planar assemblies of stator and mover such that the magnetic flux travel is perpendicular to motion. They are, for example, used over linear stages, gantry systems, and pick-and-place robots. The simplicity, in turn, leads to some intentional efficiency loss, which is usually because of uneven force distribution and end effects, causing vibrations [4] .

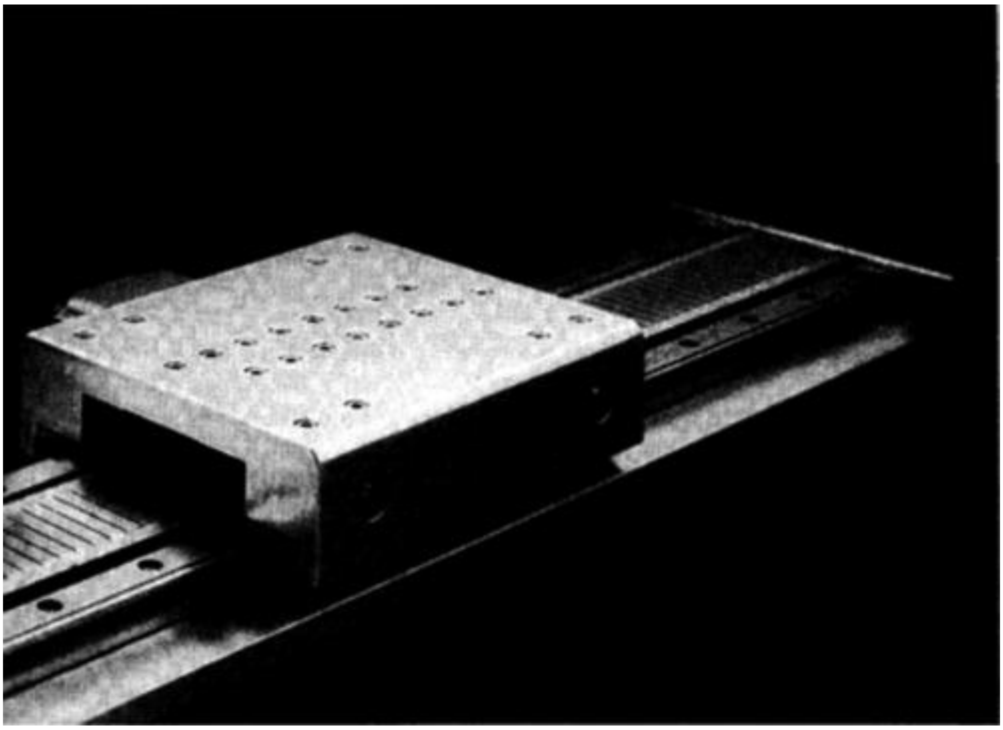


Figure 2.2: Flat Type Linear Machine [4]

U-shaped Linear Machines

A linear machine having a U-shape is also a linear machine within which the stator wraps around the mover or vice-y-versa and creates closely concentrated path for magnetic flux and enhances thrust generation. U-shaped machines find application in industry from medium to high forces excluding magnetic leakage and improving mechanical integration[4].

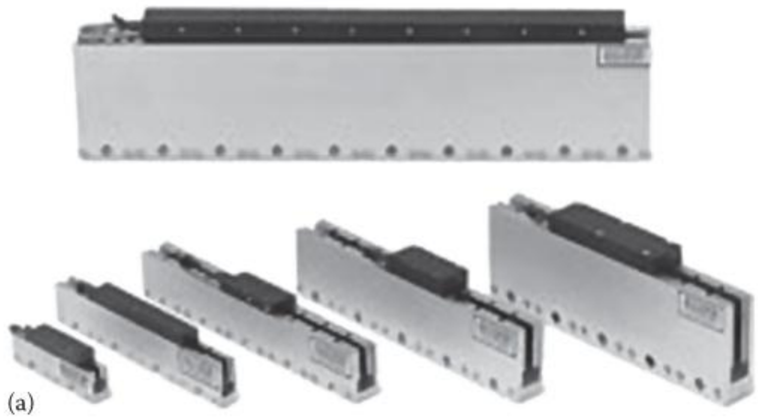


Figure 1.3: U-shaped Linear Machine [4]

Tubular Linear Machines

These exhibit the cylindrical type of configuration that resembles a rotary machine naturally unwrapped into a linear form. The geometry ensures that radial forces are balanced and thrust is symmetrically imparted, yielding higher efficiency and lower vibration. Tubular machines are suitable for applications requiring high precision, such as medical devices, compressors, and actuators for aerospace systems [1].

Figure 2.4: PM Linear Electric Generator

2.2.3 Classification by Operating Principle

Linear electromagnetic motors (or LEMs) transform electromagnetic forces, governed by Faraday's and Ampere's laws, into linear motion directly. Such a linear motion can be progressive (Figure 2.1a) or oscillatory (Figure 2.b1) [4].

Of all the criteria available for classifying linear electric machines (LEMs), the operating principal classification happens to be one of the most technically significant. This classification divides them according to the fundamental mechanism by which electromagnetic energy is converted into linear mechanical motion. The main categories of LEMs in this context include linear induction motors (LIMs), linear synchronous motors (LSMs), linear brushless direct current (BLDC) motors, and linear brushed direct current (DC) motors. Each category possesses its own specialized electrical, mechanical, and control characteristics within the set of devices, informing performance considerations and application adequacy [4].

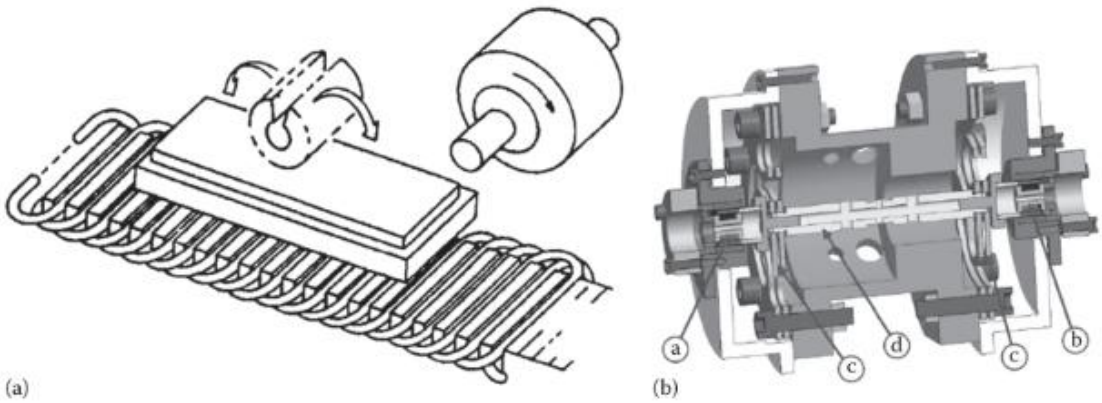


Figure 2.5: Linear electric machines (a) with progressive motion (LEMs) (After Boldea, I. and Nasar, S.A., Linear Motion Electromagnetic Devices, Taylor & Francis, New York, 2001); (b) with oscillatory resonant motion (LOMs): motor plus generator (a. linear motor, b. linear generator, c. resonant springs (features), d. coupling shaft) [4].

Linear Induction Motors (LIMs)

The linear induction motors essentially employ the same principle and topologies of rotary induction motors, by "cutting" and unrolling to attain flat LIMs (Figure 2.5).

Linear-induction machine can be defined as the linearly related counterpart of a conventional rotary induction motor. Electromagnetic induction is what makes the operation of these machines; in that, the stator generates a time-varying magnetic field, thereby inducing eddy currents in the conductive secondary, which are composed of aluminum or copper, and its interaction with the air gap produces a Lorentz force that causes a resulting linear motion.

The slip between the secondary mover and the magnetic field is the only defining characteristic of LIMs. Such machines are excellent for applications on high-speed drives because they are simpler mechanically and do not require mechanical contact for operation. The drawbacks of LIMs include reduced efficiencies compared to synchronous machines due to the effect of eddy currents and magnetic leakage losses. Generally, they are used in transport systems, such as maglev trains; however, they are also used in various industrial operations that require contactless motion, including material-handling systems and conveyor systems [4].

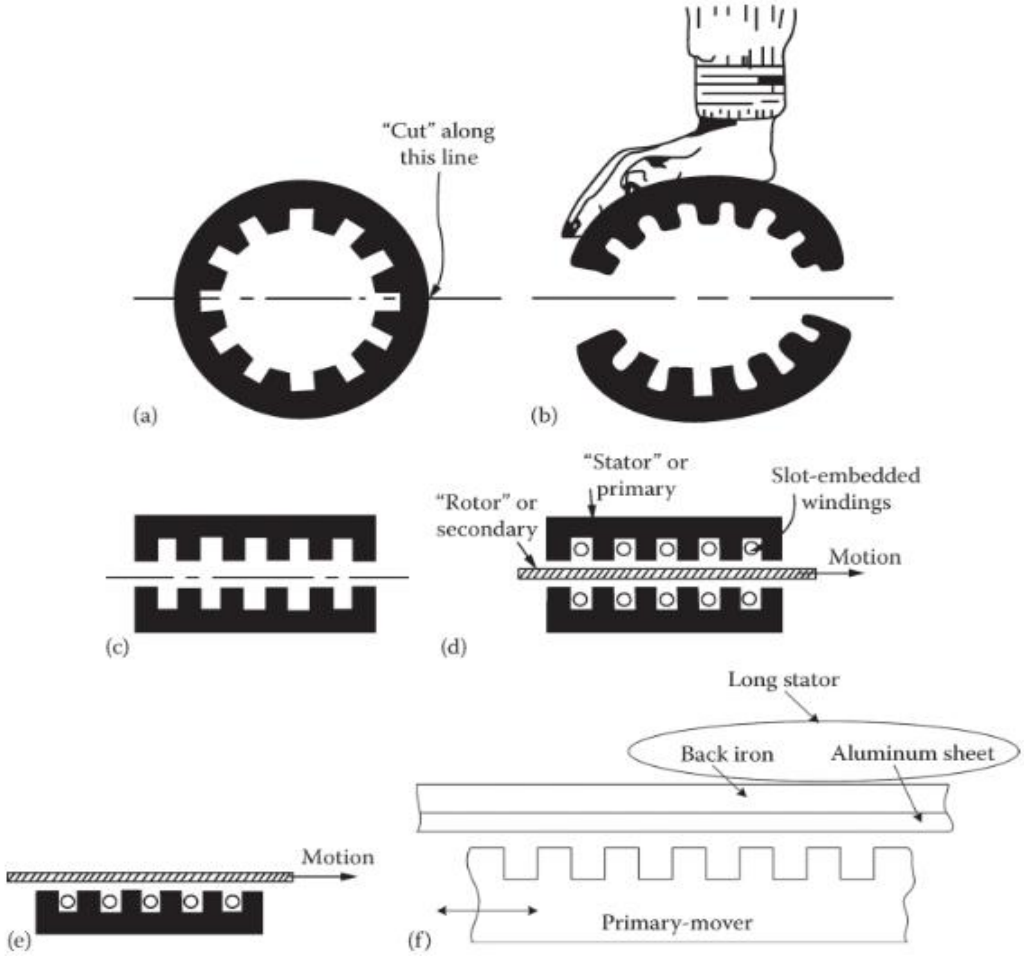


Figure 2.6: Double- and single-sided LIMs: (a) round primary, (b) unrolling of primary (after cutting), (c) flat double-sided LIM primary with slots, (d) double-sided LIM primary plus Aluminum (copper) sheet secondary, (e) single-sided LIM (primary) plus Al (copper) sheet, and (f) with back iron in the secondary. (After Boldea, I. and Nasar, S.A., Linear Motion Electromagnetic Devices, Taylor & Francis, New York, 2001.) [4].

Linear Synchronous Motors (LSMs)

This is synchronous motion for linear synchronous motors, wherein velocity and that of the mover match with the traveling magnetic field produced by the stator; the moving part contains either permanent magnets or an arrangement of field windings interacting directly with the stator's magnetic field such that synchronized propulsion occurs without slip.

Efficiency is far better, and force density and positional accuracy are higher compared to LIMs. Their operational characteristics render them valuable in high-precision applications such as computer numerical controlled (CNC) machines, semiconductor wafer stages, magnetic levitation transport, and robotic actuators. However, an LSM implementation comes with complex control systems, and for the designs based on permanent magnets, they are rare-earth materials-based, increasing costs and thermal sensitivity as well [4].

Figure 2.7 - JFK-New York Air Train on wheels propelled by single-sided LIMs [4]

Linear Brushed DC Motors

Linear brushed DC motors represent the simplest configurations of LEMs. They are mechanically commutated by a brush-commutator system that reverses current in the armature windings. The linear arrangement of such motors normally employs a moving coil in a static magnetic field.

Although linear brushed DC motors have simplicity and low initial cost, they are limited by frequent maintenance, contact wear, and sparking due to their brush system. Therefore, they are used only in applications of low demand or in experimental and teaching situations [4].

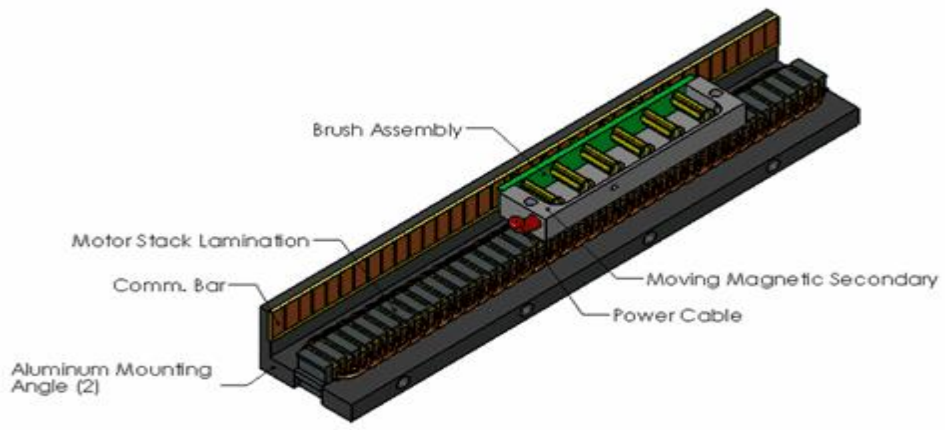


Figure 2.8: Linear Brushed DC Motors [www.h2wtech.com/category/brush-linear#technical1]

Linear Brushless DC Motors

In linear BLDC machine architectures, the mover consists of permanent magnets, while the electronic commutation is done in the stator windings. Unlike brushed types, the brushless type employs sensors (Hall-effect sensors or encoders) to determine the position of the mover and switch the stator phases accordingly.

Since no brushes are used, these motors have high operational efficiency with very low acoustic noise and minimum maintenance. Hence, they are very suitable in applications that require compactness, reliability, and moderate-to-high precision, namely, in the case of automatic doors, medical equipment, and mechatronic actuators (Boldea & Nasar, 2018). The main disadvantage is the resorting to sophisticated electronic drives and feedback systems.

Figure 2.9: Linear Brushless DC Motors [www.h2wtech.com/category/brushless-linear#productInfo1]

Table 2.1 provides a relative comparison of the main characteristics of various Linear Electric Machine (LEM) types-such as LIMs, LSMs, BLDCs, and Brushed DC motors- which differ largely with respect to excitation manner, efficiency, maintenance need, and typical application area. LSMs, therefore, are high-efficiency motors often used in automations and high-speed transport systems and are well-adapted for precision motion systems. On the contrary, Brushed DC motors are much simpler and require more maintenance and are intended mainly for low-cost applications. The comparison clearly and convincingly supports choosing the most suited actuation technology for the proposed linear magnetic conveyor system.

Machine Type	Excitation Type	Efficiency	Maintenance	Typical Applications
LIM	Inductive	Medium	Low	Conveyors, maglev transport
LSM	Synchronous	High	Medium	High-speed trains, automation
BLDC	Electronic	High	Low	Robotics, medical devices
Brushed DC	Mechanical	Low	High	Toys, office equipment

Table 2.1: Comparison of Linear Electric Machine Types

This comparison indicates that LSMs are superior for precise and modular motion; hence, LSMs would be an ideal choice for the suggested linear magnetic conveyor system. The subsequent patent review further elaborates on how such systems are being realized in the industry today and provides an extensive overview of existing implementations based on LSMs.

2.2.4 LSM Patents and Market-Ready Industrial Solutions for the Selected Conveyor System

Intelligent Conveyor System

One of the innovations in intelligent conveyor systems includes US Patent 10773847B2, which is titled "Packaging Machine with a Magnetic Movers Conveyor" and was awarded in 2020 to CAMA1 S.p.A. This patent introduces a packaging machine using magnetic-drive conveyor systems with independently controllable movers. One important feature of this movement is the dynamic adjustability of the master/slave configuration between the motion controls of the conveyor and the operational devices of the packaging machine. This dynamic coordination adds flexibility by synchronization across different workstations, improving overall efficiency and adaptability in the packaging process.

These principles available in this patent resonate with this thesis, whose aim is to develop a linear magnetic actuated conveyor system feeding assembly lines. The system would possess an ability to achieve improved positioning, integration into automated manufacturing environments, beneficial towards intelligent material handling solutions, via the implementation of customizable solenoid layouts and advanced control algorithms.

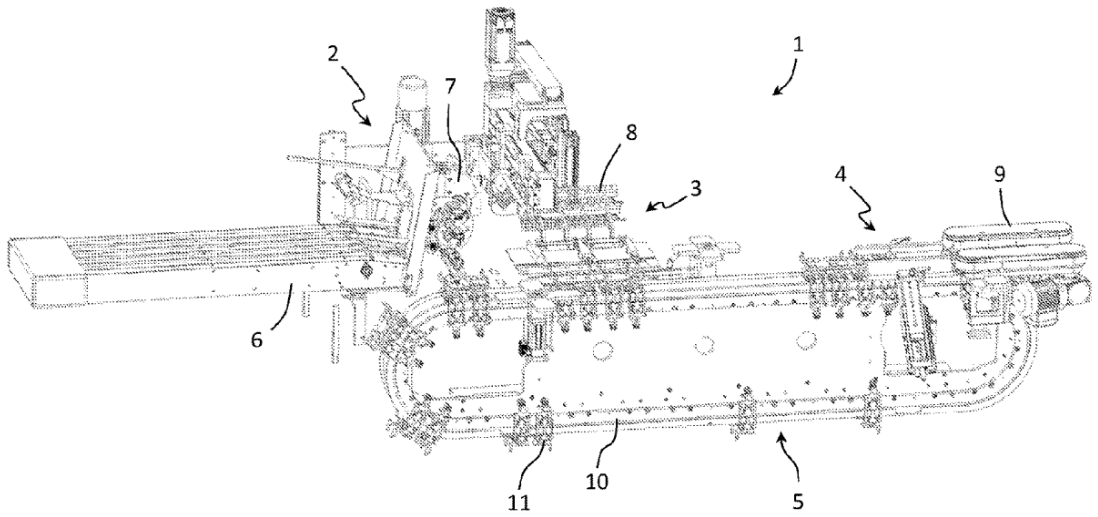


Figure 2.10: Packaging Machine with a Magnetic Movers Conveyor from the patent 10773847B2

Intelligent material handling

Another patent in the area of intelligent material handling is US9988165B2, titled "Packaging System and Method Using Intelligent Conveyor Systems" granted to Procter and Gamble in 2018. This patent describes a modular conveyor system that has its own sensors and control mechanisms for the accurate and autonomous movement of products through places of processing. The system is intended to make it possible for flexible production, increased uptime, and versatility in the requirements of various production needs—concepts that are very much aligned with the workings of modern assembly line automation.

The intelligent handling strategy and real-time feedback features of the US9988165 This linear magnetic actuated conveyor system using an electric actuation mechanism equivalent to a motorized conveyor would create modifications, modularity, and space integration.

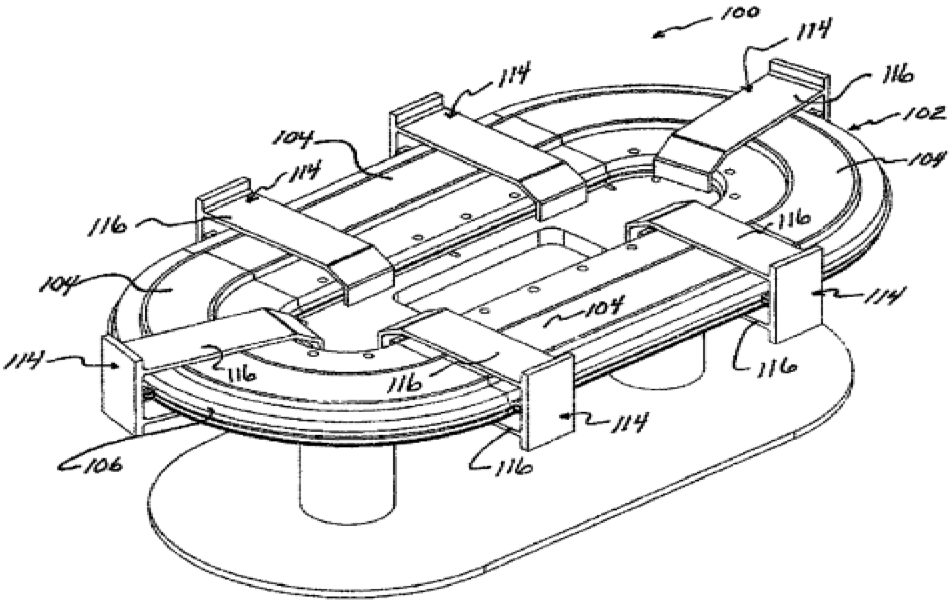


Figure 2.11: Packaging System and Method Using Intelligent Conveyor Systems from the patent US9988165B2

Industry 4.0 has continued to progress, often leading to changes in many other aspects of modern manufacturing and logistics, or more accurately, gradually focusing on energy-efficient, highly precise automated systems that are flexible. Historically, conveyor systems have been regarded as the best types of transport due to their simplicity, reliability, and cost-effectiveness. However, driven by increasing demands for rapid, high, and modular transport solutions, Linear Synchronous Motors (LSMs) have emerged as one of the promising alternatives to conventional conveyor systems in modern production lines. This section presents a comparative literature study of Linear synchronous motors and traditional conveyor belt systems regarding energy consumption, maintenance, system integration, and cost considerations. It aims to provide a clear understanding of how and when LSMs[1] may surpass or complement conveyor systems within the smart factories of the future.

[1] Linear Synchronous Motors

Beckhoff XTS (eXtended Transport System)

Beckhoff XTS is a commercially available transport system for industries based on the linear motor technology for controlling more than one mover independently along the path. The XTS is also the integration of motion control, sensors, and power electronics in a compact and modular form factor. It allows synchronous high-speed and flexible motion, ideally suited for environments that fit Industry 4.0 standards.

Furthermore, it operates using magnet propulsion and precise control of individual movers, thus making it a perfect real-world representation of the system proposed in this thesis. This system boasts multi-facility space efficiency, dynamic routing, and easy reconfiguration (Figure 2.12).

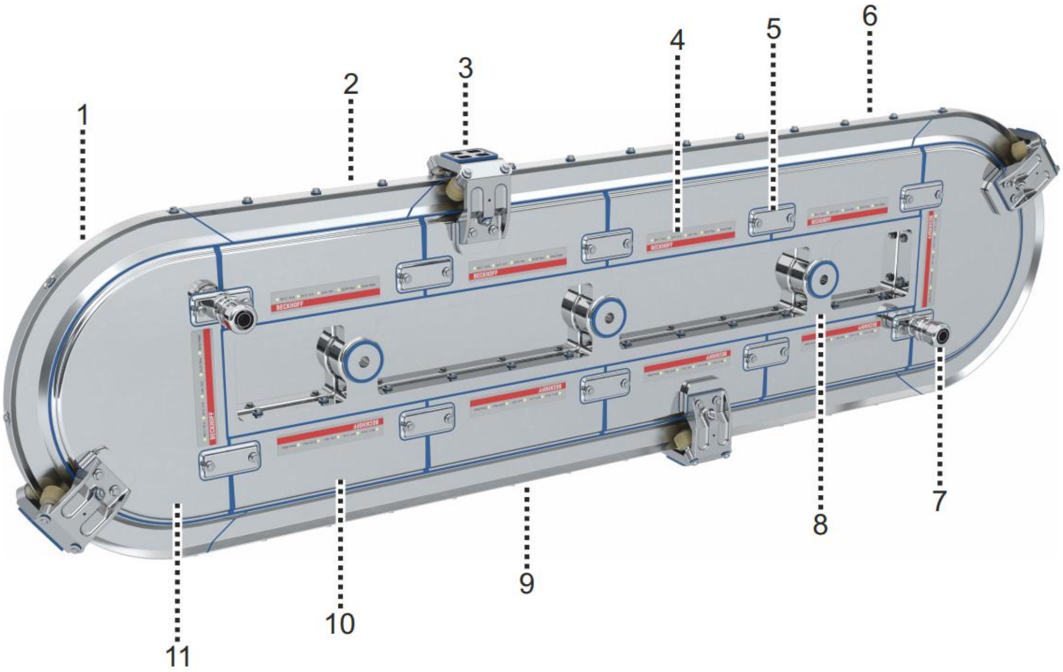


Figure 2.12: Beckhoff XTS system layout showing key components: 1. Curved rail, 2. Lock, 3. Mover, 4. LED status display, 5. Cover with connection card, 6. Straight guide rail with lock, 7. Cover with supply, 8. Machine bed, 9. Straight guide rail without lock, 10. Straight module, 11. Curved module. *(Source: Beckhoff Automation GmbH)*

Schneider Electric Lexium MC12

Another state-of-the-art linear transport system for modular, high-performance automation is the Lexium MC12 from Schneider Electric. Just like Beckhoff's XTS, the Lexium MC12 uses individual magnetic movers based on linear synchronous motors, on a closed-loop track.

It allows high dynamic performance, optimization in throughput, and intelligent integration with robotics and machine vision, thus setting the ideal platform for an automated assembly line. This system also represents the maturity and industrial readiness of such LSM-based conveyors, thus adding more weight to the choice of technology incorporated in this thesis (Figure 2.13).

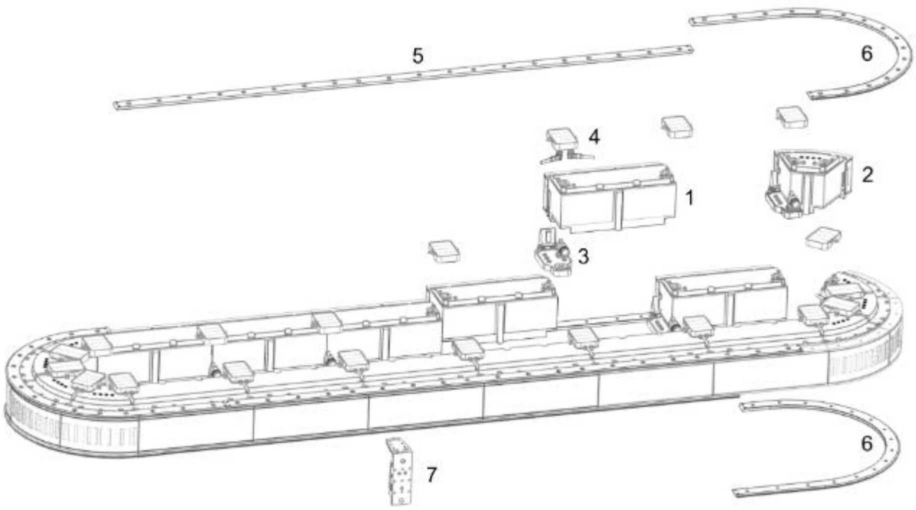


Figure 2.13: Schneider Electric Lexium MC12. 1. long stator motor segment straight, 2. long stator motor segment arc, 3. power interconnect, 4. communication interconnect, 5. guide rail straight, 6. guide rail arc, 7. Carrier

2.3 Comparative Analysis: Linear synchronous motors vs Conveyor Belt Systems

Industry 4.0 has continued to progress, often leading to changes in many other aspects of modern manufacturing and logistics, or more accurately, gradually focusing on energy-efficient, highly precise automated systems that are flexible. Historically, conveyor systems have been regarded as the best types of transport due to their simplicity, reliability, and cost-effectiveness. However, driven by increasing demands for rapid, high, and modular transport solutions, Linear Synchronous Motors (LSMs) have emerged as one of the promising alternatives to conventional conveyor systems in modern production lines. This section presents a comparative literature study of Linear synchronous motors and traditional conveyor belt systems regarding energy consumption, maintenance, system integration, and cost considerations. It aims to provide a clear understanding of how and when LSMs may surpass or complement conveyor systems within the smart factories of the future.

2.3.1 Performance Comparison

Precision and Positioning

Positional accuracy distinguishes LSM from belt conveyor options. LSM systems' submillimeter precision (±0.005 mm) guarantees applications requiring extremely low tolerances, such as CNC[2] machining, assembly machines, such as electronics assembly, and some inspection systems. In contrast, parameter accuracies of belt conveyor systems barely reach ±1-2 mm due to factors such as mechanical backlashes, elastic belt deformation, or load slippage.

Speed and acceleration

With parameter values in this regard, LSMs again outperform on dynamics, able to manage in speeds of 20-30 m/s and accelerations of more than $10 m/s^2$, all this without any loss in accuracy [6]. Ordinary conveyor systems operate below 2m/s; otherwise, acceleration would cause slippage or destruction of the belt, however, LSMs can achieve higher dynamic speeds and accelerations (up to 5 m/s and $50 m/s^2$). That puts LSMs in a good position to perform sorting, robotic transfer, and semiconductor processing at high speeds.

[2] Computer Numerical Control

Payload and load handling

Conventional conveyor belts can carry heavy payloads, which are often several hundred kilograms. In contrast, LSMs with iron-core or dual-sided configurations can carry vertical loads up to 5000 kg [5]. They also enable distributed force control for intelligent simultaneous handling of several payloads by independently driven movers.

Energy Efficiency

An essential fact that sets this system apart from others is its efficiency. Conveyors utilize various mechanical feed transmission methods, such as gearboxes, rollers, and couplings, which create different types of friction and mechanical losses. According to studies, the overall efficiency of conveyor systems is typically around 60-70%, depending on the load and design.

In contrast to LSMs, which exhibit energy conversion efficiencies of 80-95% due to the absence of intermediate components and the use of permanent magnets that reduce electrical losses [7], these systems also feature regenerative braking, which converts the energy generated by deceleration back into usable electrical energy, providing an additional means of enhancing energy sustainability in factory environments.

Modularity and Flexibility

Reconfigurability has become a crucial feature of manufacturing in today's world. Belt Conveyors are fixed-path systems, so any change in the pathways or station arrangements requires disassembling the conveyor and reassembling it for another workflow. In contrast, LSMs allow software-defined routing, enabling independent control of each mover while making simultaneous changes to paths and speeds.

This "Track and Trace" capability is particularly useful when used in asynchronous production systems where workstations do not share a synchronization signal.

Maintenance and Downtime

The continuous friction between conveyor belts and rollers, and gear mechanisms leads to mechanical wear. The regular maintenance of the system, usually scheduled every 3 to 6 months, involves tensioning, lubrication, and a change of parts.

Due to very few moving parts, LSMs have a much-reduced potential for mechanical degradation. Maintenance intervals for LSM straddle between 12 and 24 months and are often limited to cleaning and checking the thermal management system. Moreover, with no belts present, alignment issues and unplanned downtimes arising from belt failure are eliminated.

Safety and Environmental Considerations

Conveyor systems, from a safety aspect, have many hazards, including being trapped by the belt itself, pinch points, and other mechanical failures. A hazard must be continuously guarded and protected by safety interlocks. However, the LSMs provide a safer operating environment owing to enclosed or non-contact propulsion mechanisms. On the contrary, there are problems like electromagnetic interference (EMI), which can impede the operation of nearby electronics if shielding is not properly considered [10]. LSMs also exhibit better environmental resilience, especially in cleanroom applications where the concerns are the liberation of particles from the belt or contamination due to lubrication.

Cost Analysis

While LSMs outperform conveyor belts in many technical areas, their initial cost remains a major constraint. According to industry data:

System Type	Cost per meter	Typical Maintenance Cost (annually)
Belt Conveyor	\$500 – \$2,000	Moderate (~\$500/year)
LSM	\$2,000 – \$10,000	Low (~\$200/year)

Table 2.2: Cost analysis between conveyor belt and LSM

However, Total Cost of Ownership (TCO) models indicate that LSMs become more cost-effective over a 5–7-year lifecycle, particularly when factoring in productivity gains, energy savings, and reduced downtime [8].

2.3.2 Application Suitability

This comparison indicates that for smart factories, robotic cells, and high-throughput lines, LSMs provide a significantly more flexible and scalable solution.

Criterion	Conveyor Belt	LSM
High-Speed Transport	Limited to ~2 m/s	Up to 30 m/s
High Precision	±1 mm	±0.005 mm
Modular Layout	Fixed paths	Software-defined routing
Maintenance Frequency	Frequent (3–6 months)	Low (12–24 months)
Energy Efficiency	~70%	85–95%
Cost (Initial)	Low	High
Lifecycle Cost	Higher over time	Lower after 5–7 years

Table 1.3: Comparison of application suitability between conveyor belt and LSM

Summary

In a nutshell, Linear synchronous motors are a more modern technological alternative to conventional conveyor belt systems, with proven advantages in terms of accuracy, speed, energy efficiency, and modularity. Of course, having a higher initial price tag, LSM usually pays for itself over time by enhanced productivity and reduced maintenance costs, especially in high-performance manufacturing contexts.

Applications involving dynamic routing, independent payloads, and real-time control must unmistakably be LSM territory. For cheap, low-precision transport of materials, however, the conveyor belt is still a good option.

2.4 Challenges and Limitations of Linear Synchronous Motors

The LSMs can be extremely precise with fast dynamic response and contactless movement. However, there is some limitations, such motors have a relatively more complex construction as compared to normal rotary motors because of the open linear structure. The interruption of pallor magnetic alignment causes disturbances even over longer travel distances.

Key limitations are the high initial cost of permanent magnets and drive electronics, complex control requirements, internal heating causing thermal management problems, and external disturbances due to dust, vibrations, and temperature changes. In addition, there is a precise requirement for synchronization of the stator traveling magnetic field with the mover magnetic field, which place high demands on the control and feedback systems.

These challenges limit the acceptance of LSMs in traditional industrial environments, which are prioritized by robustness, cost, and simplicity. This section critically reviews the technological, economical, organizational, and environmental challenges of LSMs and addresses recent literature and industrial practices that have proposed and implemented mitigation measures to overcome the specific barriers.

2.4.1 High Initial and Integration Costs

Perhaps the most significant challenge associated with the adoption of LSMs is high upfront capital investment. Linear motor systems require:

- Permanent magnets, usually rare-earth based (such as neodymium, iron, boron)
- Precision-fabricated stators with complex winding topologies
- Dedicated servo controllers (or inverters)
- Position sensors and feedback encoders
- Sophisticated mounting systems and cooling setups

According to comparative cost analysis data, belt conveyor systems based on classic rotary systems may cost between $500 and $2,000 per meter, whereas LSMs run from $2,000 to $10,000 per meter [8]. Moreover, linear motors tend to require higher installation costs primarily because precision alignment and electromagnetic shielding are required.

Moreover, these costs increase when LSMs are fitted to existing facilities, which may not be designed for the thermal, control, or mechanical needs of such a system [6]. While lifetime maintenance and energy costs are low for LSM, the high initial capital investment remains a major challenge to their widespread acceptance, especially for SMEs.

2.4.2 Complexity in Control Systems

In contrast to rotary motors, linear synchronous motors have no physical feedback mechanisms such as rotary encoders or gears for stabilizing motion. Motion profiles, force distribution, and position synchronization are controlled primarily by advanced control algorithms. The challenges in controlling linear electric motors are:

Real-time feedback processing: Position and velocity must be tracked and updated with millisecond-level accuracy.

Field-oriented control or direct thrust control algorithms for the precise generation of electromagnetic force.

Multi-mover synchronous control: Beckhoff XTS or Lexium MC12-type systems require centralized controllers under deterministic real-time protocols (e.g., Ether CAT) [12]. And these control systems must be made resilient against variations in load, thermal drift, and noise at the supply, which raises the design and maintenance burden. In these systems, misconfigured settings or software bugs can lead to loss of synchronization or collisions of movers in a multi-carrier system.

2.4.3 Thermal Management

Among the least-known harms of LSM, particularly in high-speed or high-duty-cycle applications, is thermal dissipation: under continuous operation, stator windings heat up as a result of resistive losses (thus, Joule heating), and in certain cases, particularly with iron-core designs, involve eddy current and hysteresis losses.

Certain of the predominant thermal issues include:

- Localized Hot Spots: Long tracks develop very serious problems of performance degradation or insulation breakdown due to the non-uniform cooling.
- Permanent Magnet Demagnetization: Temperatures greater than 80-150 °C, depending on grade, can cause an irreversible change in the magnetic properties of NdFeB or SmCo magnets [11].
- Active Cooling: In many cases, this involves forced air or even liquid cooling and further contributes to system complexity and energy consumption.

Thermal management could make itself felt in system efficiency as well as life reliability and unexpected shutdowns. Thermal design is still a black hole area in LSM development.

2.4.4 Magnetic Interference and Shielding

The LSM operations are accompanied by strong magnetic fields that can even reach beyond the confines of the immediate machine itself. This leads to the challenge of Electromagnetic Interference (EMI) with adjacent equipment, such as:

- Industrial automation systems incorporating sensitive control electronics

- Medical environments (e.g., MRI[3]-compatible automation)
- Measurement and inspection systems, where signal acquisition is done with low noise

Magnetic leakage could magnetize or demagnetize nearby ferromagnetic structures, causing attraction or signal distortion, respectively. To contain them, generally effective magnetic shielding such as mu-metal or soft iron enclosures is required, which adds weight, cost, and complexity [10].

When the LEM is mobile (for example, with AGVs or maglevs), further designs must be considered for dynamic shielding or retracting the magnets, which poses another engagement issue.

2.4.5 Limited Force Output in Ironless Designs

Ironless and slotless linear synchronous motors present features increasingly preferred because of their smooth operation and lower snagging and inertia. However, they are at the same time known to develop thrusts lower than those produced with conventional LSMs because of the absence of iron in the flux path. Ironless and slotless designs limit their applications to the following:

- Heavy loads (payloads above 500–1000 kg)
- A vertical actuation against the gravity force
- Applications that require instantaneous changes of direction or acceleration

Iron-core or dual-sided motors are chosen in such cases, where the performance demand calls for swift actuation, although they bear an added penalty in size and complexity due to extra cogging torque and thermal management requirements [5].

In other words, performance in terms of acceleration and smoothness can be traded off for the force performance depending on the load profile within the application.

[3] Magnetic Resonance Imagin

2.4.6 Environmental Sensitivity and Operational Limits

LSMs are very sensitive to environmental parameters, which might either degrade their performance or damage their components.

- Dust and debris: The accumulated dust in the air gap can reduce magnetic coupling and cause uneven force distribution.
- Humidity levels: Without proper sealing, they can corrode copper windings, inner magnets, or mounting structures.
- Temperature changes: They can affect resistivity, thermal expansion, and the calibration of feedback sensors, especially for systems requiring accuracy down to the micron level.
- Metal chips contamination: In machining environments, loose metal chips can be attracted to the exposed magnets, leading to a short circuit or mechanical jam.

Such sensitivity warrants protective housing, IP-rated enclosures, and active environmental control for factories, labs, or cleanroom installations. By contrast, belt conveyors tend to tolerate wider environmental deviations and require less protection.

2.4.7 System Scalability and Standardization

Despite granting a great deal of modularity, LSMs pose certain obstacles to the scaling of the product via:

- Customized motor geometries (e.g., tubular vs flat vs U-channel) are not easily interchangeable.
- There is no standard interface protocol between movers, stators, and controllers.
- The systems are dependent on vendor-specific systems (e.g., Beckhoff, Schneider), limiting cross-compatibility.

This has caused a difficulty in mixing and matching components from different manufacturers or in rapid scaling of systems without redesigning hardware and software together. The industry is gradually moving towards standardized platforms for linear motion systems, similar to the degree of modularity offered by industrial PLC[4]s or SCARA [5]robots.

2.4.8 Safety Concerns

Even though LSMS is avoiding mechanical safety risks that are encountered in traditional conveyor systems, it brings its own safety concerns, such as:

- Sudden accelerations: Actuation of high-force and high-speed causes injuries, for instance, when a human is between the operational range.
- Movement unintentionally during shutdown: Residual magnetic forces move lightweight payloads or carts if proper grounding is not done.
- Electric shock risk: Especially in liquid-cooled designs or high-voltage stator configurations > 400 V.
- Fire hazard: Overheating in a compact environment can pose ignition risks if cooling or thermal sensors fail.

Redundant safety systems, such as emergency brakes, force sensors, and over-temperature protection circuits, are part of the aforementioned list of safety solutions. However, LSM-specific safety protocols should be carefully evaluated and documented by a system integrator.

2.4.9 Summary and Outlook

Notwithstanding the multiple benefits offered by linear synchronous motors, there are still situations where they provide no favorable solution and need to be matched to

[4] programmable logic controller
[5] selective compliance assembly robot arm

specific requirements laid down by an application. The limitations are highlighted as follows:

Category	Key Limitations
Economic	High initial costs, integration expenses
Technical	Complex controls, thermal issues, and force limitations
Environmental	Sensitivity to dust, heat, humidity, and magnetic particles
Electromagnetic	EMI and magnetic interference risks
Safety and Maintenance	New safety protocols are required, although less frequent maintenance is required.
Scalability	Vendor lock-in, lack of standardization

Table 2.4: Key limitation of LEMs

Advances in materials, simulation tools, embedded systems, and modular design platforms continuously address many of these limitations. For instance, improved cooling systems, integrated condition monitoring, and AI-enhanced motion control systems are already taking LSMs into new domains.

Weighing the challenges against the benefits of performance and efficiency provided by linear electric motors, especially in applications where precision, speed, and flexibility are vital for success, is the last consideration in deciding to use linear electric motors.

3 Proposed Concept and Analytical Models

The purpose of this thesis is to study, design and control of a linear magnetic actuator targeted for integration into Cosberg's modular automation machines. The actuation system comprises a moving carriage with permanent magnets and a fixed stator with distributed electromagnets. This arrangement allows for contactless and programmable linear motion with precision and energy efficiency.

Establishing the architecture of the system began with identifying the essential components for motion generation and mechanical support. Through conceptual sketches, literature review, and functional analysis of the Cosberg's system, four main elements were selected: guide rails, carriages, electromagnet, and permanent magnets. Each of these components plays its own critical role in providing smooth motion, structural stability, and efficient electromagnetic force generation.

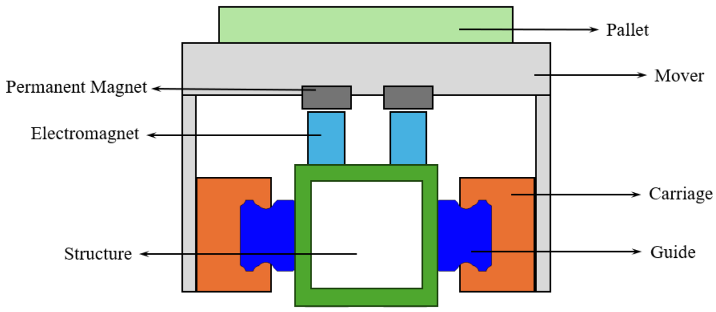


Figure 3.1: A Schematic of Linear Synchronous Machine (LSM), showing the main system components, such as a mover with permanent magnets, a stator with electromagnets, two guide rails, structure, and pallet. This diagram represents the working principle of the actuator used in the prototype.

The concept proposed, with independently controlled solenoids and a magnetized carriage, provides modularity, precision, and adaptability-these characteristics are essential for modern flexible manufacturing systems. The following subsections provide detailed analytical models for the guide system, carriage dynamics, and solenoid force generation to support a comprehensive design process based on mechanical and electromagnetic analysis [13][1][4].

3.1 linear actuation concept

The proposed actuation system consists of electromagnetic solenoids acting on a carriage with a permanent magnet.

The stator of the system comprises an array of stationary solenoids placed along the base structure of the machine. Every solenoid is energized exactly when necessary, according to the position and the motion profile of the carriage to achieve point-to-point or continuous programmable motion. This makes motion segmentation by actuation as efficient energy utilization as possible because it energizes only the necessary solenoids during movement.

The movable part of the system- the mover- is equipped with an array of permanent magnets, that couple with the magnetic fields produced by the solenoids. It is important to optimize their positioning to ensure that the interaction in magnetism creates a constant pulling force on the carriage, permitting smooth, contactless motion on guide rails. The gap between the solenoids and magnets is kept at a minimum to improve force transmission while managing mechanical clearance and thermal safety.

The solenoid design's modularity caters to easy extension or reconfiguration of the stroke length of the actuator. Further, such a design would ease the maintenance and replacement procedures compared to continuous windings. Mechanically contactless motion improves wear and operational noise.

The proposed linear actuation system is intended for inclusion within a circular structure of linear conveyor architecture, which is a prime component of Cosberg's part handling and assembly processes (Fig. 3.2). This system is responsible for feeding unfinished parts into workstations and transporting finished parts out, enabling a continuous, high-throughput manufacturing flow.

In the proposed layout, there is a secondary conveyor located under the main conveyor, dedicated to transporting pallets or carriers. The two-level structure improves the material flow and sets the rehandling of the next collection of parts. To support the pallets' return path, both straight and curved conveyor modules will be needed to follow the layout defined by the available space and flow constraints.

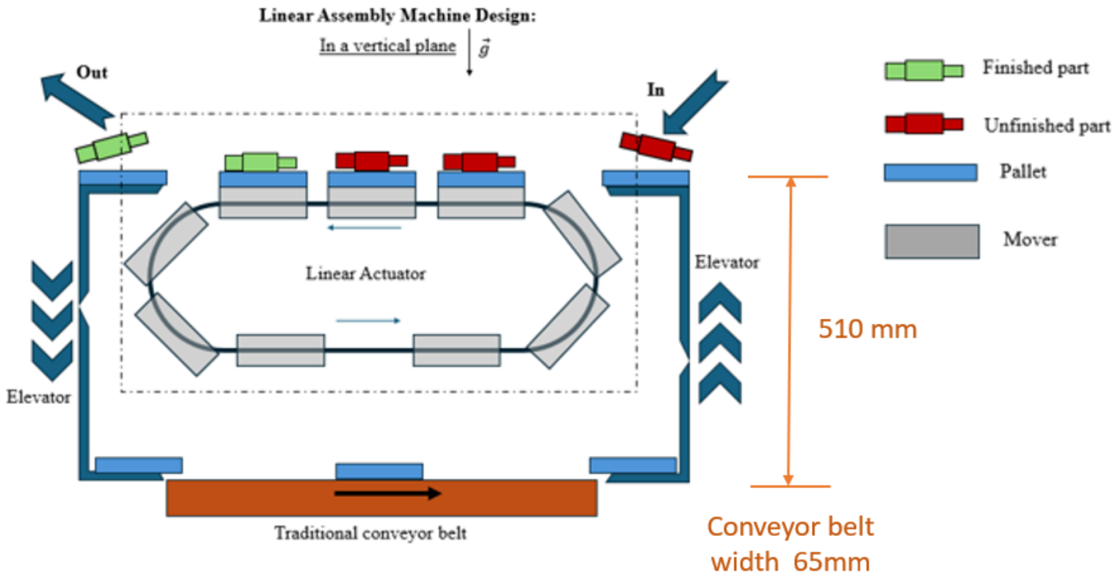


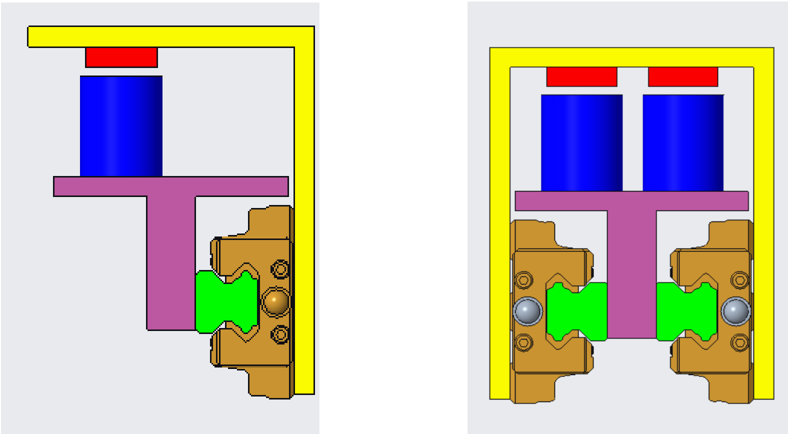
Figure 3.2: Schematic of the proposed solution, showing the conveyor system. The upper-level transport the pallets with workpieces, and the lower-level aim is to return empty pallets to the starting point. Key components such as the main conveyor, secondary return conveyor, and potential module configurations are indicated.

The subsequent sections discuss the conceptual and analytical basis of the guiding, carriage, and solenoid subsystems in detail [13][1][4].

3.2 Guide and Carriage Analytical Models

The initial design stage for the linear synchronous actuator began an extensive evaluation of two principal configurations for the mechanical support system. They are the single guide rail configuration and the dual guide rail layout (Fig. 3.3).

The main objective was to evaluate the max. load in stationary pallet condition (e.g. riveting station or other assembly operations with high loads) to select a structure that has very high stiffness, minimum deflection, and compact structure with minimum cost.



(a) (b)

Figure 3.3: Initial Designs: (a) one guide rail, (b) two guide rails

Objective

The goal of this evaluation was to find the best structure for the support of the pallet under two critical conditions of loading:

Processing (e.g., riveting or assembly): While the pallet is held stationary, a vertical force of 500 N is applied to it.

In motion: While in motion, another vertical force acts on the system, caused by the magnetic attraction between the solenoids and the permanent magnets.

The chosen structure must guarantee stiffness while giving minimal vertical deflection, compactness, and low cost.

3.2.1 Single Guide Rail Configuration

This configuration transfers the entire load and consequential moment along with the load through a single guide rail. While the structure is simplified, the high mechanical load on the guide, which has to resist both vertical forces and bending moments with least deflection, is a difficulty.

When pallet processing occurs, a vertical force $F_l = 500\ N$ acts on the carriage. As the point of application is offset from the guide rail by $b = 70\ mm$, it generates a moment about the rail:

$$M_A = F_l \,.\, b = 500\ N \times 0.07\ \text{m} = 35\ \text{N.m}$$

Where:

- $F_l = 500\ N$ is the vertical load from the processing station,
- $b = 70\ mm = 0.07\ m$ is the lateral offset from the guide rail to the point of load application.

The schematic diagram in figure 3.4 shows the applied forces and the resulting moment on the single guide rail. The picture defines a vertical load F_l acting on the pallet, at an offset of distance b, causing a moment, which this moment must be completely resisted by the guide rail structure.

For these mechanical demands, a high-stiffness guide such as THK HMG45 would be required. According to specifications by the manufacturer, however, this rail requires a minimum bending radius of 800 mm, which makes it unsuitable for the compact circular track layout used in Cosberg's system. Moreover, the calculations based on THK design tables show that this configuration can only support loads 350 N with acceptable deflection. Hence the single-rail configuration was not considered adequate for the 500 N load needed during processing [14].

Figure 3.4: Schematic of forces and moment acting on the single guide rail configuration.

3.2.2 Dual Guide Rail Configuration

In a dual-guide system, the load is symmetrically distributed between the two carriages on the parallel rails. The structure was hyperstatic because it had five constraint reactions, and during analysis, three equilibrium equations are needed; thus, two redundant reactions should be brought up: a horizontal force X_1 a and a torque X_2 at point C (Figure 3.5).

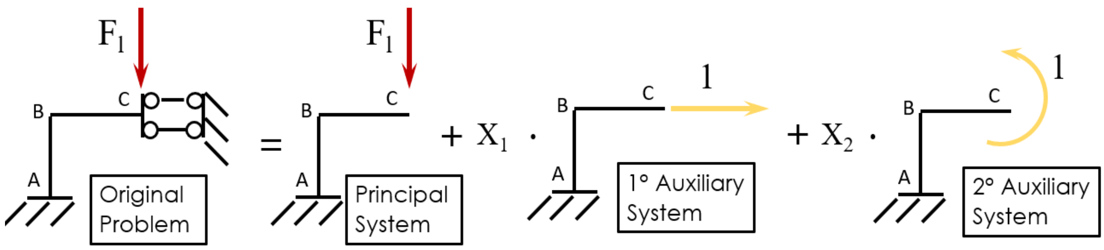


Figure 3.5: Schematic representation of the hyperstatic model used for analyzing the dual-guide rail configuration.

The implementation of the analysis was through method congruence and superposition that made use of Mohr's integrals to discuss the resulting displacement of the system when subjected to the action of unit loads.

The compatibility equations concerning the deformation of the system to the loads and the redundant reactions applied are:

$$\delta_1 = \delta_{1F} + X_1 . \delta_{11} + X_2 . \delta_{12}$$

$$\delta_2 = \delta_{2F} + X_1 . \delta_{21} + X_2 . \delta_{22}$$

Solving this system provided the values of hyperstatic reactions:

$$X_1 = -146.96\ N,\ X_2 = 182.37N$$

This solution facilitates precise prediction of support reactions thereby enabling the selection of a compact yet efficient guide system. The guide rail models selected were THK HMG15 (straight) and HMG15-R150 (curved), suitable to meet loads with reduced size and full compatibility with the circular conveyor layout.

After establishing the solution, support reactions were predicted accurately, leading to a compact and efficient guide system design. Selected guide rail models were THK HMG15 (straight) and HMG15-R 150 (curved), which can withstand loads with a small footprint and be integrated perfectly into the circular conveyor layout [4].

3.3 Carriage Structural Model

The Carriage acts as the interface between the guide rails and the magnetic mover. It must withstand the vertical force transferred from the processing station and the horizontal actuation force induced by the solenoids. In a dual guide arrangement, loads are symmetrically applied to minimize deformation and enhance stability.

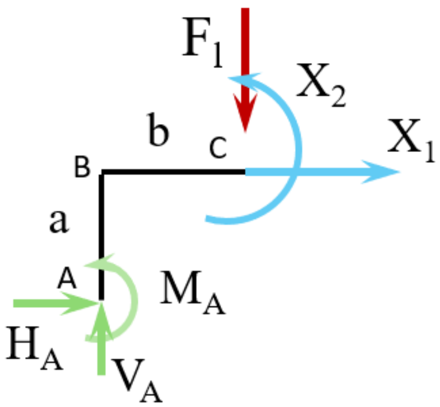


Figure 3.6: Free-body diagram of the L-shaped beam under applied force F_l. The structure consists of vertical and horizontal segments a and b, with support reactions at point A. Force F_l acts vertically at point C, creating internal moments and shear forces along paths X_1 and X_2.

In structural analysis, assuming the carriage behaves as a supported beam under combined loading, the following expressions were used to estimate internal forces:

$$\mathrm{M_A} = F_l \cdot \frac{b^2}{3a+6b}$$

$$\mathrm{V_A} = F_l$$

$$\mathrm{H_A} = F_l \cdot \frac{b^2}{a^2+2ab}$$

With $F_l = 250\ N$, $a = 64\ mm$, and $b = 65\ mm$

The results showed:

- Vertical reaction: $\mathrm{V_A} = 250\ N$
- Moment at support: $\mathrm{M_A} = 1.81\ N$
- Horizontal reaction: $\mathrm{H_A} = 85.07\ N$

3.4 Analytical Model of Solenoid

The analytical modeling of the electromagnetic force produced by the solenoids in the proposed linear synchronous actuator is presented in this section. The objectives of the study are the determination of the solenoid force required for the desired acceleration profile of the carriage and the subsequent use of this model in selecting a commercially viable solenoid.

Force Analysis and Motion Equation

To model the dynamics of the carriage (mover), all significant forces acting along a positive x-direction were considered. Among these forces are:

- F_{mag} Horizontal component of the magnetic force of the coils in the stator
- F_{Air} Air resistance force proportional to the pallet's speed
- F_{μ} Coulomb friction force
- $m.\ddot{x}$ Inertial force is associated with the carriage acceleration.

This equation represents a linear second-order differential equation with a constant forcing term:

$$F_0 = F_{mag} - \mu mg:$$

$$m.\ddot{x} + b.\dot{x} = F_0$$

The following shows in Figure 3.5 all the forces acting on the mover during linear motion. The forces are magnetic propulsion, frictional resistance, air drag, and the gravitational load.

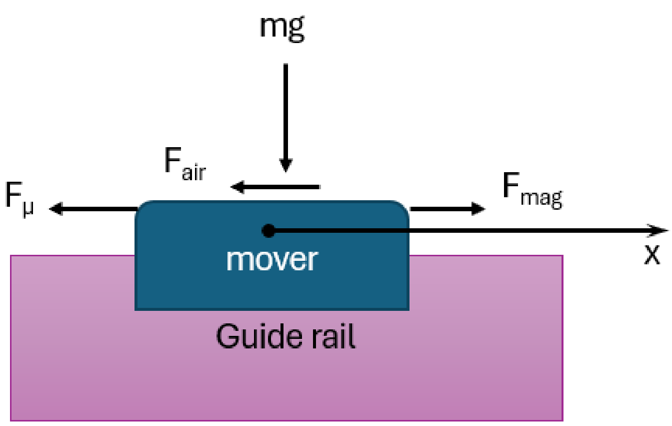


Figure 3.6: Free-body diagram of the mover during linear motion. The diagram shows the main forces acting on the carriage (mover) in the direction of motion. The magnetic force F_{mag}, created by the stator solenoids, pushes the carriage in forward motion, while the opposing components to this motion consist of the Coulomb friction force F_{μ}, in the guide and the carriage in addition to the air resistance force F_{Air}, proportional to velocity. The gravitational force mg, serves to load normal reaction and counteract frictional resistance. The forces assist in establishing the equation of motion and evaluation of the actuation force required.

Assuming the initial conditions for analytical solution:

- $x(0) = 0$
- $\dot{x}(0) = 0$

The complete solution for displacement over time is:

$$x(t) = \frac{F_0 \cdot m}{b^2} \cdot exp^{-\frac{b}{m}t} - \frac{F_0 \cdot m}{b^2} + \frac{F_0}{b} \cdot t$$

And the velocity as a function of time is:

$$\dot{x}(t) = \frac{F_0}{b}(1 - e^{-\frac{h}{m}t})$$

From this, we can isolate the magnetic force F_{mag}:

$$F_{mag} = \frac{b.\ \dot{x}(t)}{1 - exp^{-\frac{b}{m}t}} + \mu mg$$

Using the Cosberg's system requirements and physical assumptions:

- Target speed: $\dot{x}(t) = 0.5\ m/s$
- Time to reach target speed: $t = 0.2\ s$
- Friction coefficient: $\mu = 0.015$ (based on THK rail specs [4]
- Mass of carriage and load: $m = 2\ kg$
- Gravity: $g = 9.81\ m/s^2$
- Air resistance coefficient (from Stokes' Law):

$$b = (6\pi v r) = 3.44\ \times\ 10^{-5}\ Ns/m$$

Substituting these values into the equation for F_{mag}:

$$F_{mag} = \frac{3.44 \times\ 10^{-5} \times\ 0.5}{1 - exp^{-\frac{b3.44 \times\ 10^{-5}}{2} \times 0.2}} + 0.015\ \times 2 \times 9.81 = 5.3\ N$$

This is the minimum required horizontal force that the solenoid system must provide to meet performance targets.

For solenoid force estimation and safety margin, it is considered the solenoids generate a force in a vertical direction; thus, any horizontal component intended for propulsion must rely on magnetic coupling. Literature and experimental work indicate that the vertical magnetic force typically happens to be 5-6 times greater than the horizontal resultant for propulsion force, depending on geometry and alignment [4], [14].

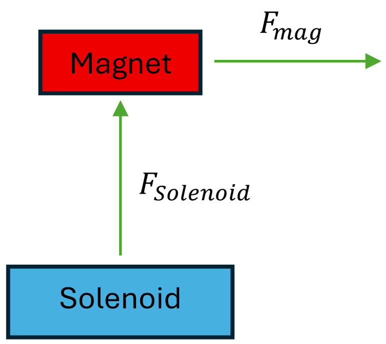


Figure 3.7: Electromagnetic force components in the solenoid–mover interaction. At the same time, the solenoid would create a magnetic attraction force $F_{Solenoid}$ that goes vertically downwards at the center of the coil. Some of this vertical force gets converted to a horizontal force component F_{mag} due to the orientation of the field and the actuator's design which moves the mover forward by that component. The transition from vertical force to horizontal force depends on magnetic geometry, field distribution, air gap, and typical ratios could be found from 5:1 to 6:1. Vertical direction.

Taking a conservative multiplied of 6:

$$F_{Solenoid} \approx 5 - 6 \times F_{mag}$$

$$F_{Solenoid} = 6 \times F_{mag} = 6 \times 5.3 \text{ N} = 31.8 \text{ N}$$

Factoring in losses from the air gap between the solenoid and the permanent magnets, a safety factor of 1.5 is applied: In practice:

$$F_{real,Solenoid} = 1.5 \times F_{Solenoid} = 1.5 \times 31.8 = 47.7 \text{ N}$$

This is the vertical force each solenoid must provide.

In result, this analytical model is the basis for the selection of solenoids and motion control design. The required magnetic force was determined accurately by solving the dynamic behavior of the carriage using Newtonian mechanics, including frictional and aerodynamic effects. Final solenoid selection will depend on its achievement or surpassing the real vertical force threshold of 47.7 N under working conditions.

4 Mechatronic Design

4.1 Description of the Linear Electric Machine Design (CAD)

4.1.1 Full Design Overview – Loop Configuration

The linear magnetic actuator proposed in this work is designed as a modular transport system based on a closed-loop trajectory. This configuration consists of two parallel straight segments connected at both ends by curved modules, forming a continuous, flexible transport path. Such loop configurations are commonly adopted in smart manufacturing environments to maximize space utilization while allowing uninterrupted carrier movement across all process stations [21].

The loop-based design enables high system modularity, facilitating easy reconfiguration for different production layouts. It allows the simultaneous presence of multiple carriers, with each carrier independently controlled, thus increasing the overall system throughput and enabling workstation-specific operations. The proposed loop has a total length of approximately 9 meters, combining two straight sections and two semi-circular curves with an inner radius optimized to accommodate smooth carrier transitions.

The entire mechanical structure was modeled using Creo Parametric CAD software. Special consideration was given to mechanical tolerances, carrier alignment, and space constraints, ensuring compatibility with industrial assembly line standards [20].

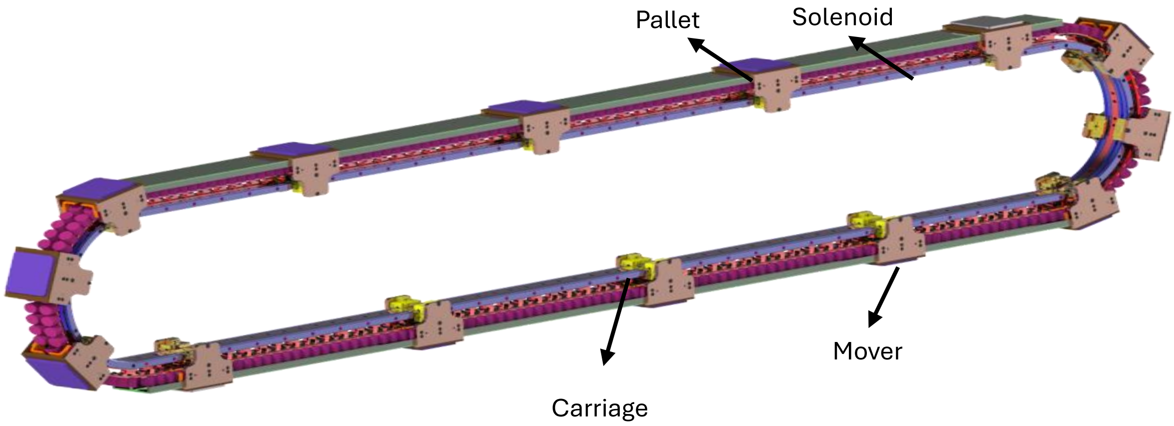


Figure 4. 1: Full Design Overview for Loop Configuration, consisting of straight and curved modules.

4.1.2 Straight Module Design

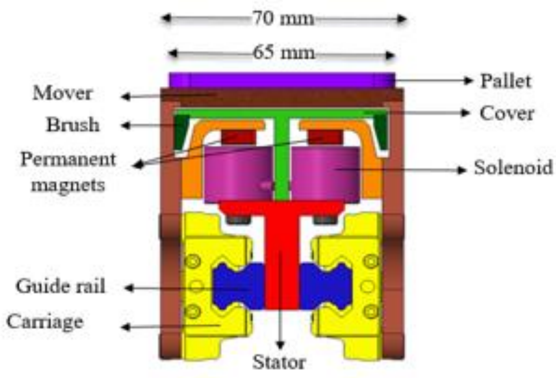
The straight module represents the core functional segment of the LEM system. Each straight section incorporates:

- A structure base providing rigidity and alignment,
- Embedded solenoid modules positioned along the length of the guide,
- Two linear guide rails to constrain the carrier motion,
- A position feedback system based on a rotary encoder coupled to the carrier.

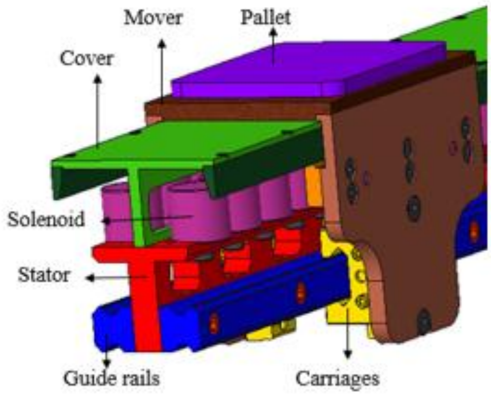
The solenoids are mounted with a positional tolerance of ±0.1 mm to ensure consistent magnetic interaction with the embedded permanent magnets on the carrier. This precision minimizes magnetic field fluctuations and ensures reliable propulsion.

A key feature of the straight module is its modularity. The solenoid arrays, wiring channels, and mechanical support frames are designed for quick assembly and replacement, allowing scalability and ease of maintenance. The CAD design was validated through structural simulations, confirming acceptable deformation under static loading and ensuring the required alignment precision.

Figure 4.2 illustrates both the front and isometric views of the straight module, highlighting its structural components and modular design.



(a)



(b)

Figure 4.2: Front view (a) and isometric view (b) of the straight module. The illustration shows the structural base (stator), embedded solenoids, linear guide rails, mover, pallet, carriages, cover, brushes, and permanent magnets. The modular design allows for easy assembly, replacement, and precise alignment.

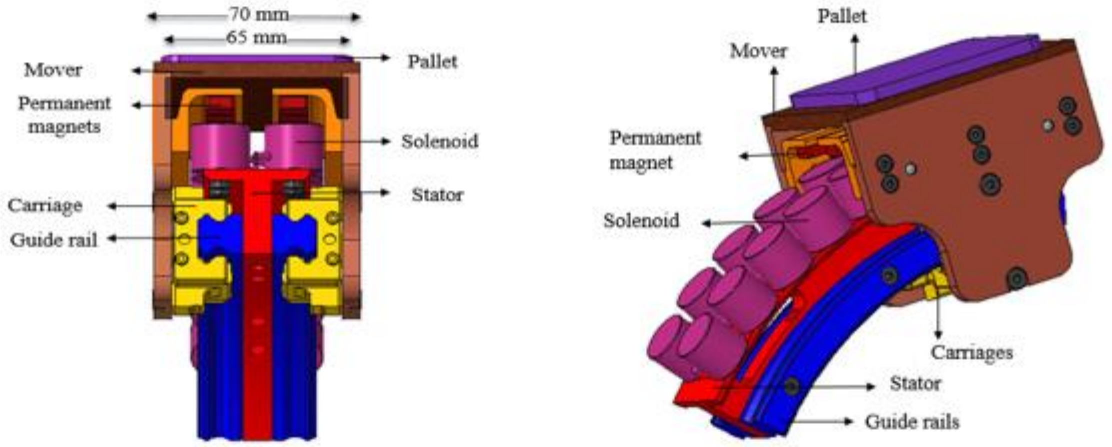
4.1.3 Curved Module Design – Future Developments

The curved module is a critical component required to complete the closed-loop trajectory. Although this element has not yet been physically implemented, its conceptual design and CAD development were carried out as part of this thesis. The curved segments were designed to:

- Maintain constant air gap and magnetic alignment between the stator and carrier along the curve,
- Accommodate passive or active guidance systems to ensure smooth transitions,
- Minimize curvature-induced mechanical stress and misalignment.

Preliminary analyses considered standard curvature constraints for similar transport systems, suggesting an inner radius of at least 75 mm to avoid excessive mechanical stress and maintain carrier stability [19]. While future physical realization and testing of the curved module remain beyond the current project scope, the developed design lays the groundwork for completing the full-loop system in subsequent development stages.

Figure 4.3 illustrates both the front and isometric views of the curved module, highlighting its structural components and modular design.



(a) (b)

Figure 4.3: Front view (a) and isometric view (b) of the curved module. The illustration shows the structural base (stator), embedded solenoids, curved guide rails, mover, pallet, carriages, and permanent magnets. The modular design allows for easy assembly, replacement, and precise alignment.

4.2 Linear magnetic actuated conveyor components

The linear magnetic actuated conveyor proposed in this work is based on a modular, CAD-driven design tailored for automated transport systems used in industrial assembly lines. As described in 4.1.1, the CAD models were developed using Creo Parametric, a well-known computer-aided design software that supports parametric feature-based modeling, suitable for iterative electromechanical systems design [16].

The geometry of the entire system consists of two straight segments, almost 9 meters long, and connected at their end by semi-circular curved sections to complete a closed-loop layout. Such geometry was chosen in order to optimally cover the area of the floor, thereby allowing carriers to operate continually over each process station. The layout is typical for modern linear transfer systems and combines throughput with ease of access to the units for servicing [17].

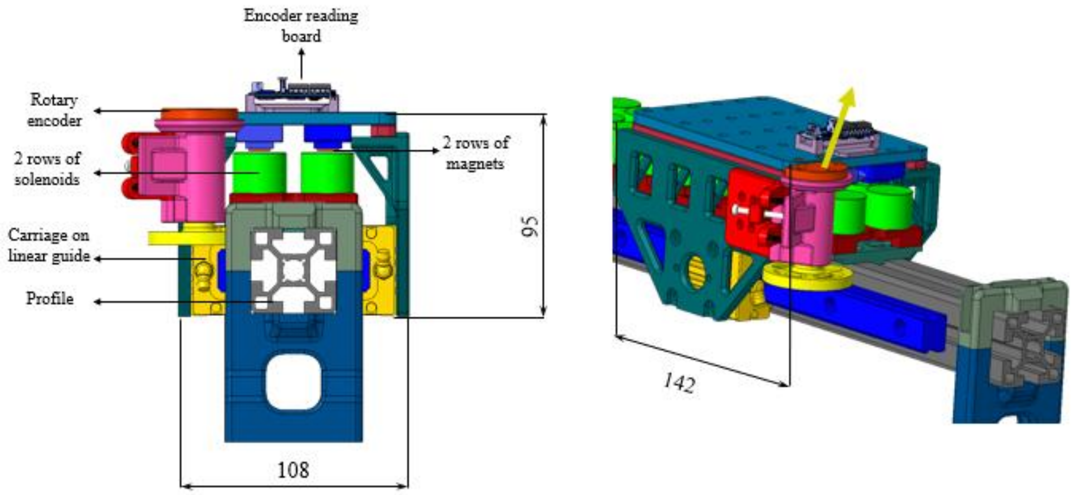
Each linear segment integrates a stator assembly composed of sequentially placed solenoid modules, aligned with a tolerance of ±0.1 mm to ensure consistent magnetic coupling with the movers (also called carriers). CAD modeling emphasized modularity, which allows these solenoids to be arranged and connected via cable channels embedded within baseplates, a design principle aligned with modular mechatronic platforms used in smart manufacturing [18].

To guarantee that the curved segments can carry magnetic propulsion without deterioration in performance, they should have had their inner and outer radii optimized based on the minimum turning radius for passive guidance rollers and maximum spacing between adjacent stators. According to standard curvature constraints defined, for example, in linear motion systems (e.g., THK HMG series), for tracks of 65-mm width, the recommended minimum inner radius is approximately 75 mm [19].

The actuator is a key component in the CAD modeling process; it consists of some magnets embedded in two non-magnetic frames, which are optimized by the underlying solenoids. This arrangement is designed to show that the configuration of the magnets increases the longitudinal thrust by improving the component of the magnetic force in the direction of motion, providing smooth and uniform motion [22].

In the CAD vertical stack-up, solenoids are mounted on the structure of the base frame, while the guide rails lie just below this. The guide rails bear the carriages, which attach to the movers to effect precise linear movement. The mechanical to be dimensioned are dimensioned on the basis of the ISO standards pertaining to ISO 2768-m and also with reference to very widely adopted general tolerances in the mechanical design of electromechanical systems [20].

Each module-linear and curved was designed separately in CAD and then assembled using constraint-based mating operations. This modular approach to CAD enables fast design iterations and is regarded as the best practice for the development of reconfigurable manufacturing systems [21].



(a) (b)

Figure 4.4: CAD Model of Linear Magnetic Actuated Conveyor. (a) Key components labeled: rotary encoder, wheel, dual-row magnets, profile, solenoids, and linear guide carriage. (b) Assembled profile showing integration of parts for linear motion.

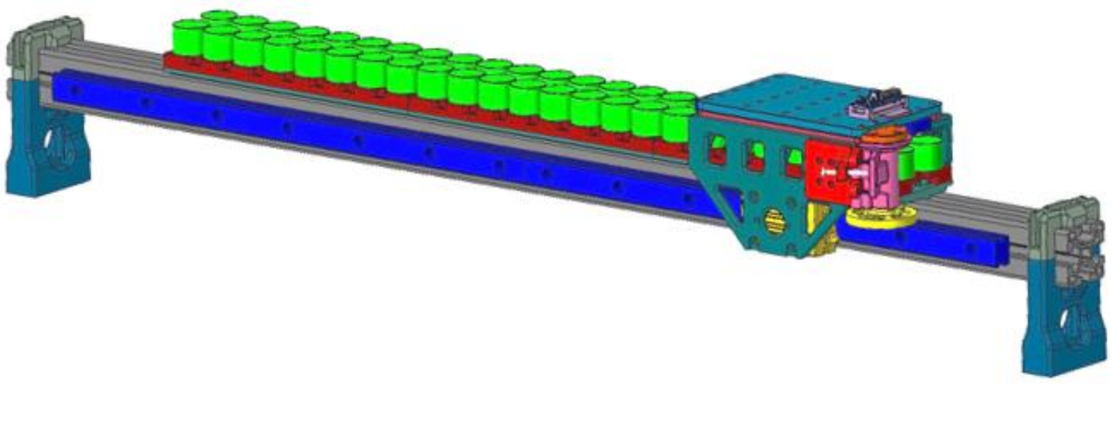


Figure 4.5: Assembled Machine Unit. System integrating the linear magnetic actuated conveyor (Fig. 4.4)

4.2.1 Component Selection

In the design of a linear synchronous machine (LSM), component selection is a critical process. It directly influences the performance, cost, reliability, and scalability of the system. Each element—from actuators to sensors and mechanical parts—must be carefully chosen to ensure integration, compatibility, and optimal functionality. Key criteria include force density, thermal performance, response time, energy efficiency, and mechanical robustness, especially in high-duty cycle industrial applications such as smart conveyors and modular transport systems [17].

The linear machine uses a mover composed of permanent magnets and a stator equipped with solenoid windings. The number and size of magnets directly impact the electromagnetic force generated. The solenoid structure, with direct current flow, ensures the movement of the carrier by generating a traveling magnetic field. To optimize force and efficiency, the system is designed with each mover containing eight permanent magnets. Each stator segment includes two rows with a total of eighteen evenly spaced solenoid coils to ensure precise positioning and minimize cogging effects [22].

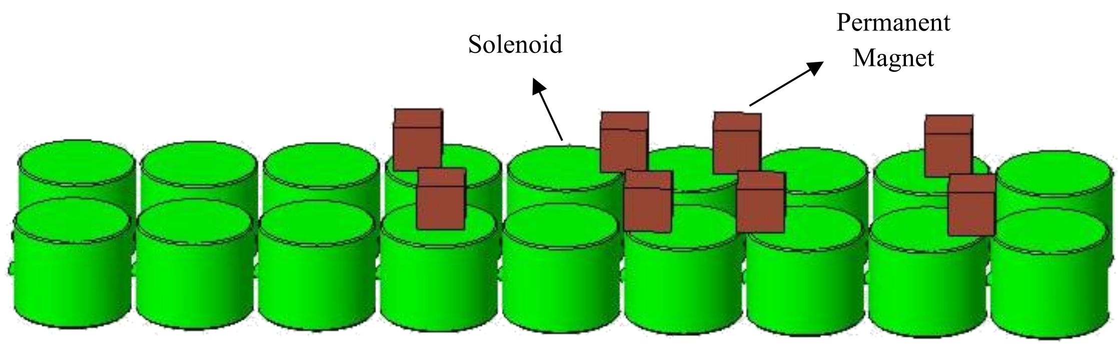


Figure 4.6: Permanent Magnet and Solenoid Configuration (CAD design)

Precise sensing is the key feedback and control element in linear systems. Position sensors, such as optical encoders and Hall-effect sensors, are commonly used. While optical encoders provide sub-micron resolution, they are best suited to applications requiring tight positional control. On the other hand, Hall-effect sensors are employed in the interest of cost-effective commutation feedback. Additionally, RFID-based identification can be utilized in systems requiring wireless, cable-free tracking of individual movers [23].

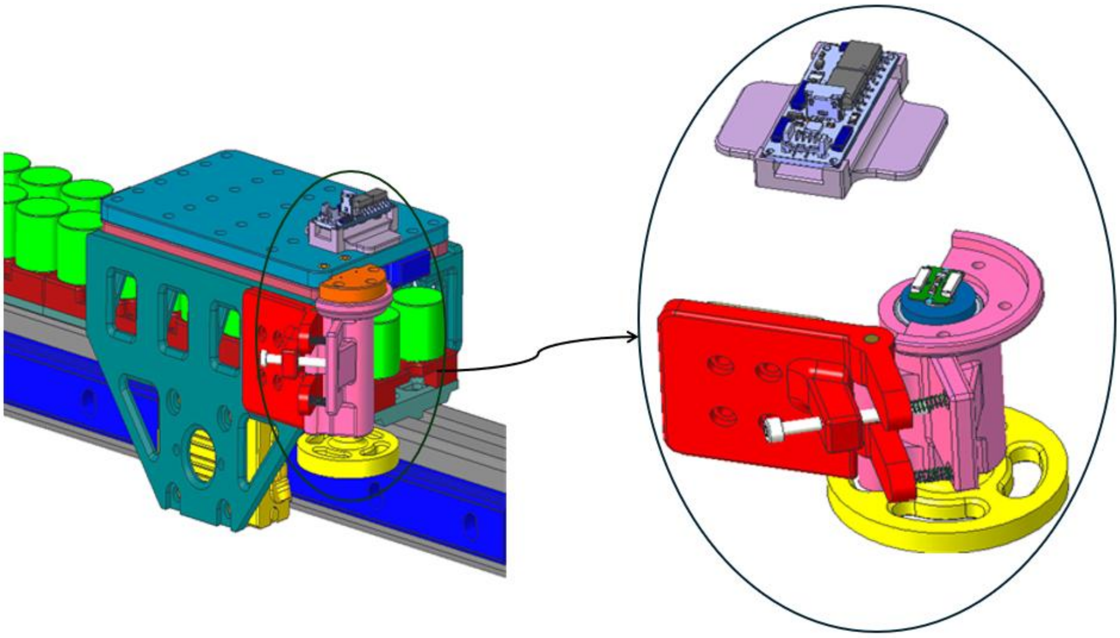


Figure 4.7: Rotary encoder for feedback and control in linear systems (CAD design). The mechanical set design to convert linear motion to rotary.

The control of LSMs requires high current switching at fast intervals by using advanced driver circuits. The Pulse Width Modulation controllers modulate the voltage supplied to the solenoid coils so that the speed and direction of the carriers can be controlled. Modern systems are DSP or FPGA-based for real-time control, PID tuning, and communication with higher-level systems such as PLCs or SCADA [24].

Linear guideways, aluminum frames, and carrier arms must be lightweight yet stiff to avoid deformation under dynamic loads. Aluminum alloy 6061-T6 is commonly used for the structure due to its balance between strength, machinability, and corrosion resistance. For linear motion components, recirculating ball-type linear guides offer precision and low friction over extended duty cycles [19].

Heat buildup in actuators and drivers can reduce efficiency and lead to premature component failure. So, passive (heatsinks) or active (air or water cooling) methods are employed based on duty cycles. For high-speed, high-thrust applications, liquid cooling of stator cores may be required to dissipate Joule and iron losses efficiently [25].

4.2.2 Guide Design

The guide system plays a critical role by ensuring that carriers in LSMs are moved smoothly, accurately, and reliably. It should constrain the motion to one or more degrees of freedom with low-friction and high-stiffness characteristics. An ideal guide should minimize backlash, resist vibrations, and permit minimum wear at high speeds and loads [26].

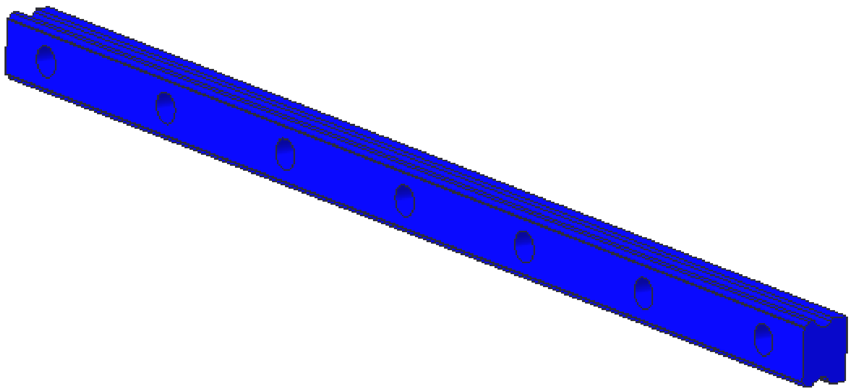


Figure 4.8: Linear guide THK HMG 15

The design of any system should consider trade-offs among a number of mechanical and dynamic criteria. Among these criteria are: mass of the moving carrier; operational velocities; applied loads; accurate definitions of positions; frictional dissipation; and spatial configurations. In an industrial setting, linear guides should also tolerate environmental factors: dust, temperature fluctuations, and vibrational effects. For high load capacities and low friction, linear guides are best designed based on recirculating ball bearings [27].

To include many types of linear guide mechanisms that are:

- Recirculating Ball Bearing Guides: These are the best for their stiffness and are often seen in CNC and automation.
- Roller guides: Have a higher load carrying capacity, along with very good damping, but are higher in cost.
- Air Bearings: These are good in ultra-precision systems but can work with a lot of dust or in an industrial environment.
- Magnetic Guides: This is where the idea of contactless movement comes into play, but it needs very accurate control systems.

Recirculating ball bearing linear guides accommodate the LSM system on account of a combination of merits: precision, strength, and availability [28].

Selecting the rail and carriage components from their specifications for force and speed is possible. For a lightweight vehicle under moderate loading, a single compact LM guide in the low-profile format with a C-type rail configuration (e.g., THK or Hiwin models) can be suitable. The coefficient of friction (~0.003-0.005) is quite effective as far as improving energy efficiency and thermal buildup is concerned [29].

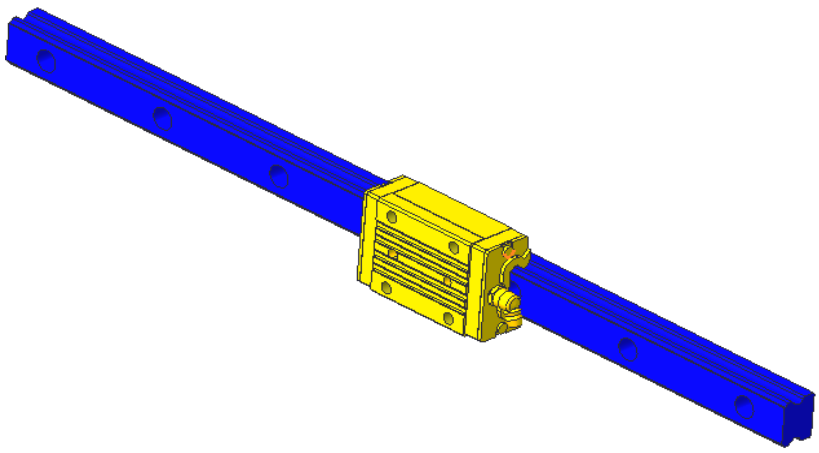


Figure 4.9: Carriage THK 220L

A critical aspect of guide design is precise alignment during installation. Misalignment can lead to uneven wear, increased friction, and early failure. So, precision-machined baseplates and alignment jigs are used during assembly. Parallelism and flatness tolerances must be maintained within ±10 μm over 1 m for high-precision motion applications [30].

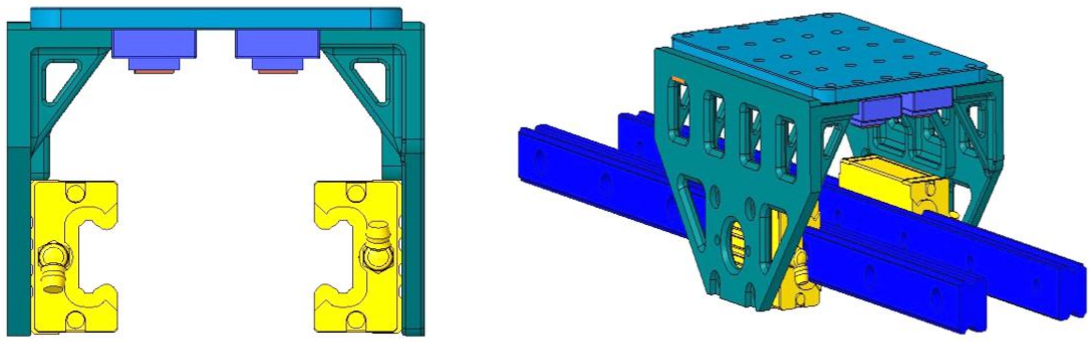
The rail and carriage units are usually made from hardened stainless steel or high-carbon steel that is surface-treated (nitriding, black oxide) to enhance corrosion resistance and durability. Carriages may also include polymer scrapers or end caps to prevent debris ingress in industrial environments. Proper lubrication (manual or automatic) is essential to extend the life span and maintain consistent motion performance [31].

During high-speed operations, mechanical noise and vibrations may arise from the linear guides. Due to the effect of vibrations on the positional accuracy and comfort to the user, this ought to be considered. Dynamic simulations and finite element analysis (FEA) assess modal frequencies and address resonance issues. Damping materials can be added, or guides may be selected with internal dampers to significantly lower the vibrational response [32].

Finally, the guide must be integrated with the stator base and mechanical carrier. This involves designing mounting slots and ensuring that the guide rail does not interfere with the magnetic circuit or airflow for cooling. The carrier baseplate is aligned to ride smoothly with minimal torque, especially when curving sections or Y-junctions are included in the machine layout. Valid integration supports modularity and ease of maintenance in the final system [33].

4.2.3 Carrier Design

The carrier, which is also called mover or shuttle, is the key element in linear synchronous motors (LSMs) to ensure force and motion transmission between the electromagnetic drive system and the payloads to be moved. The design of such component is important both for mechanical robustness and for motion precision, dynamic responsiveness, and compatibility with other modules such as sensors or guides.



(a) (b)

Figure 4.10: Front view (a), and isometric view (b) of the carrier set designed.

The carrier should meet many functional requirements. The carrier must support the payload without deformation and embed any internal electronics, while minimizing mass to reduce inertial effects. Furthermore, it must be geometrically relevant to the guideway and the electromagnetic interaction space (typically an air gap over the stator coil array).

Mechanical stiffness and weight-to-strength ratio are thus key trade-offs. An excessive amount of mass increases the energy an operation requires and hinders dynamic response, while a lack of stiffness can create unwanted vibrations, excessive misalignments, and control instability when traveling at high speeds [29].

The various parameters motivating the selection of the material for the carriers are mechanical strength, low density, thermal stability, and electromagnetic neutrality. Among the lightweight metal options, aluminum alloys are often favored because they offer a high stiffness-to-weight ratio and are easy to machine. On the other hand, fiber-reinforced polymers, such as carbon fiber composites, would provide a greater advantage in terms of reduced weight but could complicate manufacturing and incur higher costs.

Typically, the carrier comprises:

- A base frame, usually CNC machined.
- Mounting surfaces for the sensor or workpieces.
- Interfaces to bearing blocks or rollers to reduce friction along the linear guides themselves.

In LEMs where the mover has permanent magnets, passive and active coils on the stator should be used; the material must be non-magnetic to avoid eddy currents or flux distortion that can lead to energy loss and uneven force profiles [34].

In the chosen LEM topology, permanent magnets are integrated into the carrier. These magnets are responsible for interacting with the traveling magnetic field generated by the stator coils. They produce Lorentz forces that propel the carrier forward.

To ensure continuous thrust generation, the magnets must align perfectly along the stator axis with suitable spacing to ensure a constant net force.

The transmission of electromagnetic thrust to the mechanical load is direct. but must account for:

- Vibration damping
- Thermal expansion
- Shock resistance in industrial environments.

Simulation studies and experimental evaluations confirm that optimizing the spacing and orientation of the magnets significantly improves dynamic stability and force linearity [29].

The carrier must ride along a precision guide rail to maintain trajectory and minimize undesired lateral motion. For this reason, co-design with the guide system is essential. Misalignments or uneven wear can result in degraded performance or mechanical interference.

The carrier's base is typically fitted with:

- Recirculating ball bearing blocks (e.g., Hiwin HG series),
- V-groove rollers or linear bushings, depending on speed and load requirements.

For high-speed applications, the contact surfaces must be finely ground, and preload must be carefully tuned to avoid backlash without over-constraining motion [34].

To monitor the position of the mover in the linear electric machine system, a non-contact magnetic rotary position sensor (model JST04) was selected. Even though the motion of this actuator is inherently linear, a custom mechanical conversion system is designed to convert this linear motion into rotary motion. This system allows for the use of a rotary encoder for precise feedback.

This mechanism, illustrated in the CAD view (Figure 4. 4: rotary encoder for feedback and control in linear systems (CAD design)), consists of a mechanical set that links to the moving carriage. The rotary sensor is actuated through a lever or linkage system that rotates proportionally to the linear displacement, As the mover travels along the guide, the encoder senses the rotation of a magnetic disc (or shaft), enabling the system to calculate the exact position of the mover.

The benefits that this technique offers:

- High reliability due to the non-contact magnetic type sensor, reducing wear and noise in the signal.
- Compact integration-no long cables along the track.
- Compatible with Arduino-based control boards through a level converter circuit for proper voltage adaptation and signal conditioning.

The selected setup does not involve complicated track-based wiring or wireless data transmission onto each carrier, thus minimizing maintenance and augmenting robustness for industrial environments. It also supports modular sensing whereby each unit can be individually calibrated and replaced without inducing effects on the others [34].

During fabrications, tolerances must be maintained tightly a controlled to prevent misalignments of magnet and coil. For the carrier base, CNC machining is usually used with insert mounts for the magnets, bearings, and sensor modules. To have modularity, there are many often threaded inserts or dovetail grooves for varying tooling or payloads.

Assembly procedures preferably do not demagnetize or misalign the magnetic elements. Special jigs are usually made integrated into the design so that correct positioning before bonding or clamping the magnets is possible, or 3D-printed with practical awareness and application [34].

4.2.4 Design Considerations

The design of linear synchronous motors (LSMs) in industrial automation settings involves tightly integrating electrical, mechanical, thermal, and control subsystems. A failure to address interactions between these domains during the design phase can lead to inefficiencies, instability, or early wear. So, a system-level design approach is necessary, where mechanical layout, electromagnetic design, power management, sensing, and motion control are optimized in parallel [35].

To make possible an accurate motion control in permanent magnet linear motors (PMLMs), it is a requisite that the linearity in the force profile has been achieved. The necessary measures include an optimum number of stator windings per unit length, which will be associated with the magnetic spacings and end effects taken into consideration on the start and stop of coils. Asymmetric field distribution can result in cogging, harmonic ripples, and reduced dynamic accuracy. To mitigate this, the design includes:

- Array arrangements for flux focusing,
- Slotless stator design to reduce cogging,
- FEM-based simulations to fine-tune coil currents and pole pitch.

Magnetic shielding and correct grounding practices are also critical to avoid electromagnetic interference (EMI), especially when integrating wireless sensors or control systems [36].

Reduced machine performance and shorter life span occur because joule losses in the windings cause heat, eddy currents, and magnetic hysteresis in the stator core. For this reason, thermal management is an essential part of LSM design. Strategies include:

- Using laminated silicon steel or ferrite cores to minimize core loss,
- Selecting low-resistance copper windings with large cross-sections,

Temperature sensors can be embedded in the stator coils to detect overheating and feed signals back to the control system for protective shutdown or throttling [37].

LSMs are leaning on precision guide systems and direct drive mechanisms, meaning that they are susceptible to mechanical friction, vibration, and resonance effects. If not controlled, these effects can create noise, wear, or reduce positioning accuracy. To manage these issues:

- Lightweight carrier designs are used to lower inertia,
- Preloaded recirculating ball guides minimize backlash,
- Damped mountings and compliant connections act to absorb mechanical shock.

Finite Element Analysis (FEA) will be used to analyze structural modes and locate resonant frequencies. These frequencies can be shifted out of the operating range through adjustment of material, mass, or damping strategies [36].

An important goal in industrial system design is scalability.

The architecture must allow for:

- Adding or removing drive modules without redesigning the entire system,
- Supporting modular guide tracks (straight, curved, and junction segments),
- Maintaining signal integrity across expanding control buses.

Achieving this in the design is accomplished through plug-and-play electromagnetic modules, modular guide segments, and separately controlled carriers. This is the ideal condition for modularity in reconfigurable manufacturing systems (RMS), quick adaptation to changing production requirements [35].

Considering that LSM systems would often be operating in factory-like settings, the design must ensure maintainability, robustness, and safety. The aspects of a maintenance-friendly design include:

- Snap-in solenoids and carriers for simpler replacement,
- Diagnostic LEDs or sensor feedback for localized fault finding,
- An emergency shutdown feature that is tied to overheating or overspeed sensors.

Magnetic shielding, no exposed moving parts, and fail-safe logic in the control system in case of communication loss and electrical failure are all aspects included under safety considerations [37].

4.3 Control Architecture

4.3.1 Positioning Control System Development

Linear synchronous motors' (LSMs) positioning control systems should have a very high precision and reliability, as is the case, for instance, with Cosberg smart assembly lines, where stop and release cycles directly impact production cadence, and hence influence productivity. This thesis is based on a system that integrates hardware and software components for feedback in real time, enabling low-latency actuation and scalable integration with industrial controllers [34].

4.3.2 Control Architecture

The core of the control system is an Arduino-compatible microcontroller platform fitted with a logic-level converter for signal interfacing purposes. This ensures seamless communication between the rotary position sensor (JST04 magnetic encoder) with digital control logic without any voltage misalignment. The microcontroller runs a real-time loop that:

- Reads rotary position input from the mechanical encoder (conversion from linear motion),
- Calculates the current location of the mover,
- Raises the correct control signals to fire the appropriate solenoids in sequence [34].

This loop operates with a frequency of approximately 1 kHz, which is appropriate for applications where the mover appears to travel at speed under 1 m/s and position resolution requirements are in the sub-millimeter range [38].

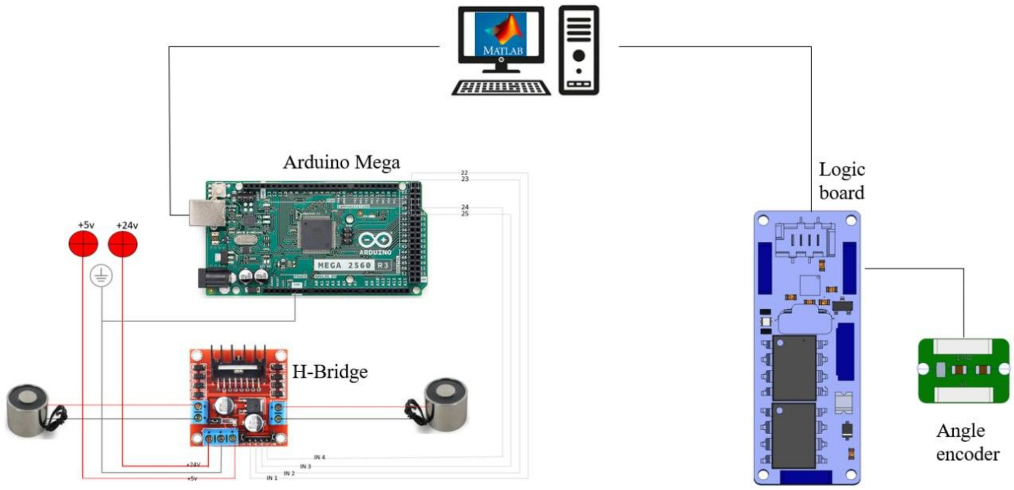


Figure 4.11: Control system layout including Arduino, H-Bridge driver, connected solenoids, and Sensor setup.

4.3.3 Linear-to-Rotary Feedback Mechanism

Custom-designed mechanical converters convert the linear displacement of a mover into angular rotation for adapting low-priced rotary encoders for a linear track. This approach eases the sensing hardware while maintaining high resolution through careful calibration. Such an approach is also cost-effective and fairly accurate for transport and positioning systems not requiring nanometer-level precision [34].

4.3.4 Actuation and Signal Timing

Solenoids embedded along the track receive pulse-width modulated (PWM) signals from the controller based on the decoded position data. Each solenoid is energized for a duration that ensures the mover advances incrementally in synchrony with the magnetic force generated. Delay compensation and signal synchronization are programmed into the firmware to ensure smooth motion transitions and to avoid overshoot or oscillation [38].

PID (Proportional–Integral–Derivative) tuning algorithms work to maintain speed and acceleration for the movers and, thus, increase positioning accuracy. These algorithms were tested and validated based on simulation tools such as Proteus and actual real-time data acquisition from the physical prototype [34].

4.3.5 Future Integration Potential

The following future upgrade options are possible since the design is modular and scalable:

- Integration of industrial PLCs via Modbus or CAN bus protocols.
- More advanced PUI for system diagnostics and monitoring.
- AI-based algorithms for episode prediction of trajectories related to predictive maintenance and optimization [38].

And this way, the structure gradually fits into the future standards of Industry 4.0 - where data-driven control loops and modular smart systems provide flexible and autonomous approaches in a smart setup for manufacturing [38].

4.4 Conclusion

The design and control architecture of the linear magnetic actuator, consisting of a modular stator, a permanent magnet mover, and a real-time feedback system, was presented in this chapter. The controller uses encoder data and PWM outputs to drive the solenoids with excellent accuracy.

A low-cost linear-to-rotary sensing and PID-based timing control action were utilized for smooth motion and accurate positioning. The design conforms to the fundamental principles of linear electric machines and is aimed at their future integration with industrial systems [4].

The next chapter will focus on the experimental validation of the system through prototype testing and performance analysis.

5 Experimental Validation

This chapter present the experimental procedures and their results to corroborate the findings of theory and simulation earlier presented in the other chapters. The experimental validation is done on three levels: (1) Magnet-solenoid interaction characterization, and (2) mockup system. Within these stages, there are specific experimental setups, methodologies by which the experiments were run, and various aspects of performance evaluations.

5.1 Magnet-solenoid interaction characterization

The interactional behavior between a permanent magnet and an energized solenoid is fundamental to the operational principle of linear magnetic actuators as developed in this thesis. The exact modeling and experimental validation of this interaction remain crucial in assessing force generation characteristics, contributing to solenoid design, and establishing system reliability in high-speed automation environments. The experimental setup and procedures followed to characterize the attraction and repulsion forces will be presented in this section, followed by a comparison between theoretical predictions and real-life measurements.

5.1.1 Experimental Setup and Procedures

A proper test bench was constructed to characterize the axial magnetic interaction forces. The test bench is representative of the essential functionality of a linear actuator system, where the solenoid–magnet pair is decoupled from the rest of the system to facilitate clarity, control, and repeatability in the measurements taken.

A permanent neodymium magnet (Grade N52, size: 10 × 10 × 10 mm) was mounted on a non-magnetic linear carriage with the guidance of high-precision linear bearings. This configuration ensured accurate alignment of the central axes of the solenoid and arrangement. The net horizontal and vertical interaction forces were sensed behind the magnet by an ATI Mini45-E force/torque sensor, which has a resolution of 0.012 N.

The model of the solenoid used was a commercial ITS-MS-2520-24VDC, having a nominal axial holding force of 60 N at 24 V, threaded by 25 mm outer diameter and 20 mm axial stroke. The solenoid was directly mounted to a fixture that enabled manipulating its axial air gap, which was set to be 0.3 mm during the conducted trials—typical for small-scaled linear actuators [3][4].

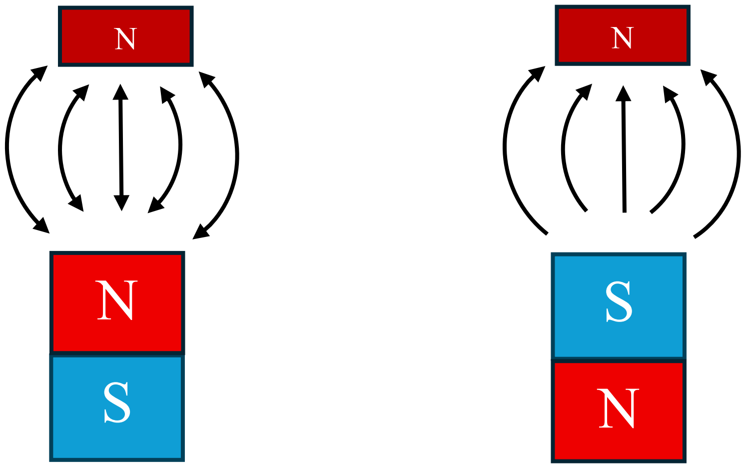


Figure 5.1: A basic schematic of the interaction between solenoid and permanent magnet's poles – Solenoid on bottom, permanent magnet on top.

The solenoid was energized by a programmable DC power supply (EA-PS-2042-10B, 0-42 V, 0-6 A). Voltages of -24 V, -12 V, 0 V, +12 V, and +24 V were applied one after the other, keeping the current constant at 3 A. The three actuation states were thus established:

- De-energized (0 V): Passive magnet–solenoid interaction
- Attraction (+12 V, +24 V): Enhanced pull toward the solenoid
- Repulsion (−12 V, −24 V): Magnetic field reversal to repel the magnet

lateral displacements of the magnet were applied at each voltage in increments of 0.5 mm over a total of 20 mm. The average horizontal force was recorded and averaged through three iterations for statistical purposes.

Data acquisition and process analysis were done with a MATLAB-based interface to allow real-time logging, filtering, and force-displacement plot generation. The test protocol is considered a best practice in respect to the characterization of electromechanical systems [1], [2].

5.1.2 Data Collection and Results

This section presents the experimental data and analysis arising from the characterization of the interaction between a solenoid and a neodymium permanent magnet under controlled conditions. The experiment aims to verify theoretical predictions on the generation of magnetic force and provide empirical knowledge for the optimization of the solenoid-magnet arrangement in the Linear Magnetic Actuated Conveyor.

The primary aim of the whole experimental campaign was to quantify the magnetic forces set up between a commercial solenoid actuator and a cubic neodymium permanent magnet (grade N35) in several operational modes and spatial configurations. The results serve two pivotal roles: first to validate the analytical models that were developed before, and second to inform the design of an effective actuator to satisfy Cosberg's dynamic requirements for high-speed and accurate positioning.

The experimental arrangement was carefully molded to afford exact measurement of the horizontal force exerted between a linear solenoid and a permanent magnet under pre-arranged conditions. The force was measured using an ATI Mini45 Force/Torque Sensor in that it was selected to have high resolution and to ascertain accuracy in the measurement of vector components of force. The solenoid utilized in this study is the ITS-MS-2520-24VDC model whose nominal axial force at 24 V is 60 N according to the manufacturer.

A neodymium permanent magnet of a cubic form measuring 10 mm × 10 mm × 10 mm served as the magnetic source. The magnetization took place through the thickness of the magnet, which has the North-South pole orientation perpendicular to both square faces.

Both the solenoid and the magnet were fitted in customized 3D printed holders which were made of non-magnetic synthetic polymer ABS for mechanical stability. These fixtures guaranteed an accurate alignment during measurements while keeping the distances consistent in all tests.

A steady air gap of 0.3 mm was maintained between the solenoid casing and the magnet surface. This figure fitted well within practical minimum gaps expected in the final prototype while maximizing magnetic interaction and avoiding physical contact.

The solenoids received standard power supply of 12 V and 24 V, both in positive and negative polarities to deliver regulated DC power supplying a constant 12 V and 24 V for evaluation of different modes of their operations. The experiment was carried out under three main modes of operation:

First, the de-energized mode, OFF in which the solenoid remained unpowered and hence the evaluation of passive magnetic attraction due to the ferromagnetic casing.

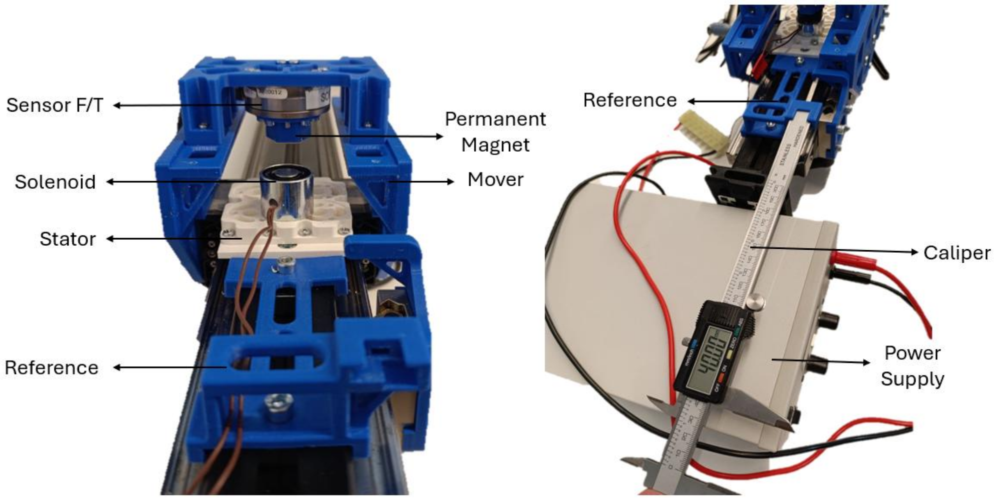
Second was the attraction mode where the solenoid was energized at +12 V and +24 V, these voltages represent reduced and full excitation conditions respectively.

Third, the repulsion mode was tested with −12 V and −24 V polarity by reversing the current direction to repel the magnet from the unusual polarity conversion of the magnetic field.

This completely and reproducibly designed setup forms the basis for the accurate characterization of the magnet-solenoid interaction and also describes its utility for the industrial motion systems.

Force measurements were made for each of the chosen displacement values in the three operating modes described above, namely, de-energized (OFF), attraction, and repulsion. By this way, it has been possible systematically to investigate the dependence of the horizontal magnetic force on relative position in the experimental arrangement between the solenoid and the permanent magnet. In particular, this experiment was aimed at observing how the force magnitude depended on axial misalignment. Then, the performance of the two modes, attraction and repulsion, was compared; and finally, the impact of supply voltage on the entire force generation was quantified.

In addition, the measurements could say a lot about that system under conditions of absence of actual excitation and thereby brought to light existence and extent of parasitic forces due to the ferromagnetic construction of the solenoid. For accuracy and reproducibility, each of the measurements was performed several times at each of the different displacement points. Average values were subsequently used in the analysis to eliminate and minimize noise and variably in the data.



(a) (b)

Figure 5.2: (a) Physical setup with ATI Mini45 sensor, (b) Method of using caliper by reference

5.1.3 Experimental Results

This section presents and interprets the experimental data obtained from the characterization of the magnetic force generated between a commercial solenoid actuator and a neodymium permanent magnet under different voltage excitation modes. The experiment was a check on theoretical expectations and a test of any practical feasibility in the context of the Linear Magnetic Actuated Conveyor prototype.

5.1.4 Experimental Force Curves

Figure 5.3 depicts the measured horizontal force F_x as a function of the lateral displacement δ between the solenoid and the permanent magnet, under five different voltage levels, in order to facilitate an extensive range of force interactions:

- +24 V (Full Attraction)
- +12 V (Reduced Attraction)
- 0 V (De-energized / Passive interaction)
- −12 V (Weak Repulsion)
- −24 V (Full Repulsion)

The lateral displacement valued between 0 mm to 20 mm in 0.5 mm. A constant air gap of 0.3 mm was maintained for all trials to have uniform experimental conditions.

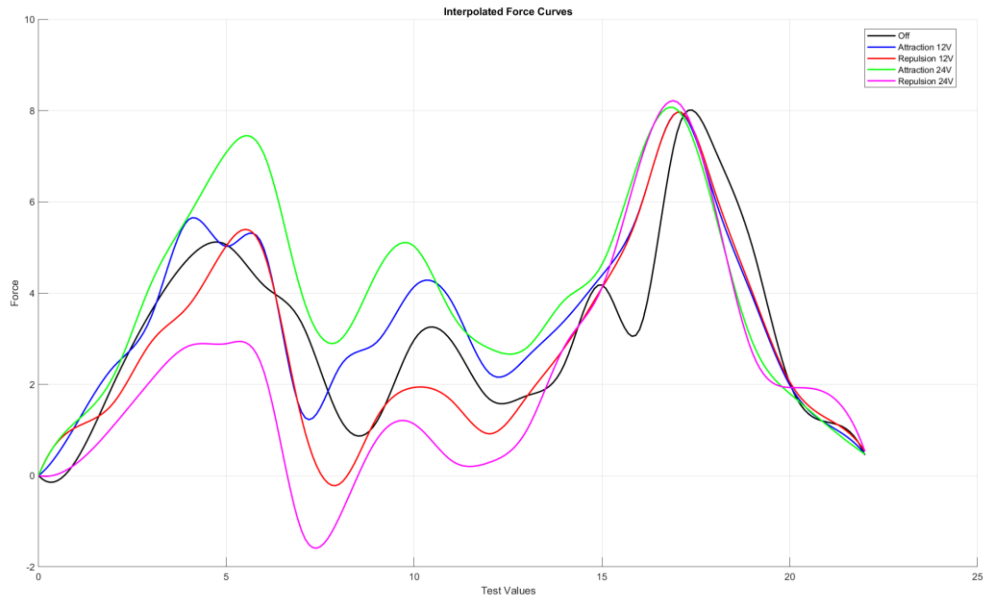


Figure 5.3: Horizontal force F_x vs. displacement δ at 0 V, ±12 V, and ±24 V: Attraction clearly dominates; repulsion is localized and weaker.

5.1.5 Key Observations

The results from the experiment indicate some interesting trends. First of all, out of the very small horizontal forces measured in the reliable displacement range of 0 to 15 mm, the maximum is about 8 N for horizontal attraction forces at +24 V. These forces are clearly lower than the nominal axial pull force produced by the solenoid. The force registered at 0 V shows a constant passive interaction, which arises from the presence of ferromagnetic casing surrounding the solenoid. The repulsive forces from reverse polarity (-12 V and -24 V) are weak, localized, and unstable at such levels that repulsion cannot be expected to serve as an effective primary mode of actuation. Further, it is observed that force output increases with applied voltage, as expected due to the relation between coil current and strength of magnetic field. The forces stared at have been limited in terms of the strength generated from single solenoid-magnet pairs; therefore, multiple pairs will have to operate in synchrony to accomplish the propulsion and positioning performance that will finally be required from the conveyor system.

Summary of Experimental Configurations

Mode	Voltage	Description
De-energized (OFF)	0 V	No excitation; passive interaction via casing
Reduced Attraction	+12 V	Partial excitation; weaker magnetic attraction
Full Attraction	+24 V	Maximum excitation; strongest attraction force
Weak Repulsion	−12 V	Reverse polarity with weak repulsive effect
Full Repulsion	−24 V	Reverse polarity at maximum voltage

Table 5.1: Summary of experimental operating modes and corresponding voltage conditions.

Voltage	Mode	Peak F_x [N]	Force Behavior
+24 V	Full Attraction	≈ +8 N	Peak attraction centered; smooth decay
+12 V	Reduced Attraction	≈ +6 N	Lower magnitude, similar distribution
0 V	OFF (Passive)	≈ +5 N	Symmetric passive force due to casing

Voltage	Mode	Peak F_x [N]	Force Behavior
−12 V	Weak Repulsion	≈ 0 N	Localized, weak, inconsistent repulsion
−24 V	Full Repulsion	≈ −2 N	Stronger but unstable repulsion

Table 5.2: Peak horizontal force values and qualitative force behavior measured within the reliable displacement range (0–15 mm) for each voltage mode.

Aspect	Observation
Reliable Range	Data within 0–15 mm displacement is consistent and reproducible
Force Limitation	Max horizontal force (~8 N) slightly exceeds carriage friction (~5 N)
Repulsion Behavior	Weak, unstable repulsion unsuitable as main actuation mode
Casing Effects	Ferromagnetic casing causes persistent passive attraction
Voltage Sensitivity	Force magnitude increases with applied voltage
Design Implications	Single pairs insufficient; multi-pair configurations required

Table 5.3: Key experimental insights derived from the analysis of measured forces and system behavior.

The experimental results indicative of some very important facts concerning the dynamics of interaction between the magnet and solenoid are analysed and summarized in Table 5.2 in the following way:

- The horizontal force exerted by the solenoid on the permanent magnet reacts greatly with respect to the relative lateral displacements between them, which is clearly non-linear as opposed to a simple monotonic decrease with distance.
- Counter to common assumptions, maximum horizontal force is not necessarily at the least gap, instead, with complex variations due to competition between the magnet and the ferromagnetic casing of the solenoid.

- The interaction forces measured are not sufficiently high to power the motion of the mover for a single magnet-solenoid pair. Thus, multiple pairs must be set up in parallel to provide a combined force to overcome friction and accelerate the system.
- The solenoid's excitation state directly affects the magnetic force in terms of strength and polarity, thus highlighting the solenoid state as the most influential parameter to control force modulation in the system.

These findings are the very essence for the design of the Linear Magnetic Actuated Conveyor and show the need to properly optimize the arrangement of magnets-solenoids and control strategies for excitation in order to satisfy the dynamic performance.

5.2 Mockup System

The mockup system was a necessary intermediate validation step that was developed in order to bridge the gap between the theoretical world of modeling and practical implementation. The purpose of this mockup was to ascertain the feasibility of realizing controlled linear motion using magnetic actuation between a solenoid and a permanent magnet.

The mockup system had multiple purposes, to verify predicted force levels generated from simulations, to test control strategies for the solenoid, and to assess mechanical integration problems. Using simplified, off-the-shelf components, the system concentrated on core functions, allowing for rapid iterations that provided critical feedback before advancing toward final prototype development.

5.2.1 Experimental Setup and Procedures

The mockup system is a feasibility study to test the actual implementation of magnetic actuation via solenoid-magnet interaction. This phase has been necessary to merge model theory with the injectable build of a final prototype. The purpose was to create an entire working system with simplified components and to test controlled linear motion with the prototype under lab conditions.

5.2.2 Component Selection and Assembly Strategy

Even though the component selection is originally carried out based on analytical and simulation results, the physical assembly of the mockup system was performed from available parts in JOiiNT LAB to minimize the development time and resources. The pragmatic approach allowed efficient progress within the project while maintaining basic design intentions and validating the most important performance parameters.

The principal components used in the mockup were:

- Guide Rail: SXRN28, straight – 400 mm
- Carriage: SXRN28, ball type
- Profile Structure: AL-HSB8, 40 × 40 mm aluminum profile
- Solenoid: ITS-MS-2520-24VDC, rated at 60 N axial force at 24 V

These components were fixed onto a linear base structure for supporting the experimental tests. Two linear guide rails were fixed to the aluminum profile, allowing the smooth and constrained motion of the carriage (or mover), which carried the permanent magnets.

Figure 5.4: Mockup system showing guide rails, carriage with mounted magnets, and stator solenoids.

5.2.3 Magnet and Solenoid Configuration

The carriage was fitted with eight neodymium permanent magnets, each measuring 10 mm by 10 mm by 10 mm and belonging to grade N35: it was equipped with two parallel rows, each containing four magnets, and fixed at the underside of the carriage through an adhesive. The distance between magnets was purposely made uneven to reduce force ripple and make the net thrust better. Specifically, in the first row, there were spacings of 39 mm, 72 mm, and 110 mm, while the second row had 16 mm shift lateral offset, as shown in Figure 5.5.

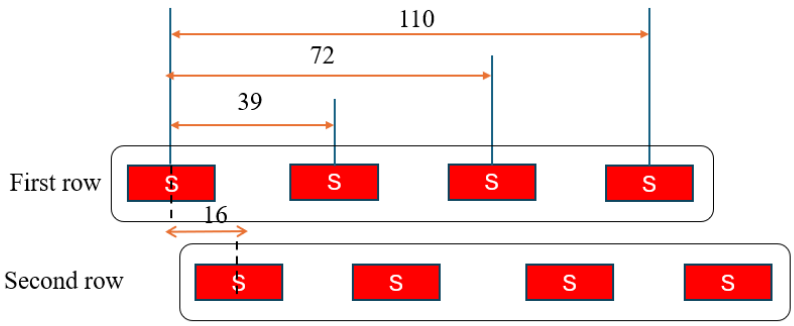


Figure 5.5: Magnet array layout on the carriage, showing non-uniform spacing and 16 mm offset between rows. Solenoids (diameter 25 mm, pitch 26 mm) are aligned below the magnet rows.

Each row of magnets corresponded to a row of electromagnetic solenoids below. These solenoids, model ITS-MS-2520-24VDC, had a diameter of 25 mm and were installed in-line with a centre-to-centre pitch of 26 mm. This tight pitch required a carefully calculated arrangement of the magnets to ensure that each magnet had sufficient magnetic overlap with one or more solenoids at every moment of motion, while avoiding mechanical interference.

All south poles of all available magnets were oriented downward, thus rightly ensuring that either attraction or repulsion will occur in accordance with the polarity of the solenoid. Exposed poles of neighboring magnets in the rows and across rows had been aligned for mutual repulsion, thus improving in-the-ways stability and uniformity of the magnetic field. The final configuration, including distance and offset, resulted from an optimization process conducted by Alessio Salvatore, who tested in simulation thousands of layout combinations to maximize average driving force and minimize variation across the actuation stroke.

This setup was the result of an optimization in simulation done by Alessio Salvatore, and it tested thousands of combinations of magnet pitch, row offset, and polarity of solenoid to find the layout maximizing net thrust, minimizing ripple and delivering consistent force throughout the stroke.

To verify this configuration, a number of pictures were produced, which show the forces acting on individual magnets in the optimized layout, as the mover travels over the solenoids. These are shown in Figures 5.6 to 5.10:

- The values seen above each of the magnets represent the forces exerted by the solenoids on its left and right.
- The values drawn below the magnet represents the resultant force acting on that magnet.

- The number in large digits shown under the mover represents the total net force acting on the complete carriage.
- Positive values indicate forward thrust (to the right), while negative values indicate braking force (opposing motion).

The solenoid states are color-coded:

- Blue: –24 V (repulsion mode)
- Red: +24 V (attraction mode)
- Black: OFF

These force distribution diagram at 0 mm, 12 mm, 15 mm, 22 mm, 25 mm, and 26 mm show that the interaction of the solenoid polarity with the magnet positioning leads to useful force patterns, mostly in the forward direction. It is important to note that after 26 mm, the spatial arrangement of magnets changes, although the distribution of forces is repeated in exactly the same manner to that first seen at the 0 mm position due to the periodic nature of the design of the system.

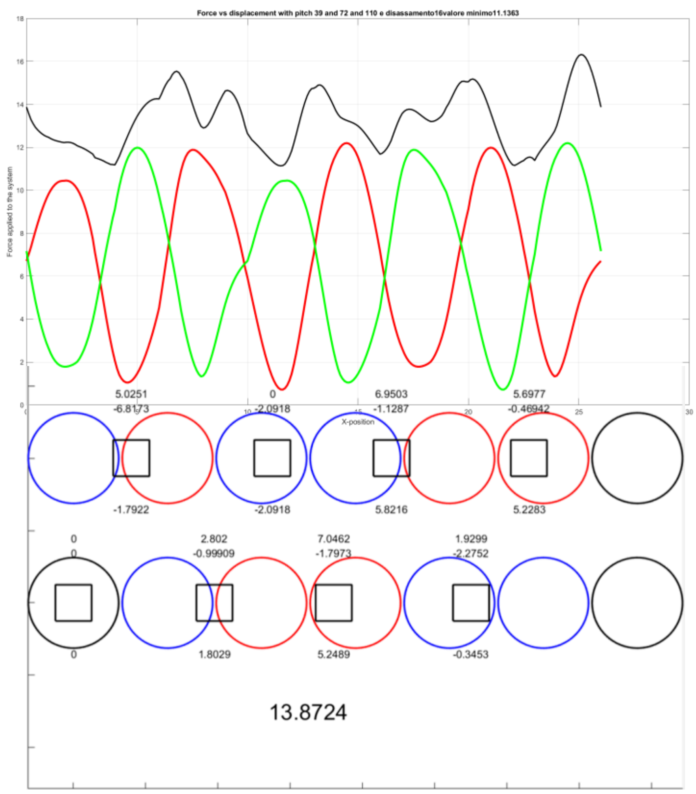
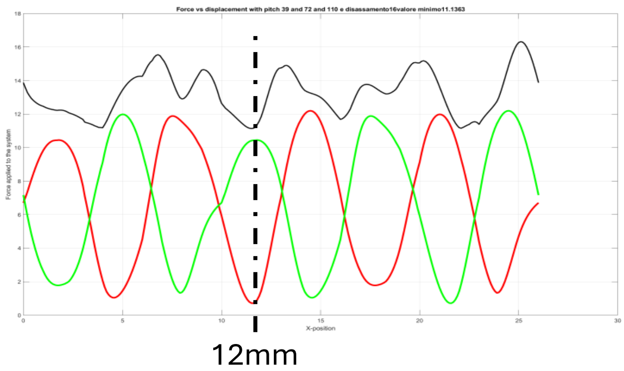


Figure 5.6: Force distribution at 0 mm displacement. Each magnet experiences two opposing forces from its adjacent solenoids (shown above), with the resulting net force indicated below. The total net thrust on the mover is shown in bold. Solenoids are color-coded: red (+24 V, attraction), blue (–24 V, repulsion), black (OFF).



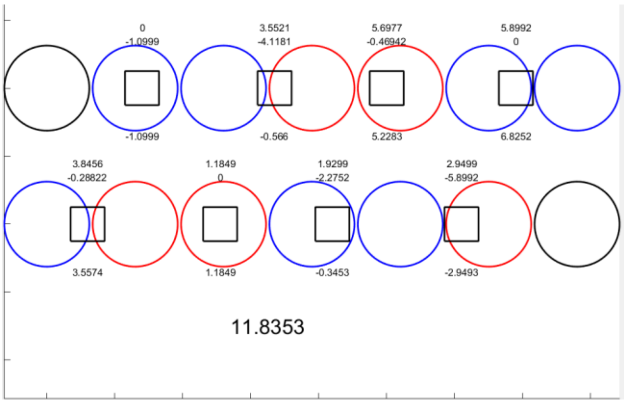
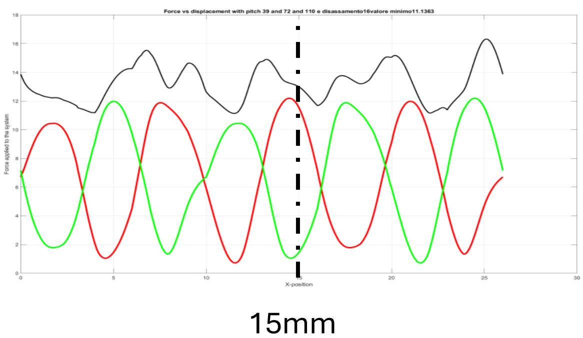


Figure 5.7: Force distribution at 12 mm displacement. Polarity arrangement of solenoids continues to create a net driving force in the positive direction.



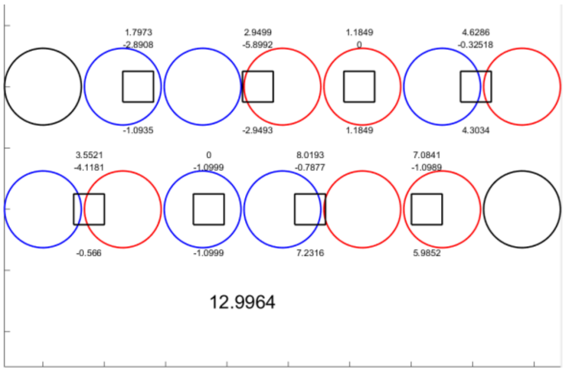


Figure 5.8: Force distribution at 15 mm displacement. The asymmetric solenoid configuration maintains a forward-driving force profile.

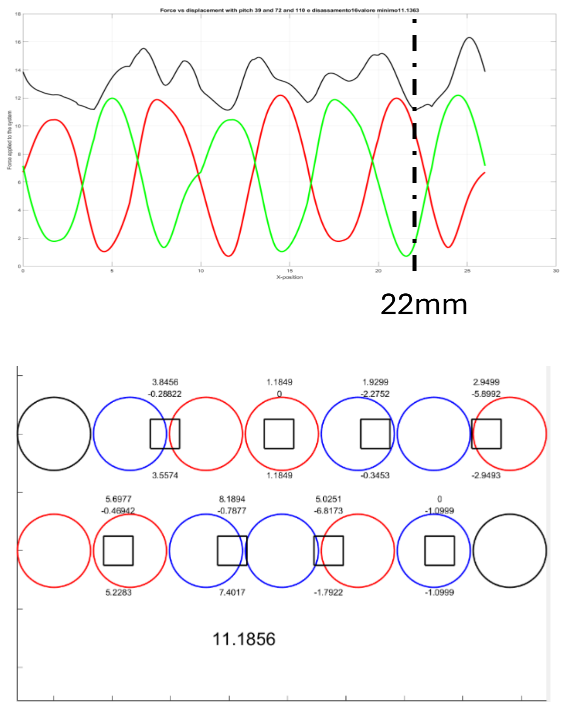
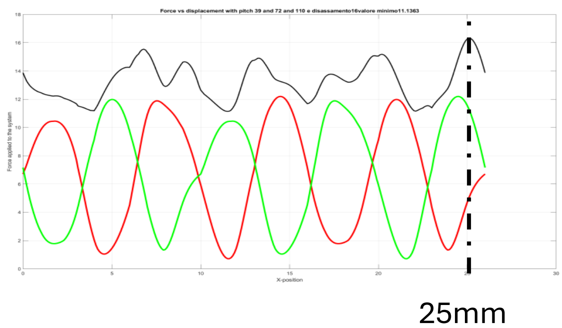


Figure 5.9: Force distribution at 22 mm displacement. The actuator still produces net thrust, demonstrating the consistency of force generation across the stroke.



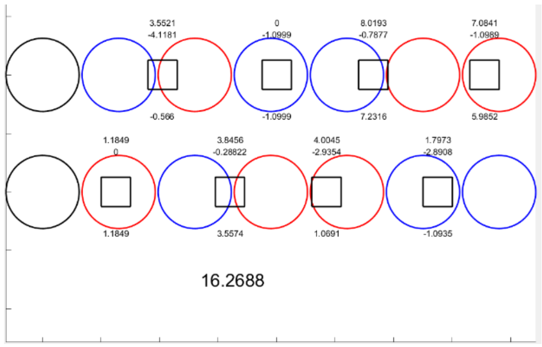


Figure 5.10: Force distribution at 25 mm displacement. This late-stage configuration verifies the effectiveness of the layout even near the transition point.

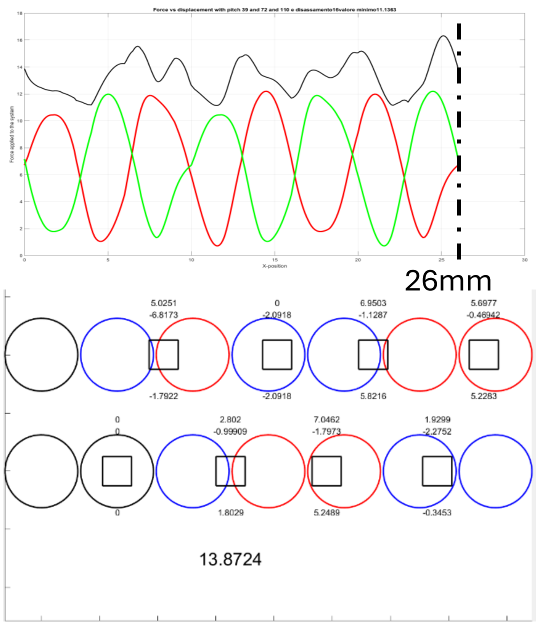


Figure 5.11: Force distribution at 26 mm displacement. This configuration repeats the force profile observed at 0 mm, confirming the spatial periodicity of the magnet–solenoid interaction over a full solenoid pitch.

5.2.4 Position Sensing and Feedback

The real-time tracking of the mover's position along the rail was accomplished by integrating a rotary magnetic position sensor (JST04 model) via an ingenious custom rotary-to-linear transmission system. The non-contact sensor was employed to measure angular displacements corresponding to linear movements of the carriage. The output signal was conditioned through a logic-level interface and transferred to the Arduino Mega 2560 as a master controller.

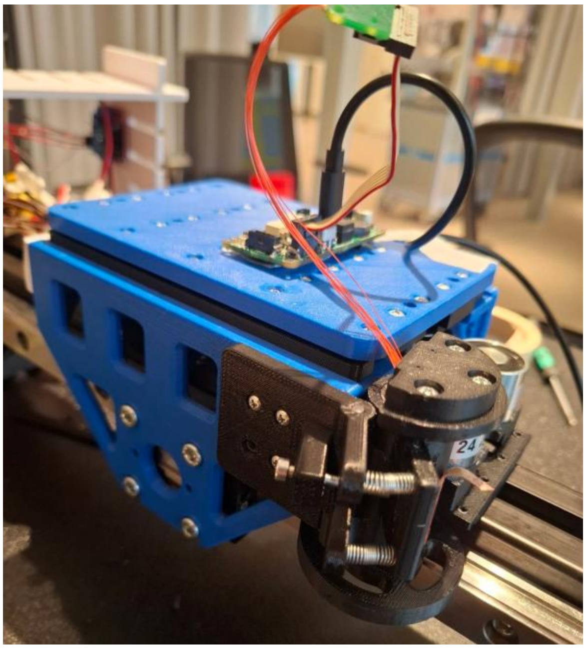


Figure 5.12: Position sensor with mechanical transmission for linear position feedback to the control unit.

5.2.5 Control Architecture and Implementation

As previously presented in Figure 4.9, the solenoids were actuated using an L298N H-Bridge driver, which was connected to the Arduino. Embedded code was programmed with a simple position-based activation algorithm that turned on/off solenoids depending on the present position of the carriage. Such a control scheme allowed magnetic attraction under a controlled way for one-way travel.

The control logic design and implementation were done by Alessio Salvatore, who contributed much to the integration of sensor feedback, driver module, and solenoid control loop. His input was valuable in getting timing and synchronization of solenoid activation consistent, which were key to obtaining measurable and repeatable motion.

5.2.6 Experimental Procedure

The system was tested by manually positioning the carriage at the starting point of the track. The next moment that power was applied, the Arduino began to read from the sensors and started to activate solenoids based on predefined positional thresholds. As the mover approached a solenoid, that solenoid was activated, pulling the corresponding magnet forward. This process continued in sequence, creating small yet perceptible steps in translational motion along the linear axis.

Each test cycle was repeated several times to check for consistency, with qualitative observations recorded on smoothness, response, and accuracy of motion. By iteratively changing experimental parameters such as solenoid voltage, timing delay between activations, and magnet alignment, the performance was refined.

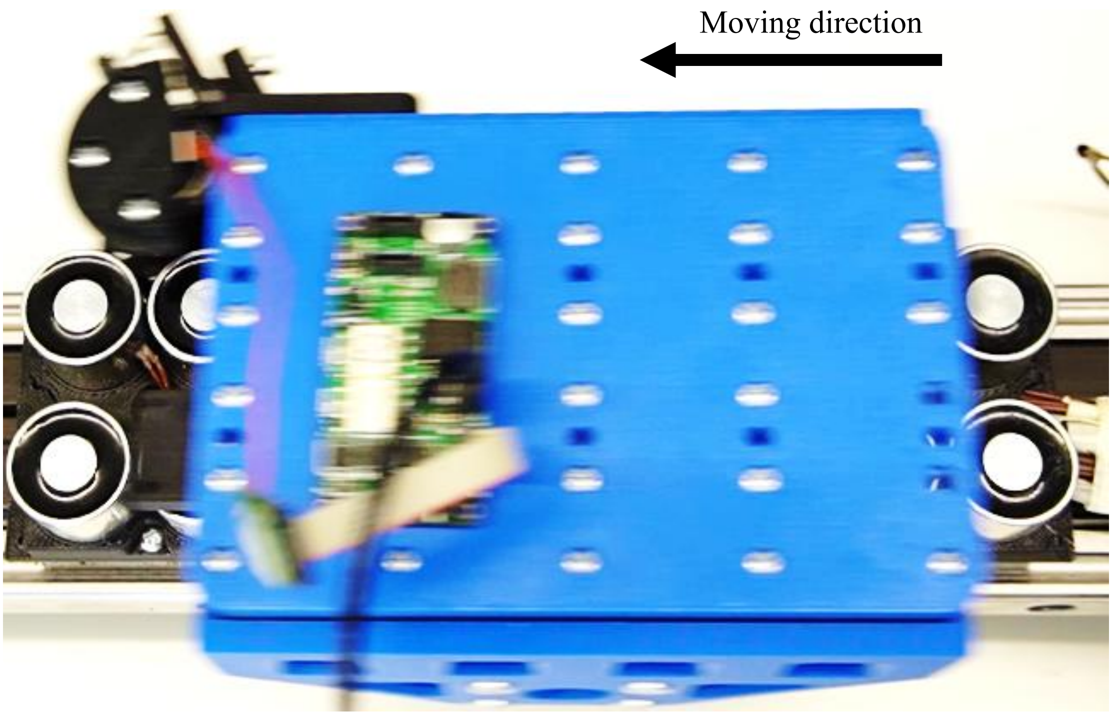


Figure 5.13: illustrating of a test run for the Linear Magnetic Actuated Conveyor shows the carriage moving with solenoids sequentially energized to provide controlled motion.

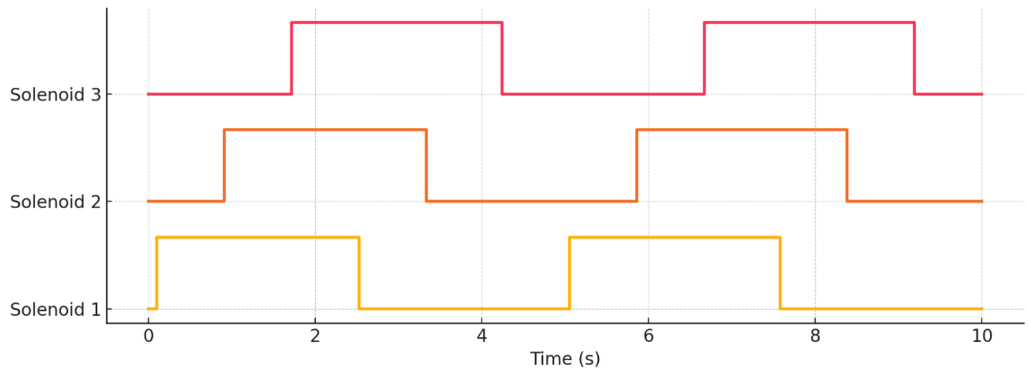


Figure 5.14: Solenoid Activation Sequence (Timing vs. Time)

The preliminary mockup, though elementary in construct, successfully proved the use of solenoid–magnet interaction for controlled linear actuation. The system, albeit built of available laboratory components, was able to generate repeatable motion profiles under the programmed expectation. The experience gained from matters related to magnet configuration, activation logic, and sensor feedback were highly instrumental in the development of the final prototype presented in the next section.

5.2.7 Data Collection and Results

This preliminary experimental phase was aimed to qualitatively assess the operational behavior of the proposed linear magnetic actuator. Rather than focusing on quantitative data such as the displacement precisions, the tests were conducted to ascertain the feasibility of generating linear motion by solenoid–magnet interaction, while looking at alignment, polarity, and activation patterns in a controlled but simplified setup.

The experimental arrangement consisted of eighteen cylindrical solenoids with a diameter of 25 mm arranged into two parallel rows of nine over a stationary base. Arrayed about 26 mm apart from each other (centre-to-centre), the solenoids obtained an overall active length of about 30.5 cm. Above this array, there was a lightweight carriage carrying eight cubic permanent magnets arranged in two parallel rows with an offset of 16 mm laterally to each other. The magnets were arranged to have the same magnetic pole (South) facing downward towards the solenoids. During the tests, it was ensured that an air gap of about 0.3 mm was maintained uniformly between the magnet array and the solenoids.

Manual power supply of the solenoids was performed with a 24 V DC power supply. Various activation patterns were implemented to explore different operating scenarios. These included activating one solenoid at a time, putting entirely a row on simultaneously, symmetric activation of two rows, and sequential activation in one direction along the array. So that dynamic testing could occur, Alessio entered a simple control routine that was allowing the simultaneous activation of six solenoids, with three from each row operating adjacently. This grouping allowed the carriage to move in an inhomogeneous magnetic field for preliminary testing of the stepwise motion across the array.

In this phase, force or position sensors were excluded. The system's behavior was evaluated via direct observation, with qualitative interpretation. The observed results showed that in attraction mode, energized solenoids habitually pull the carriage quite readily. The above-described joint activation of several solenoids was found to produce some small movements of the carriage, thus confirming that magnetic coupling is successful. Sequential activation provided observable step motion along the guide rail in support of the actuation concept's validity.

However, operation in repulsion mode (polarity was reversed) did not generate any appreciable response, reinforcing the analytical modeling conclusion that attraction is a better option for this arrangement.

In conclusion, the preliminary testing proved that electromagnetic attraction could indeed induce motion in the proposed system. While qualitative, these results confirmed the fundamental design assumptions, and pointed out critical parameters such as magnet alignment, solenoid positioning, and timing of activation sequences. This knowledge was applied to the subsequent phases of refinement and integration.

5.2.8 Summary

The final experimental validation shows that the solenoid–magnet interaction could lead linear motion in industrial automation. Parameters measured meet initial design requirements for controlled motion but have deficits in force magnitude and motion smoothness that should be improved. The comparison with current benchmarks validates choice of attraction-based actuation per se while indicating the improvement fronts. Those insights lay the firm groundwork for progressing toward a final prototype and to more advanced control strategies as detailed in the following chapters.

6 Conclusion

This work presented the work related to the study, design and control of a linear magnetic actuated conveyor for assembly lines developed by JOiiNT LAB in collaboration with Cosberg S.p.A. Major goals of the project included tackling some severe limitations faced by conventional conveyor technologies in mechanical wear, rigidity, and inefficient reconfiguration in manufacturing environments with a new flexible intelligent actuation concept that fits Industry 4.0 principles.

To accomplish this with magnetic linear actuation, solenoid and permanent magnet interaction was chosen for non-contact propulsion. A literature review showed that, despite challenges like cost and thermal control, linear synchronous motors present themselves competitively for high precision applications. This analytical glimpse gave support to the electromagnetic force modeling, mechanical stability analysis, and carriage dynamic modeling. The results show the necessity of dual guide rails and that a solenoid force of roughly 47.7 N should enable performance expectations to be met.

The design process involved a CAD output from which solenoids, permanent magnets, feedback components, and others were selected in such a way that performance and cost were balanced. The control system based on Arduino allowed real-time positioning to be carried out and validated its suitability in the laboratory environment for controlled motion.

Initial tests confirmed that tests were performed under conditions suitable for validating proof of concept of magnetic actuation. Using attraction mode solenoids gave results of up to 8 N force produced at 24 V and a hold time on a mockup system for basic step-wise linear motion. These preliminary results confirmed, however, that optimized arrangements of solenoids and better control strategies are needed since there were limitations such as friction and force insufficiency.

In a nutshell, this work verifies the feasibility as well as the potential of LSM-based conveyors in industrial automation, with such an offering of precision, flexibility, and maintenance benefits over common systems. Future research should delve deeper in the field of thermal optimization, improvement of the control system, and integration of curved track modules for facilitating full-loop operation. The findings contribute to Cosberg's technological roadmap and broader efforts towards more intelligent, reconfigurable production systems.

Bibliography

[1] D. J. Griffiths, *Introduction to Electrodynamics*, 4th ed. Cambridge, U.K.: Cambridge University Press, 2017.

[2] M. Bolderman, M. Lazar, and H. Butler, Structured physics-guided neural networks for electromagnetic commutation applied to industrial linear motors, 2023.

[3] A. M. Knight, *Electric Motors and Drives: Fundamentals, Types and Applications*, 4th ed. Oxford, U.K.: Newnes, 2014.

[4] Boldea, I., & Nasar, S.A. *Linear Electric Machines, Drives, and MAGLEVs Handbook*. CRC Press, 2018.

[5] Zhu, Z. Q., & Howe, D. (2007). Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles. *Proceedings of the IEEE*, 95(4), 746–765.

[6] Wang, J., et al. (2018). A review on slotless tubular permanent magnet linear motors: Design and applications. *IEEE Transactions on Industrial Electronics*, 65(3), 1051–1061.

[7] Greenfield, D. (2010). Energy Efficiency: Linear Synchronous Versus Linear Drive Motor Technology. *Control Engineering*. Retrieved from https://www.controleng.com

[8] Siemens (2021). *Total Cost of Ownership in Smart Motion Systems*. Siemens Automation White Paper.

[9] Atencia, J., García Rico, A., & Flórez, J. (2013). Linear Induction Motor Models for Simulation and Control. *IEEE Latin America Transactions*.

[10] Jin, X., et al. (2019). Electromagnetic Compatibility Design of High-Speed Linear Motors. *IEEE Transactions on Magnetics*, 55(7).

[11] Du, Y., et al. (2014). Investigation of thermal demagnetization in permanent magnet motors. *IEEE Transactions on Magnetics*, 50(11), 1–4.

[12] Gieras, J. F. (2011). *Linear Synchronous Motors: Transportation and Automation Systems. CRC Press.*

[13] R. Krishnan, *Electric Motors and Drives - Fundamentals, Types and Applications*, 4th ed., Pearson, 2010.

[14] THK Co., Ltd., "Technical Report: Linear Guide Friction and Performance," THK Corporation, Tokyo, 2023.

[15] A. Hughes and B. Drury, Electric Motors and Drives: Fundamentals, Types and Applications, 4th ed. Oxford, U.K.: Newnes, 2013.

[16] PTC Inc. (2020). Creo Parametric 8.0 User Guide. PTC University.

[17] Boldea, I., & Nasar, S. A. (2001). Linear Electric Actuators and Generators. Cambridge University Press.

[18] Gröger, B., Lanza, G., & Nyhuis, P. (2016). "Assessment of manufacturing systems using a modular and reusable simulation model." Procedia CIRP, 57, 135–140. https://doi.org/10.1016/j.procir.2016.11.024

[19] THK Co., Ltd. (2024). THK Linear Guide HMG Catalog. Retrieved from https://www.thk.com/catalog/

[20] Kalpakjian, S., & Schmid, S. R. (2014). Manufacturing Engineering and Technology (7th ed.). Pearson Education.

[21] Mourtzis, D., & Doukas, M. (2012). "Design and planning of reconfigurable manufacturing systems." Procedia CIRP, 3, 453–458. https://doi.org/10.1016/j.procir.2012.07.078

[22] Yamamura, S. (1972). Theory of Linear Induction Motors. University of Tokyo Press.

[23] Ibáñez, J., & Zeadally, S. (2018). "Sensor Technologies for Intelligent Transportation Systems." Sensors, 18(4), 1212. https://doi.org/10.3390/s18041212

[24] Krishnan, R. (2010). Electric Motor Drives: Modeling, Analysis, and Control. Prentice Hall. ISBN: 9780130910143

[25] Wang, J., & Jewell, G. W. (2004). "Thermal Analysis and Management of Linear Permanent Magnet Machines." IEEE Transactions on Energy Conversion, 19(2), 352–358. https://doi.org/10.1109/TEC.2004.827706

[26] Honegger, U., & Hufschmid, P. (2009). Precision Linear Bearings in Machine Tools: Performance Requirements and Selection Criteria. Journal of

Manufacturing Processes, 11(1), 45–50. https://doi.org/10.1016/j.jmapro.2009.03.003

[27] Honegger, U., & Hufschmid, P. (2011). Linear Motion Technology for Automation Applications. ICPE Conference.

[28] Weck, M., & Brecher, C. (2006). Production Systems 2. Springer. https://doi.org/10.1007/3-540-31253-3

[29] Kolar, M., & Tichy, M. (2018). “Experimental Investigation of a Linear Guideway System for Mechatronic Applications.” Applied Sciences, 8(5), 718. https://doi.org/10.3390/app8050718

[30] Radzevich, S. P. (2012). Dudley’s Handbook of Practical Gear Design. https://doi.org/10.1201/b12170

[31] HMT Machine Tools. (2013). Production Technology. Tata McGraw Hill. ISBN: 9780070964433

[32] Altintas, Y., & Weck, M. (2004). Chatter stability of metal cutting and grinding. https://doi.org/10.1016/S0007-8506(07)60032-8

[33] Bolton, W. (2015). Mechatronics (6th ed.). Pearson Education. ISBN: 9781292076683

[34] Salazar, P. D., Chen, W., & Shin, Y. C. (2020). “Design and Control of a High-Speed Linear Motor Stage for Precision Positioning.” Micromachines, 11(8), 717. https://doi.org/10.3390/mi11080717

[35] ElMaraghy, H. A., et al. (2012). “Complexity in engineering design and manufacturing.” CIRP Annals – Manufacturing Technology, 61(1), 793–814. https://doi.org/10.1016/j.cirp.2012.05.001

[36] Liu, H., et al. (2020). “Electromagnetic Design and Optimization of SlotlessLinear Permanent Magnet Machines.” Energies, 13(3), 576.https://doi.org/10.3390/en13030576

[37] Lu, J., et al. (2022). “Thermal Modeling and Control of High-Performance Linear Motors.” Machines, 10(2), 120. https://doi.org/10.3390/machines10020120

[38] Liu, Y., Li, L., & Lu, Y. (2021). “Review of Position Control Strategies for Linear Motor Drives in Automated Production.” Machines, 9(7), 144. https://doi.org/10.3390/machines9070144