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SCIENTIFIC INFORMATION

Linear motor concept and applications in industrial material handling and processing

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ABSTRACT

Nowadays, linear motor is widely applied in industry. One of the most importance applications is industrial material handling and processing. The paper introduces the concept of linear motor and the studying trends of linear motor applied for industrial material handling and processing. In the trends, there are many challenges for researchers to study and solve.

1. Introduction

A linear motor can be defined as being the result of a cylindrical rotary electric machine, which has been mentally split along a radial plane, unrolled and flattened (Eric R, 1975). The result is an electrical machine in which the primary and the secondary are linear and parallel as shown in Figure 1.

In contrast to a rotational electric motor, a linear motor generates a linear force (thrust force) along its length, i.e. there is no torque or rotation is produced by the relationship between electric currents and magnetic field. By supplying suitable currents to the primary with a suitable excitation in the secondary of a linear motor, they will move relatively in a linear path. This makes linear motors have a number of advantages over rotational motors in linear motion. Linear motors overcome most of the disadvantages of the most commonly used linear motion systems, which consist of rotational electric motors and ball screw systems. The advantages of linear motors are high speeds or acceleration rates, faster response, more stiffness, no zero backlash and cheaper maintenance free operation. Therefore, the linear motors are applied in many applications in recently.

Be invented in the early days of the electric motor, linear motor was firstly applied in public transportation area. The first linear motor applied in transportation was the “Axial Engine” developed by Charles Grafton Page (1812-1868) (Post, 1972). The later developments were inventions of Alfred Zehden (1905) (U.S. Patent), Hermann Kemper (1935) (Gerd Hugenberg, 2001) and Eric Laithwaite (late 1940s). Nowadays, many transportation systems are using linear motors like the Maglev propulsion system, for instance, the Japanese Linimo magnetic levitation train or the German high-speed train Transrapid.

Other transportation systems without magnetic levitation are Bombardier´s Advanced Rapid Transit systems and number of modern Japanese subways. One more technology using linear motor is in the roller coasters (web).

Besides the public transportation applications, the linear motors are also applied in lifting mechanisms and many motion control applications. With small limitations of space and the required height, the vertical linear motors are suitable for skyscraper or deep mining elevators. Linear motors are also used in industrial or military lifting systems. In addition, they are offered to use on sliding doors of trams, buildings or elevators (Pasanen et al., 1991). Dual axis linear motors also produced and applied to the applications that require X-Y motion, such as in precision laser cutting machines, automated drafting machines and others kind of CNC machine tools.

With the long development time, as well as many application domains, there are many types of linear motors, which exist in reality. If classified by structural geometry [Rodigo Benavides], the linear motors can be split into categories as shown in Figure 2. Depending on the primary and the secondary shape, a linear motor is called *tubular linear motor* when the primary and the secondary have coupling shape instead of flatbed shape in *flat linear motors*. In the two categories, the linear motors are built in *long stator*- (long primary) or *short stator*- (short primary) categories. The long stator linear motors have longer electrical supplied parts (primary, winding) in comparison with secondary parts. In this case, the secondary parts are moving (moving track – static forcer). In contrast, the short stator linear motors have longer secondary parts in comparison with primary parts and moving primaries (moving forcer – static track). The flat linear motors are further classified into *single side* linear motor or *double side* linear motor by the number and the arrangement of linear motor primary parts and secondary parts. If classified by electrical characteristic, linear motors have equivalent categories as rotational motors; linear induction motors (LIM), linear synchronous motors (LSM), linear DC motors, linear stepper motors, etc.

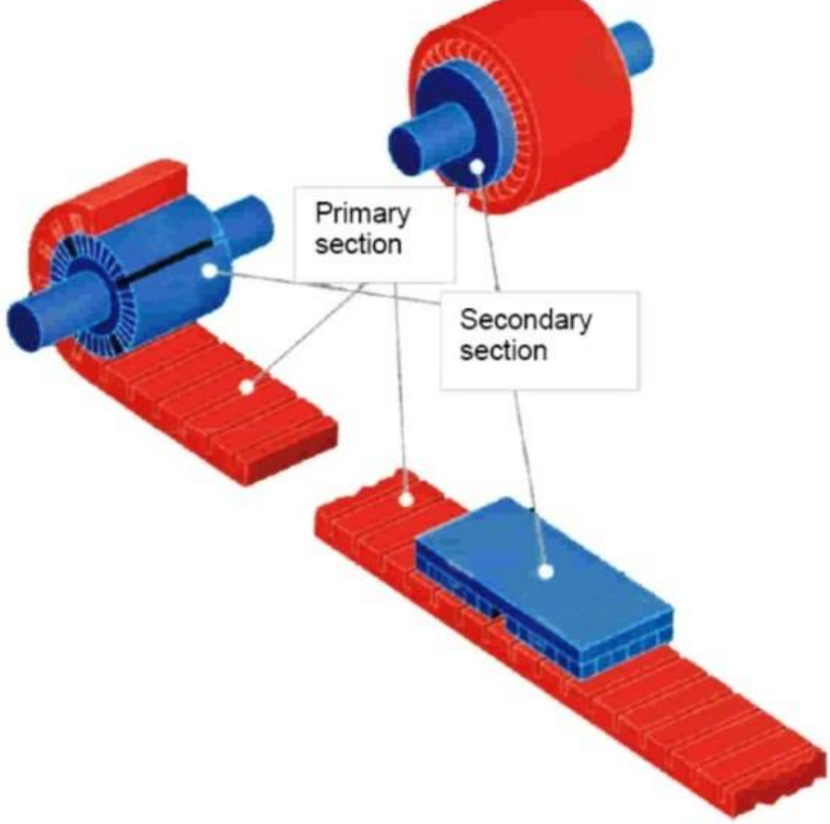


Figure 1. Imaginary process of splitting and unrolling a rotary machine to produce a linear motor

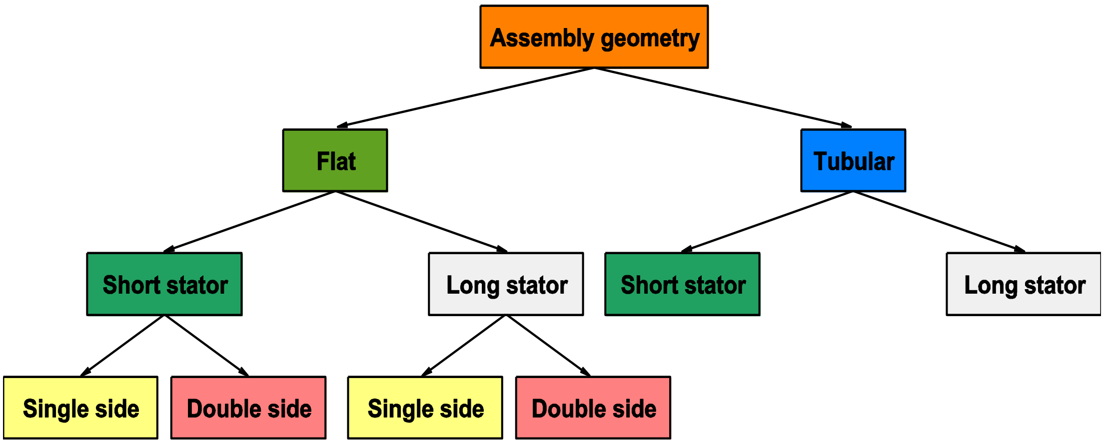


Figure 2. Linear motor categories

Altogether, the linear motors have a long development time, many types and applications in practice. The researches to use the advantages of linear motors in practical applications are continuing. In paper, the researches to apply linear motor in the process integrated material handling will be introduced.

2. Linear drives for industrial material handling and processing

As mentioned above, the linear motors are used today more and more in industrial applications because of their advanced features.

With their advanced mechanical structure over the rotational motors in linear motions, the linear motors have attracted many interests in the industrial material handling and processing applications.

In industrial production lines, materials must be processed and transported between processing stations. The raw materials are processed sequentially to transform from a raw state into finished parts or products. Each operation is done in one processing station. Within the processing stations, for high precise operation, materials need to be fastened when they are moving in and released when they are moving out. The final parts or products are completed at least after passing several stations. In between the stations, the raw materials are transported by conveyor belts, mobile vehicles or robots.

In traditional processing method, the materials are tightened and released in each operating station. That takes time of the process. In order to eliminate the significant time-consuming for tightening and releasing, material handling systems nowadays have a newly developing trend. That is using the high precise mobile mechanism, which can stop or move precisely within the processing stations. With that, the process can be operated on the mobile mechanism in each processing station. Therefore, the raw materials just need to be fastened to the mobile mechanism at the beginning of the processing chain and released at the end.

As the requirements mentioned above, the linear drive is a good option for the new trend of the industrial transportation and processing system. By using the linear drive (P. Mutschler, 2007) directly for processing and transportation without releasing and re-adjusting the work pieces, with a linear drive system will result in many benefits as follows:

- High productivity;
- High dynamic and high precision (few μm);
- No mechanical transmission $\rightarrow$ reduced wear, assembling and maintenance costs.

Figure 3 shows a simple example of combined transportation and processing of materials with a linear drive system. In such applications, the following properties are necessary for the linear drive system:

- On a guide-way (track), several vehicles travel with a high degree of independency.
- Each vehicle is controlled very precisely (few μm) when the vehicle operates within a processing station.
- The carriage allows for horizontal and vertical curves and for closed paths.

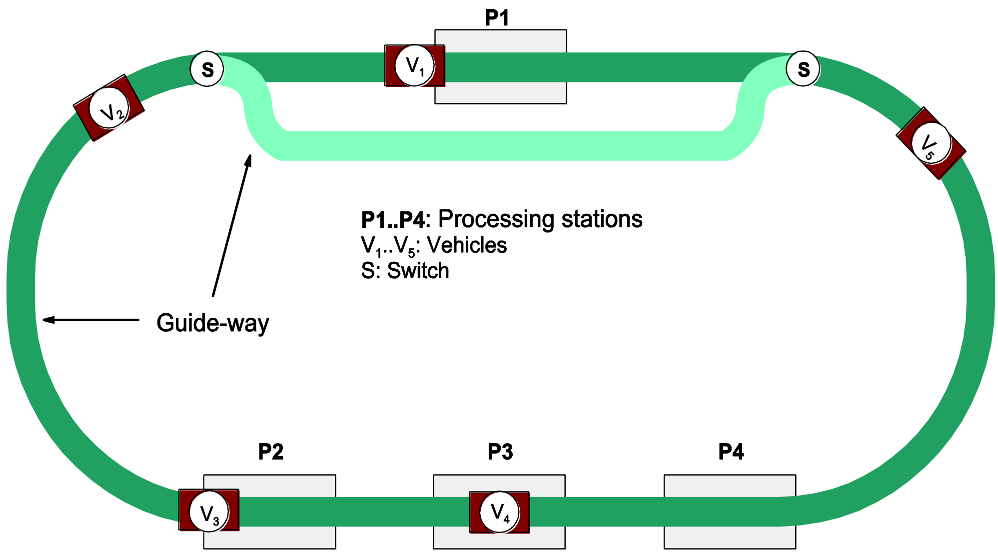


Figure 3. An example of proposed linear driver system for combined transportation and processing of material

A circular linear transport system for a concatenation of machine tools was proposed already by (N. A. Duffi et al., 2007). However, the transverse flux induction machine, which was designed for this project, needed very close air-gap tolerances, i.e. a high precision of the carriage way. Additionally, the reactive power of the inverter had to be rather large due to the large air-gap and thus the system was not optimal. In an application like in Figure 3, the track passes through processing stations (Pl...P4). In the processing stations, typically high-precision positioning and high forces are necessary. For high-precision positioning, position sensors cannot be avoided. However, outside of the processing stations, typically a lower precision in positioning is sufficient. In these parts of the track, motion control without using sensors for speed or position should be realized.

2.1. Topology of linear motors applied in industrial material handling and processing

After a long developing period, linear drives are manufactured in many different kinds, suitable for different applications. For industrial material handling and processing, the properties of linear drives need to be analysed to make suitable choices. In this section, the two main distinguished categories of linear motor (short primary and long primary) are analysed. They are all the linear drive for industrial material handling and processing, but in each special case the suitable category need to be chosen.

In short-primary linear motors, the winding is mounted on the moving part. Hence, the short-primary linear drive requires active vehicles i.e. energy and information must be transmitted to the vehicle. The solutions for energy transmission can be running cables, sliding contacts or contact-less (inductive energy transmission). The running cable solution is not applicable in industrial material handling and processing, as the vehicle has to travel long distances and closed paths. In many industrial production environments, sliding contacts should be avoided because of the safety for workers, maintenance or exploding protection. In the short-primary category, the contact-less energy transmission is a suitable proposal. Figure 4 shows the contact-less energy transmission for short-primary linear motor proposed in (P. Mutschler, 2007). In the figure, the static part supplies electric energy with constant frequency for the transmission system. On the moving part (vehicle), a power electronic system is used to supply the energy for the winding. Beside the energy transmission, a contact-less information transmission system is necessary. The benefits of this proposal are:

- The number of the converters and control units is equal to the number of vehicles plus the converter feeding the contact-less energy transmission.

• Position sensing is much easier and cheaper when auxiliary energy is available on board of the vehicle.

• The passive track plus contact-less energy transmission may cause lower costs than a long active track, especially when an induction machine is used.

The drawbacks of this system are:

• Because of the energy transmission system and the on board inverter, the vehicles have high weight and big volume.

• The power limitation of contact-less transmission system and the vehicle weight reduce the dynamic of the vehicle.

With the above characteristics, the short-primary linear drive can be a good solution for applications with a long track, low number of vehicles and low acceleration.

In order to overcome the drawbacks of the short-primary linear drive, the long-primary one can give solutions for high acceleration, passive, lightweight vehicles by using an active track. The system does not need energy or information transfer to the vehicles. Because of its higher efficiency, compactness, but most important because it allows a higher air-gap, permanent magnet excitations are usually used in the system. For use in industrial material handling and processing applications, the primary of the system is separated in to segments. This ensures that:

• Each vehicle can be controlled and moved independently by one or two contiguous primary segments.

• The reactive power can be reduced (save energy) by switching off the stator segments not carrying any vehicle.

The proposed long-primary systems are presented in Figure 5. In order to control the vehicles, each segment can be fed by dedicated-inverters (Figure 5a) or multiplexed-inverters (Figure 5b). With these structures, one vehicle is controlled independently by one feeding segment, when the vehicle is within the segment or by two feeding segments, when the vehicle in the transition area of the segments.

As mentioned above, several suitable topologies are applicable for industrial material handling and processing. In each real application, a suitable topology should be analysis and selected.

2.2. State of the art

The main challenges of linear motor applied in material handling and processing relates to the control of the magnetic thrust and lateral force. With the two forces, many researches deal with the wide area of magnetic driving, levitation and guidance. Inspire of many differences between rotating and linear drives, many interesting documents of rotating drives in literature, concerning magnetic bearing and bearing less motors, can be referred to the strategy of the art. They are also related directly or indirectly to the research topic, but they are not discussed in detail in this paper because of the limited space.

With linear drive, these basic functions, as shown in Figure 6, consist of:

• Thrust force;

• Lift force and;

• Lateral force.

Generation can be realized in combination or be separated in subsystems. With combined realization, parts of the actuator (coil, magnet) are used jointly to generate some basic functions.

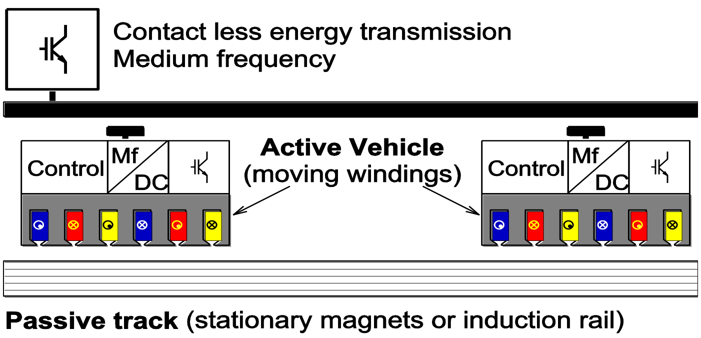
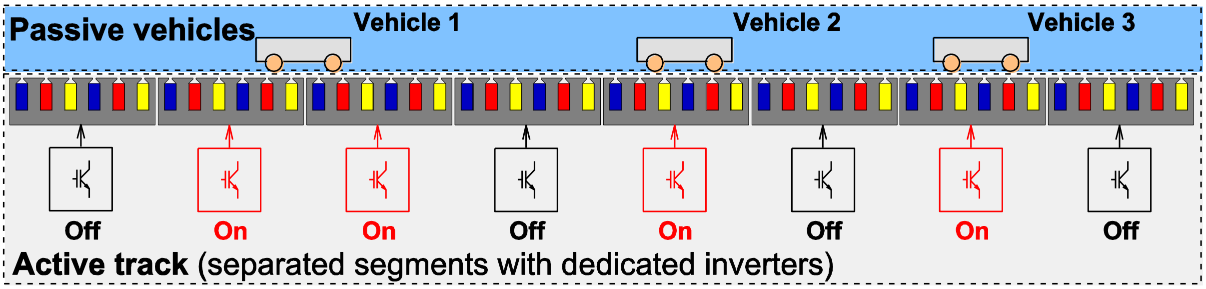
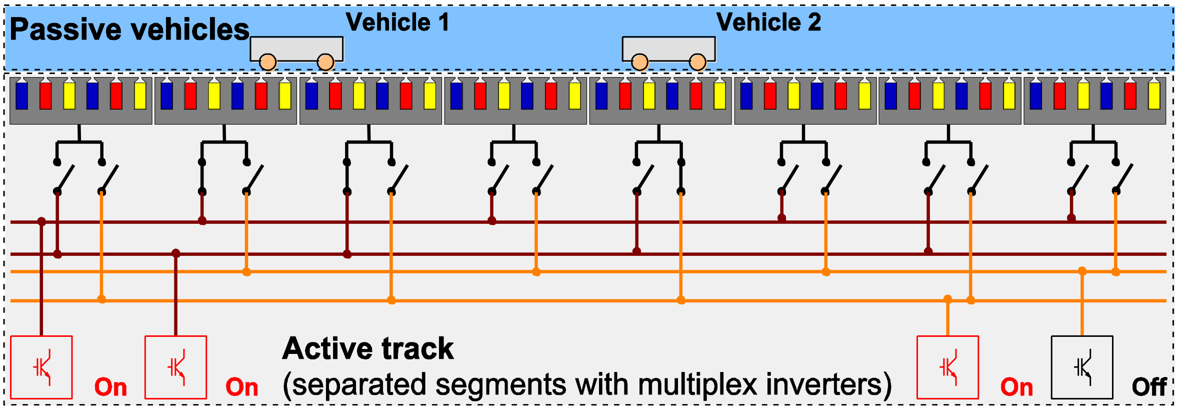


Figure 4. A short primary system with contact-less energy transmission



a. Dedicated inverters



b. Multiplex inverters

Figure 5. Proposed long primary topology

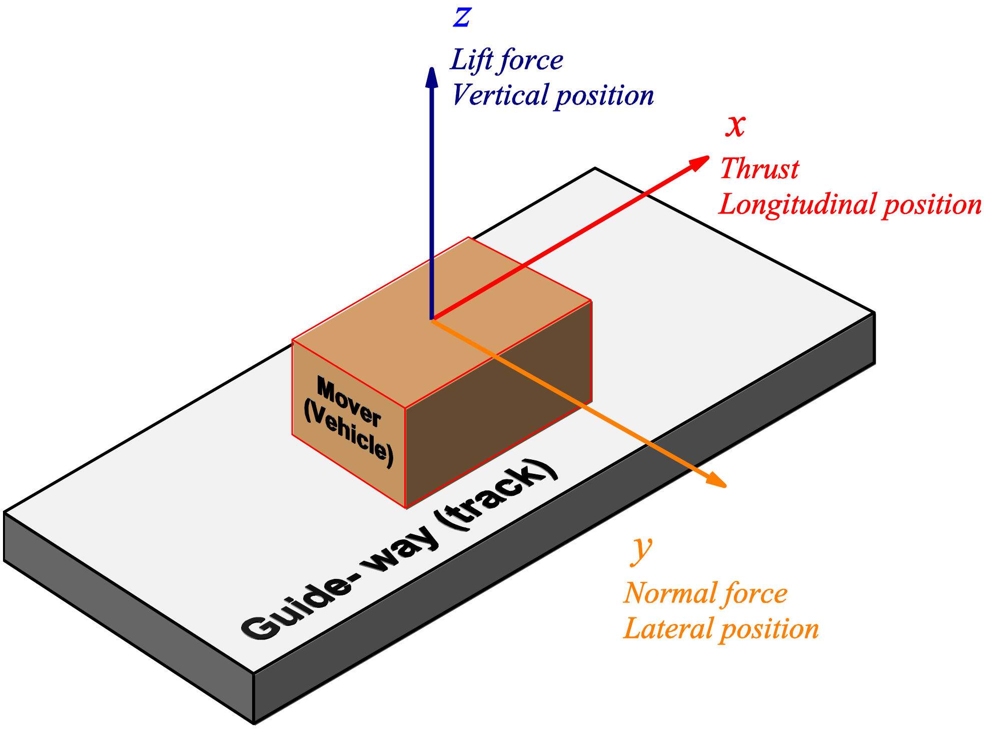


Figure 6. Basic functions of electrical linear motors

The lift force and lateral force can be generated with control, without control or with hybrid methods (Jeroen de Boeij et al., 2004)-(Wang and Busch-Vishniac., 1994). The realization without control is based on repulsive magnetic forces. These forces can be set up between the same polarity of poles of permanent magnets or with the aid of superconducting magnetic coils. By using electro-dynamic levitation or null-flux coils

(Jeroen de Boeij et al., 2005) passive magnetic guidance can be provided for one or more degrees of freedom. The drawback is the dependence on the longitudinal speed i.e. it does not provide guidance at standstill. The superconducting magnetic bearing (S. O. Siems and W. R. Canders, 2004) is a passive guidance method that works even in standstill, but it requires a cryogenic system instead. In addition, more destabilizing forces occur when the levitation is implemented (C. Navau et al., 2003). Therefore, the levitation is not concerned in this dissertation in detail.

As mentioned above, the applications here deal with linear drives for industrial material handling, consequently high-speed maglev trains are not dealt. The researches are mostly related to machine tools and building applications. Researches in this area will be presented in the next subsections.

2.3. Researches in industrial material handling and processing area

As already stated, studies based on only one basic function, e.g. on thrust generation only, such as (Kinjiro Yoshida et al., 2001), give less emphasis. Almost all the studies mentioned in this subsection try to handle with several basic functions.

In (K. Ben-Yahia and G. Henneberger, 1999), a linear drive with active translator is handled as shown in Figure 7, in which three basic functions: thrust generating, vertical lifting and lateral force are realized by separate components. In the active translator, four magnet modules assure the magnetic levitation and the guidance of the table. The levitation and the guidance here are implemented by a combination of permanent magnets and electrically excited magnet.

As shown in Figure 8, a homopolar synchronous linear motor (W. Evers and G. Henneberger, 1999) is described with contact-less energy supply for the active translator. The upper part of Figure 8 shows a lifting magnet for the levitation together with basic function of lateral guidance. The combination of lift force and lateral force is also performed in (D' Arrigo and A. Rufer, 1999), which is shown in Figure 9. However, the lateral guidance in (W. Evers and G. Henneberger, 1999) and (D' Arrigo and A. Rufer, 1999) is uncontrolled.

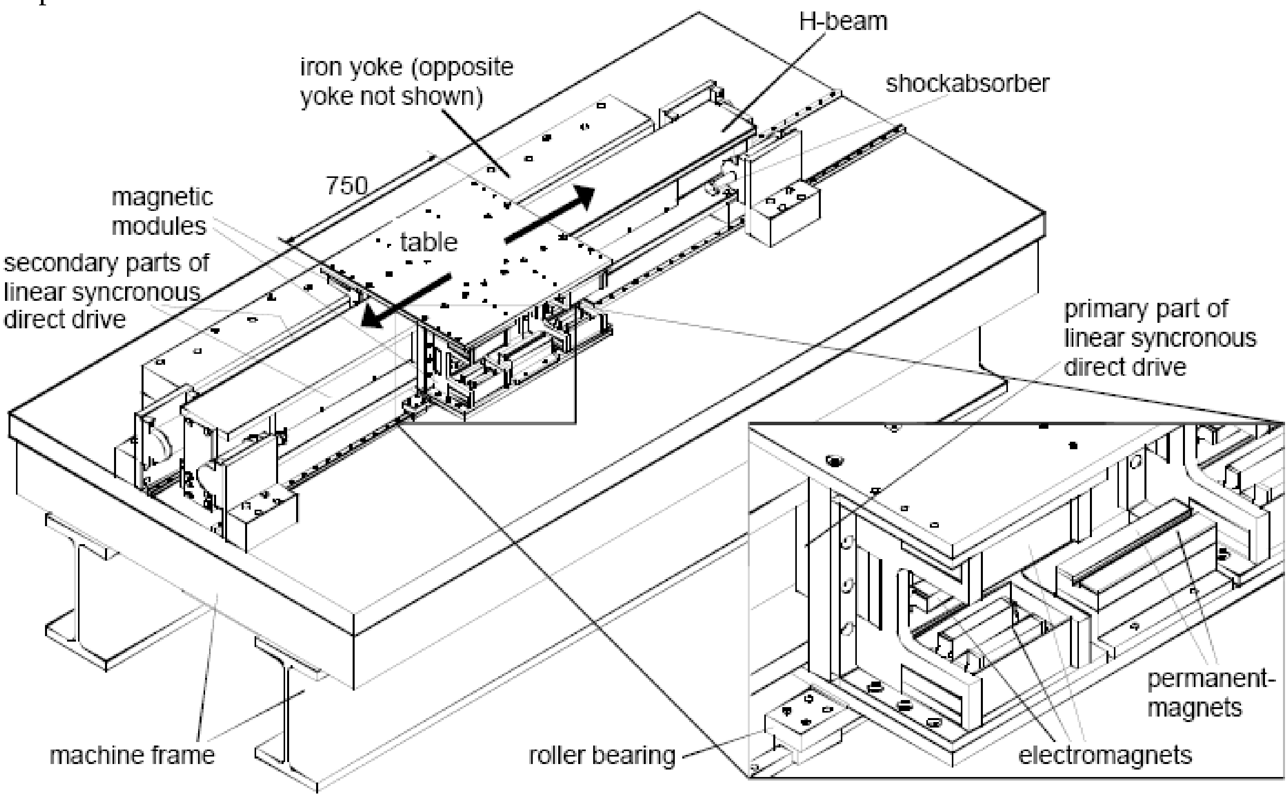


Figure 7. Linear drive with active translator (K. Ben-Yahia and G. Henneberger, 1999)

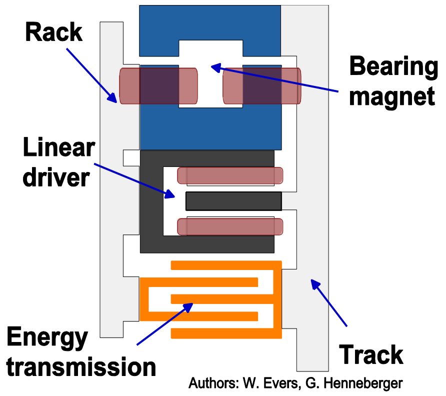


Figure 8. Non-contact energy supply

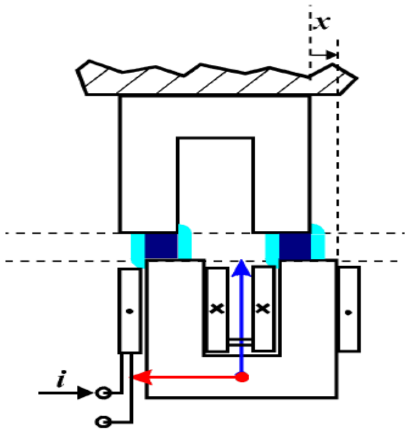


Figure 9. Lifting and guiding combination

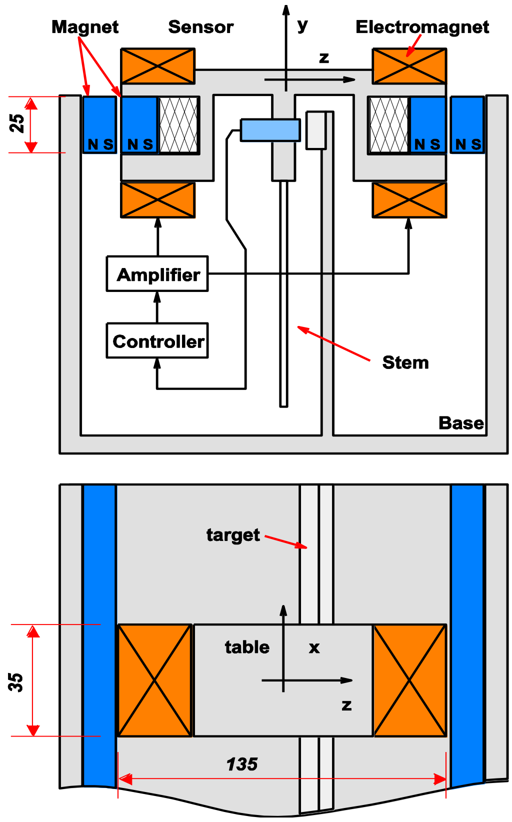


Figure 10. Lifting and guiding (da Silva and O. Horikawa, 2005)

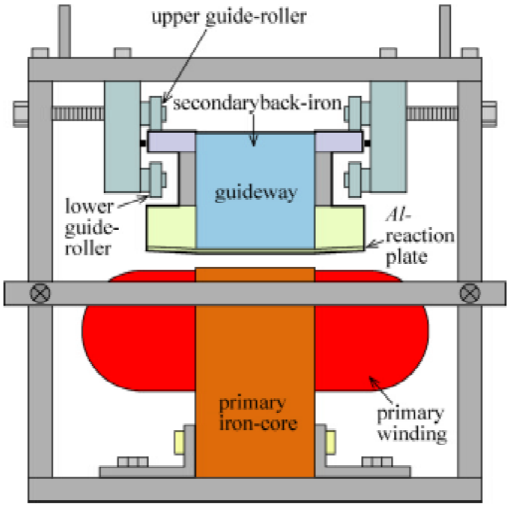


Figure 11. Lifting and guiding in (K. Yoshida et al., 2001)

The lifting and guiding functions are solved in Figure 10 of (da Silva and O. Horikawa, 2005), where the permanent magnet is lifted in y-direction and guided in z-direction by controlling the electromagnets. In this approach, an active vehicle is required in order to supply power for the electromagnets and the control system.

The combination of the lift force due to attractive normal force and the thrust, which are generated by an asynchronous short stator motor with necessarily active vehicle as discussed in (K. Yoshida et al., 2003), is another solution. This is shown in Figure 11.

In the arrangement of Figure 12 (Profumo F. et al., 1999; Profumo F. et al., 2000), the repulsive force is applied by the same polarity of magnetic poles in order to lift the vehicle up (without control) ②, ④. Thrust is produced by a synchronous long stator double side linear motor with internal ironless permanent magnet cursor ⑧. Due to the ironless magnetic cursor and the permanent magnetic lifting system, the normal and the vertical rigidity of the guidance system are very low. Consequently, only small separated actuators ⑥ with sensor ③ are included in the vehicle (active vehicle) for lateral force generation. The actuators have to generate small forces in the directions orthogonal to the motion (normal force) to align the bogie.

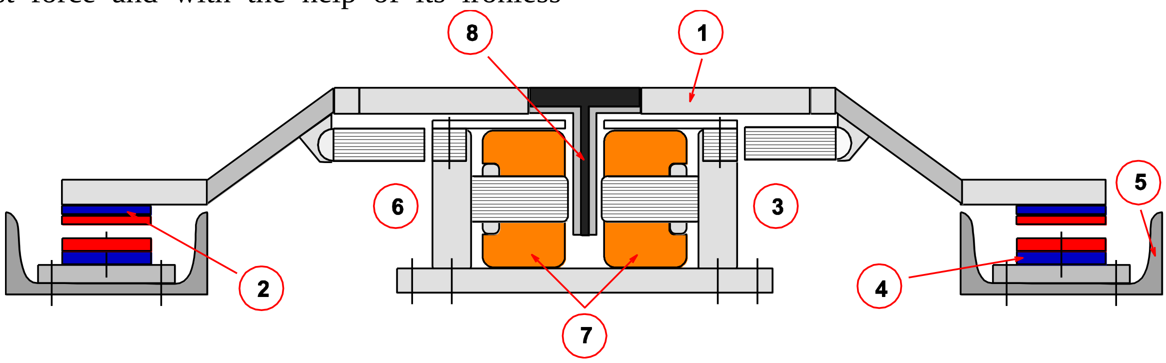
In (P.L. Jansen et al., 1993), an overview about the different arrangement of linear asynchronous is given. In contrast to the above studies, a long stationary primary is analysed to generate the thrust and the normal force for a material transportation system with very high accelerating rate. The magnetic lift force is not necessary, because the vehicle is equipped with wheels.

In addition, supporting wheels and guiding wheels are used for the vehicles of the project “new rail technology Paderborn”, e.g. (Bo Yang et al., 2001; Bo Yang et al., 2003), and (Andreas Pottharst et al., 2002) with a special feature. That is a double-sided linear asynchronous machine implemented in an active vehicle.

Similarly, supporting wheels are used in the vehicle of (Kinjiro Yoshida et al., 2001). The synchronous long stator linear motor generates thrust force and with the help of its ironless stator winding a repulsive force to reduce the axle load. This principle is shown in Figure 13a. In order to acquire feedback signals for the axle load control, force sensors and radio transmitters are inserted in the vehicle (Figure 13b).

In Figure 14, the rope-less elevator from (K. Yoshida et al., 2003) is shown. The lateral position of elevator cage is guided in the elevator shaft by forces $F_{z1} \div F_{z4}$, which are produced by current supplied coils of controlled permanent magnets (CMP). The guidance is established by controlling the positions (δ_1, δ_2) simultaneously. The positions are controlled by actuating the currents of the CMPs. Nevertheless, in (K. Yoshida et al., 2003) not many results are shown. With the proposed structure, only simulation results for a sensor-less control of the lateral position is shown. In addition, an active translator (elevator cage) is necessary.

One of the first products has been already commercialized for material handling based on linear motors is shown in (http://www.magnemotion.com). The synchronous long stator motor produces the thrust force. To produce lateral force, permanent magnets are used. The vertical force is supported by wheels. With them, the vertical force of the magnets boost the axle load i.e. friction and abrasion are increased. In Figure 15 (http://www.magnemotion.com), some other similar commercial products from MagneMotion are introduced.



① bogie, ② Magnetic guide (moving part), ③ lateral positioning sensor, ④ magnetic guide (unmoving part), ⑤ lateral reference guide, ⑥ electromagnetic actuator, ⑦ stator, ⑧ cursor
Figure 12. Lifting and guiding in (Profumo F. et al., 1999; Profumo F. et al., 2000)

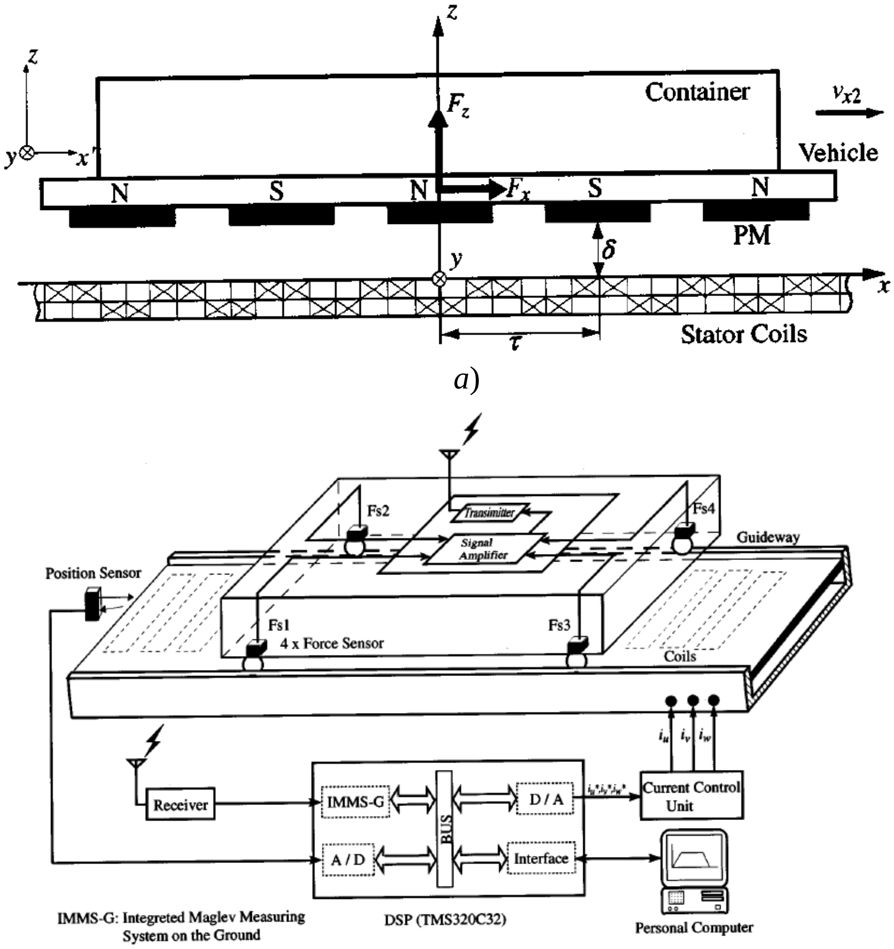


Figure 13. Supporting wheels in (Kinjiro Yoshida et al,. 2001)

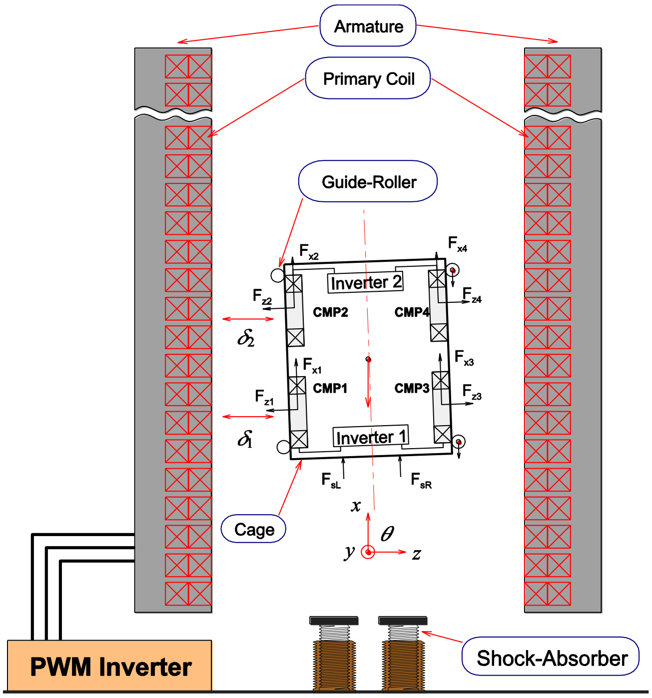


Figure 14. Elevator in (K.Yoshida et al., 2003)

Figure 15. MagneMotion system (http://www.magnemotion.com)

3. Conclusion

On the whole, linear motor is invented and developed for long time. But until now it is continuously studied in order to find out its advances in special applications. Application for industrial material handling and processing is one of the applications. In the trends of this application, there are many challenges need to be overcome. It gives to researchers opportunities to study.

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