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Re-Design of a Packaging Machine Employing Linear Servomotors: a Description of Modelling Methods and Engineering Tools

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Abstract

Position-controlled servo-systems mostly make use of electric rotary motors and gearboxes and, if necessary, a transmission mechanism to convert rotary into linear motion. Even so, especially in the field of automatic machines for packaging, it should be highlighted that most of the required movements are usually linear, so that Linear Electric Motors (LEM) should somehow represent a more convenient solution for designers. LEM can directly generate the required trajectory avoiding any intermediate mechanism, thus potentially minimizing the number of linkages/mechanical parts and, therefore, the undesired backlash and compliance that come along. On the other hand, particularly within small-medium enterprises, LEM may be rarely employed despite obvious advantages, mostly due to their high-cost as compared to rotary actuators and the lack of knowledge of the achievable performance. In light of these considerations, the present paper reports an industrial case study where an automatic machine for packaging, comprising distributed actuation and several tasks requiring a linear motion, has been completely redesigned employing different kind of LEM (i.e. iron-core and iron-less). Such machine architecture is compared to a "traditional" design where brushless gear-motors are coupled to linkage systems. The paper mainly focuses on the selection criteria for the LEM system and on the engineering tools employed during the different design stages. Qualitative and quantitative conclusions are finally drawn, which may provide useful hints for designers that are willing to actually employ LEM-based solutions in an industrial scenario

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Keywords: Engineering Design Methods and Tools for Industry 4.0, CAD/CAE, High Precision Manufacturing, Modelling and Simulation

1. Introduction

In the broad field of automated production systems, the concept of "operating flexibility" may be defined as the possibility to change/modify the production purpose and the related operations, with few or no changes in the hardware structure of the system itself [1,2]. In this case, such modifications are actually achieved only through changes in the

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governing software, that is the set of information and programs that determine the system behavior. In practice, an automated line, as well as a single automatic machine, may be classified as "flexible", or multi-purpose, when it is designed to carry out variable operating tasks, the machine purpose and the related procedures being easily changeable or modifiable throughout the machine lifetime. Henceforth, task variation is obtained by mainly acting on the information flows at software level, with negligible or limited hardware modifications. Although it is necessary to observe that, in the industrial practice, there are no automatic machines that can be defined completely "rigid" or completely "flexible", an increased operating flexibility of an automated line shall be pursued according to the needs of the process to be implemented: in a broader sense, as also explicitly requested by the Industry and Factory 4.0 paradigms [3,4], an increased flexibility aims at effectively fulfilling quick market changes that, in turn, requires an easy and fast adaptability of production means to different product mixes.

In terms of engineering solutions, the '*zero-time format change*' [5], ideally enabled by a machine allowing to instantaneously modify its production goal without part substitution, human intervention and/or tuning operations, represents an exciting challenge for machine designers. Once again recalling the I4.0 framework, designers are thus heading towards new approaches to define the control and actuation architectures, driven by this increasing demand for multi-purpose, reconfigurable production lines. In this scenario, distributed-actuation is nowadays preferred over mechanical architectures where the local movements are generated through complex kinematic chains driven by single central actuators, even if they are highly performing and reliable. The motion of each operational tool is then achieved directly, via a properly located actuator that generates the necessary trajectory by means of a programmable control system rather than by purposely-designed mechanisms (such as cams, indexers or similar devices), that are functionally rigid and best avoided. An exemplary case is reported in Fig. 1a, which depicts a Permanent Magnet Synchronous Motors (PMSM), namely the de-facto industry standard for position-controlled electric motors in the field of high-performance packaging machines, coupled to a linkage system with the interposition of a gear reducer. An interesting alternative, considering that many required movements in packaging machines are actually linear, a simpler design solution would actually employ Linear Electric Motors (LEM) that can generate the necessary trajectory without intermediate mechanisms and reduction stages, thus minimizing backlash, friction and compliance. An example is depicted in Fig. 1b, which illustrates a LEM-based design alternative to the solution schematized in Fig. 1a.

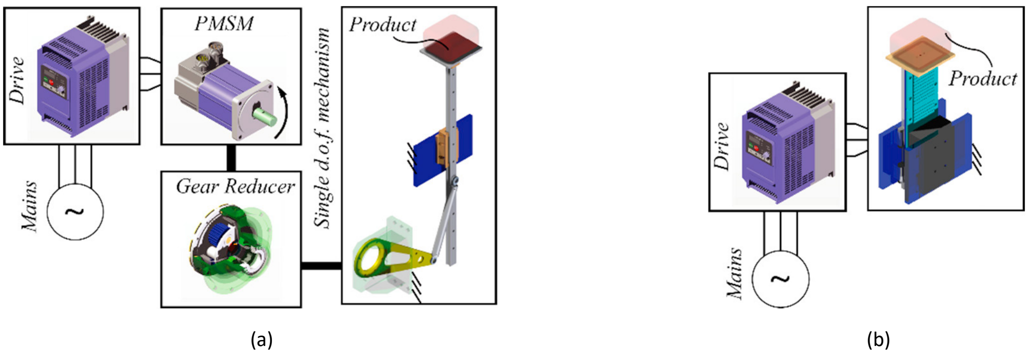


Fig. 1. Position-controlled servo-systems: (a) rotary actuator and linkage system; (b) LEM-based, direct-drive solution.

Owing to this simple consideration, the aim of this paper is to describe an industrial case-study, where a packaging machines for paper rolls, whose current embodiment design comprises several single degree-of-freedom linkages actuated by brushless gear-motors, has been completely re-designed employing different type of LEM. The aim of the paper is therefore to describe the tools employed in the conceptual design phase and to provide a critical evaluation of the novel design solution (also in terms of possible cost increase). The rest of the paper is organized as follows: Section 2 briefly recalls basic LEM background; Section 3 describes the methods and tools employed for LEM selection; Section 4 describes the above-mentioned industrial case study; Section 5 provides the concluding remarks.

2. Basic Background

Applications requiring the implementation of linear motions are countless. Common systems that may be used for the purpose are pneumatic/hydraulic cylinders, pulley/belt or rack/pinion couplings, cam or linkage mechanisms with rotary actuators (e.g. slider-crank mechanism driven by an electric motor, as in Fig. 1a), and LEM-based systems (as in Fig. 1b). The first three design solutions, although very widespread, often suffer several limitations, here including rather poor positioning accuracy, backlash, friction and noise. Cam systems and position-controlled linkage mechanisms are commonly employed in automatic machines requiring high dynamic motions and respectively characterized by either concentrated or distributed actuation systems. Focusing on the latter architecture, LEM can be envisaged as an interesting design alternative by offering the capability to directly develop a linear motion with better efficiency, longer device lifespan, improved precision, limited wear, backlash and noise [6-9].

A linear motor is basically an electric motor in which the rotor (mover) and the stator are "unrolled" instead of being circular, thus producing a force (thrust) instead of a torque. Although one may find several LEM typologies, linear PMSM represents the preferred solution for industrial automation. According to the constructive characteristics, LEM can be divided into three categories:

- *Iron-Core* LEM. They are capable of achieving the highest thrust values, also providing the possibility to achieve a good cooling thanks to the large heat exchange surface. This LEM is characterised by the presence of a ferromagnetic nucleus, thus implying a significant attraction between stator and mover, along with a high inertia of the mover itself.
- *Iron-Less* LEM. They allow an excellent exploitation of the magnetic field thanks to their symmetrical morphology, which also eliminates the presence of attraction forces. The mover's mass is lower as compared to Iron-Core LEM, whereas the heat exchange surface is smaller (due to the "closed" structure), thus limiting cooling capabilities and maximum thrust. They are particularly suitable for executing high dynamic motions.
- *Tubular* LEM. They offer an excellent exploitation of the magnetic field thanks to their axis-symmetric morphology. Since the windings are placed externally to the structure containing the permanent magnets, this type of motor provides a good thermal behaviour (i.e. a self-ventilating effect that guarantees the easiness of cooling) and it is characterised by a low construction costs of the windings. The main disadvantages are related to the limitation of the achievable stroke and to the fact tubular LEM do not offer high thrust values.

A brief overview of LEM morphologies and related exemplary CAD drawing is reported in Table 1.

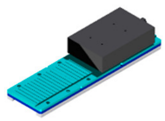
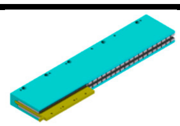
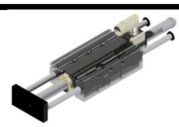
2.1. LEM performance – theoretical accelerations

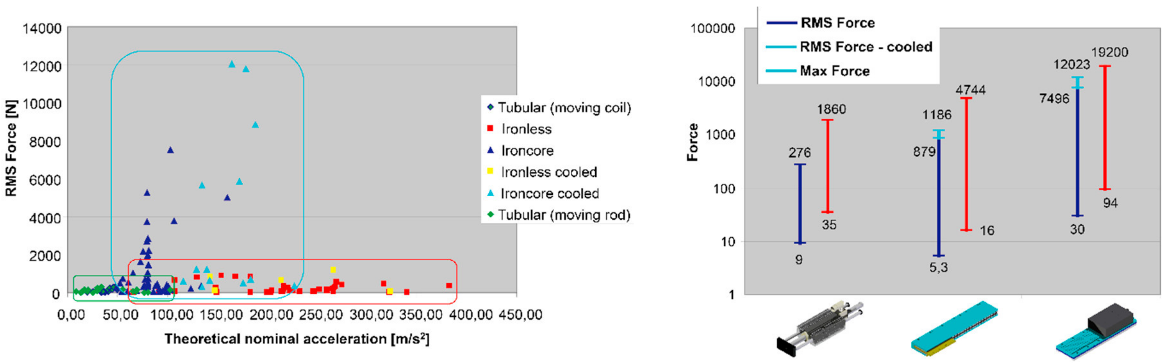
In order to quantitatively evaluate the LEM performance and easily compute if the required motion profile may be actually realized via a particular LEM model, it is useful to define a quantity, hereafter referred to as *theoretical acceleration*, that is simply computed as the ratio between the LEM thrust and the mover's mass, m_m. Theoretical acceleration values, as well as LEM thrust, can be calculated for both nominal (Root-Mean-Square, RMS) condition and peak (maximum) values. It is therefore possible to define a nominal, $a_{th,rms}$, and a peak, $a_{th,max}$, theoretical acceleration as:

$$a_{th,rms} = \sqrt{\frac{\int_0^T F_m^2(t)dt}{T}} \cdot m_m^{-1} = F_{m,rms}/m_m \qquad (1) \qquad\qquad a_{th,max} = F_{m,max}/m_m \qquad (2)$$

where $F_m(t)$, $F_{m,rms}$ and $F_{m,max}$ are, respectively, the instantaneous, RMS and maximum LEM thrust value and T is the period of the cyclic motion under investigation. The $a_{th,rms}$ value indicates the maximum acceleration that the LEM is able to perform *continuously*, by moving its own mover only. In other words, assuming to provide a linear motion to the LEM mover only, it is possible to indefinitely accelerate the mover with a maximum acceleration equalling $a_{th,rms}$. Similarly, the $a_{th,max}$ value indicates the maximum *instantaneous* acceleration. Naturally, these theoretical values represent upper limits that are not practically achievable in real applications, since it will never be possible (or at least, it is not actually useful) to set in motion the LEM mover only. The overall LEM-based system shall indeed necessarily comprise other moving parts and components such as linear guides, sensor, cables and, of course, the specific operational tool, which provides a specific function to be performed on each product unit. Nonetheless, theoretical accelerations provide very useful information regarding LEM first attempt sizing. In particular, Fig. 2 provides a comparison of the achievable performances for the various types of motors (as in Tab. 1), referring to RMS and maximum acceleration values, as well as the presence or absence of a cooling system.

Table 1. Overview of LEM morphologies and qualitative comparison.

Motor type	Iron-Core	Iron-Less	Tubular
Exemplary CAD Model			
Advantages	• High thrust (up to 30 kN); • Good capability to dissipate heat; • Stroke modularity; • High structural stiffness of the part containing the windings; • Relatively low cost; • Possibility for PM to act as mover, in case of limited stroke (thus, avoiding moving cables).	• Reduced coil mass, meaning high accelerations; • Stroke modularity. • Absence of attraction forces, due to the symmetry of the magnetic field; • No cogging.	• Absence of attraction forces, • Excellent capability to dissipate heat; • Cost effectiveness • Integrated position sensor.
Disadvant.	• Presence of a ferromagnetic core: - High attraction force (thus, high loads on linear bearings); - High mass of coil • Cogging	• Bad capability to dissipate heat, due to the closed structure • Lover structural rigidity of the of the part containing the windings • High cost	• Limited stroke; • Edge effects: reduction of thrust at stroke limits. • Limited thrust;



(a) (b)

Fig. 2. Comparison of achievable performance with different linear PMSM types: (a) RMS Force (thrust) as function of RMS theoretical acceleration; (b) comparison of RMS (with & without cooling system) and Maximum Force for Tubular, Iron-Less, Iron-Core LEM.

For tasks requiring high dynamic motions, it is frequently the case that the most demanding performance requirement to be met concerns the maximum force that can be exercised continuously, namely $F_{m,rms}$. In the event that a LEM cannot provide the required RMS thrust, it is then necessary to resort to a larger motor size (or a different typology, e.g. Iron-Core). However, an increase of size also implies an increase in mover's mass, m_m, hence limiting the consequent increase in the $a_{th,rms}$ value. As an alternative solution to the selection of larger LEM, the designer can consider cooling the motor windings (e.g., either by an airflow from a fan or compressed air jet or through water cooling). The latter solution generally allows a substantial increase in the LEM performance, at the expense of the need fto refrigerate the system and, if the windings are employed as the moving part of the motor, to provide a mean to guarantee that water tubes shall be connected to the moving part of LEM. On the other hand, it is sometimes possible to employ the LEM permanent magnets as the mover, thus obtaining a compact and "clean" design as no cables or pipes are in motion (i.e. power cables, sensors and cooling). Such design strategy is actually applicable to Tubular or Iron-Core LEM only, being unpractical in case of Iron-Less due to the large weight of the symmetric magnetic track.

3. LEM sizing: engineering methods and tools

In order to proceed with the LEM sizing, it is necessary to estimate the overall magnitude of load and inertial forces. In most applications related to automatic machines for packaging, inertial forces are, by far, the dominant load type, especially in case of very fast, intermittent motions. Naturally, in addition to inertial loads, there will be dissipative phenomena linked to the friction within the linear guides (bearings) and to the bending resistance of cables and cable holders. Generically speaking, in order for the LEM to be capable of withstand its task, the following condition must be satisfied at all times:

$$F_m \geq F_c = m_{tot} \cdot a_c + F_d \tag{3}$$

where F_m, F_c, and F_d are, respectively, the motor thrust, the overall resistive load and the dissipative forces acting in the system, whereas m_{tot} is the overall mass of moving parts that are subjected to an acceleration a_c. Since the computation of the inertial force requires the LEM mover mass, m_m, as input, which is known only once a specific actuator has been chosen, the LEM sizing procedure is necessarily iterative. Nonetheless, some simple considerations can be useful to simplify the process. In particular, the total mass of the moving parts can be subdivided as follows:

$$m_{tot} = m_m + m_{aux} + m_{ot} \tag{4}$$

where, as said, m_m is the LEM mover, $m_{aux}$is the mass of all auxiliary components, such as the linear guides, the cables / cable holders, the moving part of the position sensor, etc., m_{ot} is the mass of the operational tool of the application, also including the mass of the product unit to be handled, if present. Recalling the definition of theoretical acceleration, from Eqs. 1-4 and neglecting the contribution of the dissipative forces (i.e. $F_d \approx 0$), it can be said that, in an application requiring an effective acceleration a_c, a LEM capable of a theoretical acceleration a_{th} and having a moving mass m_m, can manage to move a total load mass, m_c (also including auxiliary devices) equal to:

$$m_c = m_{aux} + m_{ot} \leq m_m \left(\frac{a_{th}}{a_c} - 1\right) \tag{5}$$

The value of the load mass m_c from Eq. 5 can be computed by referring to RMS and maximum a_{th} values (resorting to Eq. 1 or 2). Nonetheless, one can remark that, in general, the limit load mass value in encountered imposing RMS rather than maximum accelerations (which are usually 2 to 5 times larger). In any case, Eq. 5 highlights the obvious consideration that a rational design shall aim at minimizing the moving mass as much as possible. Qualitatively speaking, it is rather difficult to reduce the total mass by trying to reduce the term m_{aux}, since auxiliary parts mostly consist of commercial products whose use is dictated by strict requirements. Consequently, in order to increase the attainable performance of the LEM-based system, it is necessary to optimize any moving component of the operational tool and possibly of the motor itself. In fact, in the case of linear PMSM, mover and stator are normally purchased as "frameless" (i.e. without housing), so that the user must take care of the LEM frame design, activity that (besides being an additional burden on the user) may allow a better integration of these linear actuators within the overall machine architecture. The second fundamental aspect entails on the optimization of the required motion law [10-12], which directly affects the LEM dimensioning (see Eq. 3).

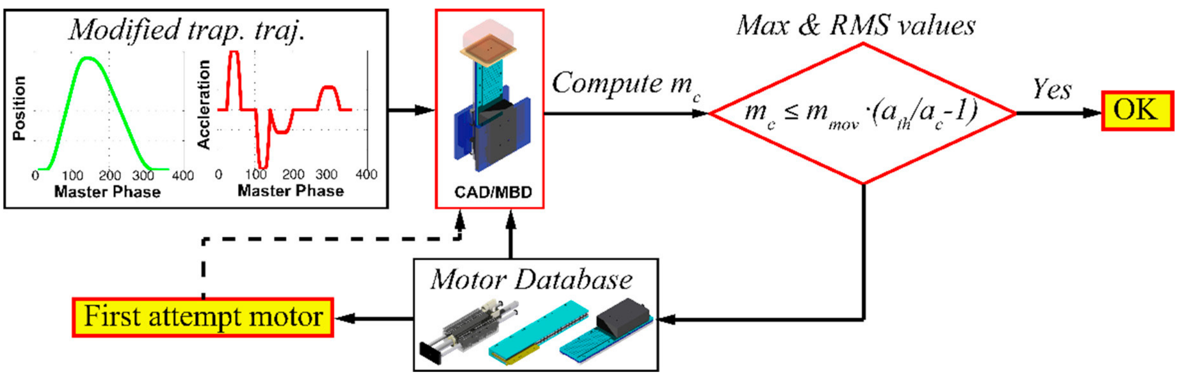


Fig. 3. Schematic of the LEM selection procedure.

Without providing further details regarding the optimization of the motion profile, which also heavily affect the system energy consumption (the interested reader may refer to e.g. [13-15]), for a rational LEM sizing, the designer can consider a trapezoidal acceleration trajectory [12], which surely represents a good compromise between the need to limit the requested RMS acceleration and the need to limit instantaneous jerk values. Accordingly, the sizing procedure is schematized in Fig. 3, the employed engineering tools being: *i)* SolidWorks as Computer-Aided Design (CAD) tool also comprising Multi-Body Dynamic (MDB) module for motion analysis; *ii)* Matlab, along with a special purpose toolbox (Slim), whose capability are well described in [5]. As for the motor database, it contains models from several LEM manufacturers (e.g. ETEL, Kollmorgen, Parker, LinMot).

4. Industrial case study: automatic machine for wrapping tissue rolls

The automatic machine considered as a case study wraps a certain number of paper rolls for domestic use. A schematic of a functional subgroup of the machine is depicted in Fig. 4: a set of rolls (six in the picture) is wrapped into a film that needs to be folded and then thermally sealed. Although the machine is specialized for mass production (up to about 200 packages per minute), it features a remarkable flexibility concerning the size change over, which allows to vary both the kind of rolls and the dimensions of the package (number of rolls and stacking type). The size changeover can be carried out quickly, with no replacement of machine parts but simply adjusting, via software, the functional parameters of the PMSM.

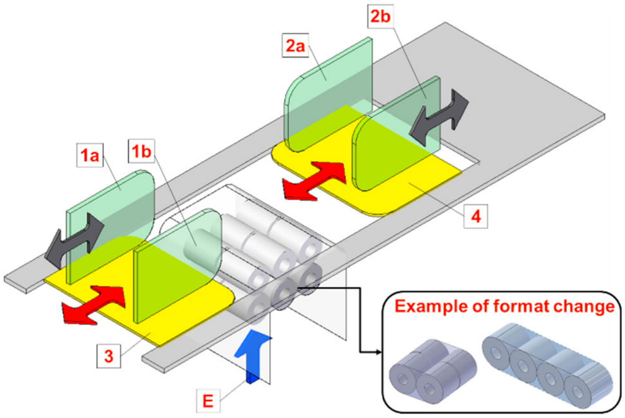


Fig. 4. Schematic of a flexible machine for paper roll wrapping-

Figure 5 depicts the 3D drawing of the actual machine embodiment design. The paper rolls are piled up and, subsequently, conveyed to an Elevator (mechanism not shown in the picture) whose function is schematized by the letter E in Fig. 4. The elevator transfers the paper rolls while enveloping them with a plastic film, that then needs to be properly folded before being thermally sealed. The lateral film hems are folded by the rigid plates 1a, 1b, 2a, 2b, shown in Figs 4 and 5, whereas the inferior hems are folded by plates 3 and 4. All plates shall provide linear intermittent motions (with programmable motion law), achieved by means of four PMSM, each coupled to a gear reducers and to a linkage system, namely slider-crank mechanisms for what concerns plates 1a/1b, 3 and 4, or a four-bar linkage connected to two slider-crank mechanisms for plates 2a/2b (see Fig. 5).

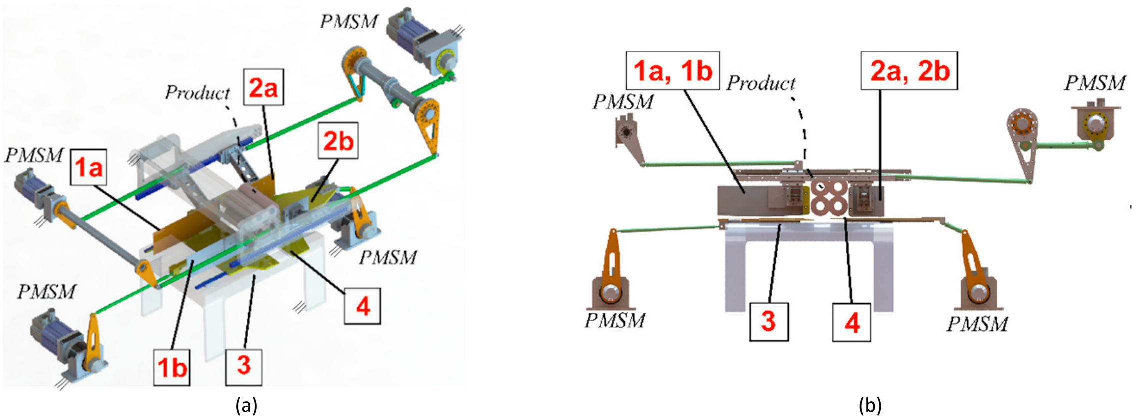


Fig. 5. CAD drawings representing the actual machine design: (a) 3D view and (b) lateral view.

The embodiment designs of two new machines architectures (*Design #A* and *#B*) employing LEM-based solutions are depicted in Fig. 6 and 7. In particular, for what concerns Fig. 6, all the selected actuators are Iron-Less linear motors. Note that plates 1b and 2b are not shown in the pictures since their actuation systems simply replicates the one employed for plates 1a and 2a, which are actuated by a single Iron-Less motor featuring 2 coils (one for each plate) and 3 magnet rails (so as to provide the required stroke). Similarly, Fig. 7 depicts a second alternative employing Iron-Core LEM whenever possible (i.e. for all plates with the exception of plate 3), hence considering the thrust limitations of this LEM architecture as compared to Iron-Less typology. In the case of Design #B, plates 1a and 2a are actuated by a single Iron-Core motor featuring 2 coils (one for each plate) and 7 magnet rails. Also plate 4 is actuated by an Iron-Core LEM, the magnet rails being employed as mover. In fact, the actual machine production rate can be achieved only providing water cooling to this last actuator (hence, the choice to fix the motor coil rather than the magnets, also avoiding moving cables).

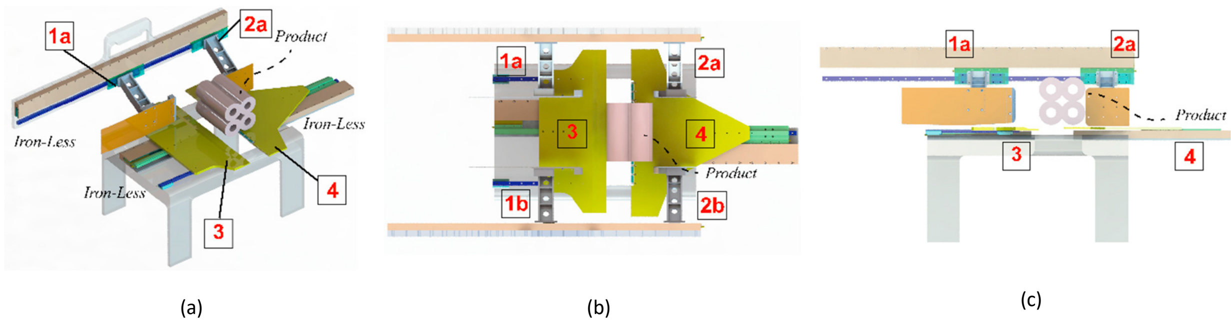


Fig. 6. *Design #A:* CAD drawings of the first LEM-based solution: (a) 3D view, (b) top view, (c) lateral view.

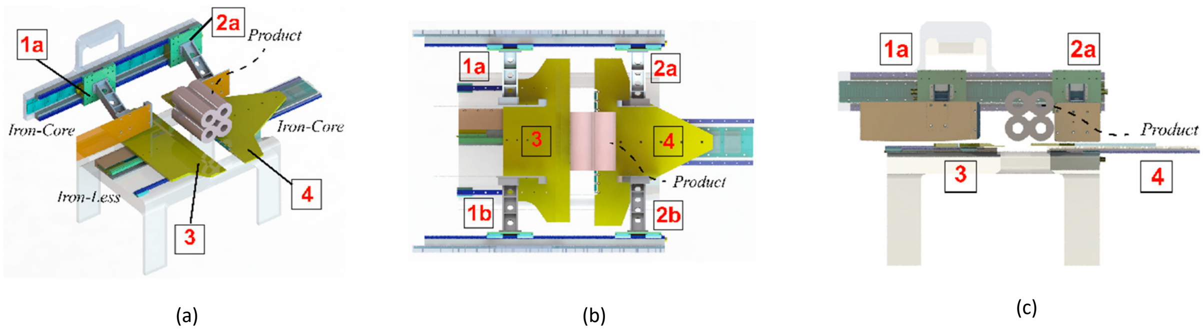


Fig. 7. *Design #B:* CAD drawings of the second LEM-based solution: (a) 3D view, (b) top view, (c) lateral view.

Table 2. LEM models overview, actuator cost, qualitative assessment of advantages and disadvantages.

Design #N	Motor Type & Model	Plate N.	Components	Cost (C)	Advantages	Disadvantages
#A	Iron-Less ETEL ILM 06-060	1a/1b 2a/2b	4 Motor Coils & 6 Magnet rails (2 & 3 each side)	$C \approx 14k€$	Directly applicable.	High cost.
#B	Iron-Core ETEL LMP 07-050	1a/1b 2a/2b	4 Motor Coils & 14 Magnet rails (2 & 7 each side)	$C \approx 5k€$	Low cost.	High vertical encumbrance.
#A/#B	Iron-Less ETEL ILM 09-060	3	1 Motor Coil & 2 Magnet rails	$C \approx 2.5k€$	Low encumbrance.	High cost..
#A	Iron-Less ETEL ILM 09-060	4	1 Motor Coil & 3 Magnet rails	$C \approx 4k€$	Low encumbrance.	High cost..
#B	Iron-Core ETEL LMP 07-100	4	1 Motor Coils & 4 Magnet rails	$C \approx 2k€$	Low cost; No moving cables.	Requires water cooling.

Overall, both *Design #A* and *#B* are more compact and better performing as compared to the solution employing rotary PMSM and linkage systems. Nonetheless, such improved design can be achieved at the expense of a substantial cost increase, which is mitigated whenever Iron-Core motors can be employed. An overview of the selected actuator models (and related costs) is reported in Tab. 2. The same table also provides a qualitative description of advantages and disadvantages of each solution (*Design #A* being the one chosen by the company for further development).

5. Conclusion

After a brief recap about linear motors typologies, the paper has described a functional group of an automatic machine for packaging that has been re-designed by substituting position-controlled rotary gearmotors, connected to linkage systems, with direct-drive linear actuators. In particular, on the basis of a machine virtual mock-up, the engineering tools employed during the design process have been presented along with the qualitative advantages and drawbacks of the proposed solution. Also, the cost aspects of this solution have been discussed. In summary, the main advantages associated with the use of linear motors may be listed as follows: • high compactness of the solution; • enhancement of the “free” volumes within the machine (allowing to place, e.g., the electric cabinet); • possibility to extend the strokes of the moving plates (thus increasing the range of formats that can be produced and the machine flexibility); • an increased positioning accuracy due to direct-drive technologies; • a possible reduction of maintenance requirements due to a reduced number of components. In parallel, as drawbacks: • presence of moving cables; • cost increase (substantial in case of Iron-Less motors).

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