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Application of Linear motor technology for variable speed passenger transportation systems

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Abstract. Moving walkways are high capacity continuous systems able to transport people. Their limitation today is the transportation time, due to the speed, to ensure a safe embarking and disembarking of passengers. The potential application of variable speed horizontal continuous systems to improve effectiveness of traditional moving walkways is analyzed in this paper.

Different existing concept alternatives to achieve variable speed are presented, stressing those that are currently open to the public. These solutions are based on mechanical systems that mostly include conventional motors with driving shafts, sprockets, gears, rollers and chain transmissions among others.

This paper gives a general overview of the background, motivation, technical solutions and challenges of variable speed solutions, focusing on the possible application of linear motor technology for the drive elements.

The normative, safety and comfort levels of variable speed transportation systems have to be analyzed under the existing knowledge and regulations of conventional moving walks and their particular aspects such as entry and exit speed, acceleration and jerk rates.

1. PRESENT AND FUTURE TRANSPORTATION CHALLENGES AND TRENDS

The twentieth century was characterized by many changes. Urban population increased from approximately 10% up to almost 50% and this trend is still ongoing today (Fig. 1). In 2012 approximately 3700 million people lived in cities and 2050 reports estimate that urban population will increase up to 6300 million representing almost 70% of the total world population. This increase in urban population is due in part to the attractiveness of the cities that arise in the economy, culture and rising living standards. There is a strong link between sustainable urban development and transport. Many cities have grown around the use of the car but this is not a universal transport. Future cities should be accessible and attractive to all residents and visitors. This means that cities must be designed for people, business, security and high quality environment.

Cities are changing, and understanding this evolution and people needs will help to define the future transportation trends. The ultimate goal is the increased use of public transportation to benefit from the economical and ecological advantages.

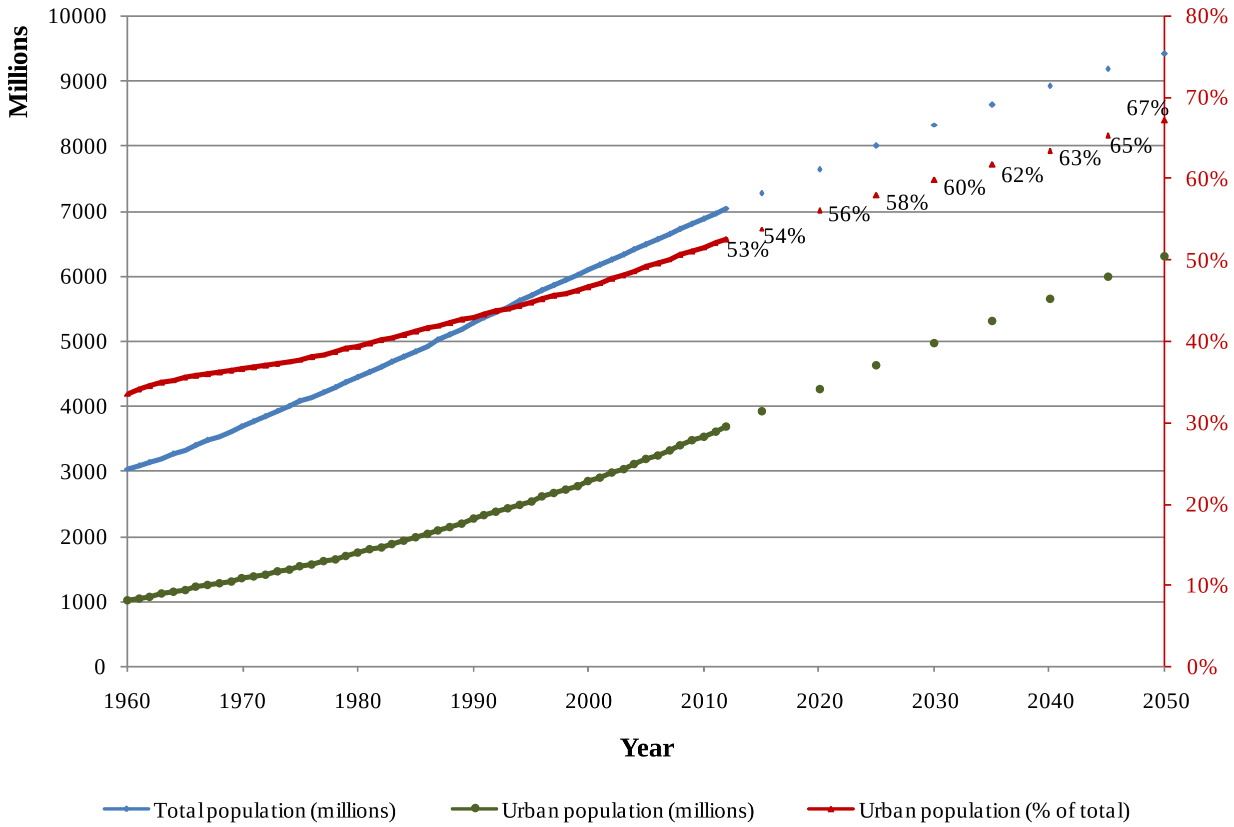

Fig. 1. Evolution of world population and urban population between 1960 and 2012 and forecasts 2050 (source: The World Bank)

Airplanes will be only used for long, cross- and intercontinental distances while high speed trains will be mainly used for long hauls. High speed subways and trains would be the main form of transportation used to get from one city to the next and from suburbs to downtown areas. Individual transport will be used mainly to cover the last few kilometers and happen only on a shared basis. Different layers of horizontal mobility will coexist at street level, underground and above street-level for pedestrians and there will be connections between them: mobility will become 3D.

On average, pedestrians do not like to walk more than 400 m, a range in which they will typically switch between modes of transportation. However, the average distance between metro stations in the city center is around 800 m to 1 km. There are some solutions capable to bringing passengers closer to conventional public transport like automated cabin based systems or PRT (Personal Rapid Transit) but they have low capacity so their use is limited in areas of high population density. To find a high capacity transport system suitable for distances between 200 m up to 1000 m could solve many challenges when configuring the cities of the future.

2. VARIABLE SPEED MOVING WALKS REQUIREMENTS

As part of present and future transportation trends and the need to fulfill increasing urban mobility requirements a gap in systems for transfer distances of between 200 and 1000 meters has been identified. Such trips are more demanded every day as urban mobility transportation needs and railway and airport sizes increase. For instance many airports use a several terminal facility structure so there is the need to commute between buildings typically 1000 m apart from each other. Other possible applications in this range are train and metro stations, transport interchangers, access from parking lots to exhibition centers, fairs or amusement parks.

Travel distances less than 200 m are normally covered by conventional moving walks, while distances higher than 2000 m are handled by APM (automatic people movers) (Fig. 2). For such distances travel time for conventional moving walks is too high as speed is usually limited for safety reasons. Cabin systems are not continuous, limiting achievable flow capacity, and requiring complex equipment, meaning higher financial and space resources. Also during breakdowns passengers are unable to complete the travel distance by their own means. As a result cabin systems are mostly used for long distance applications when their high speed effectively reduces travel time.

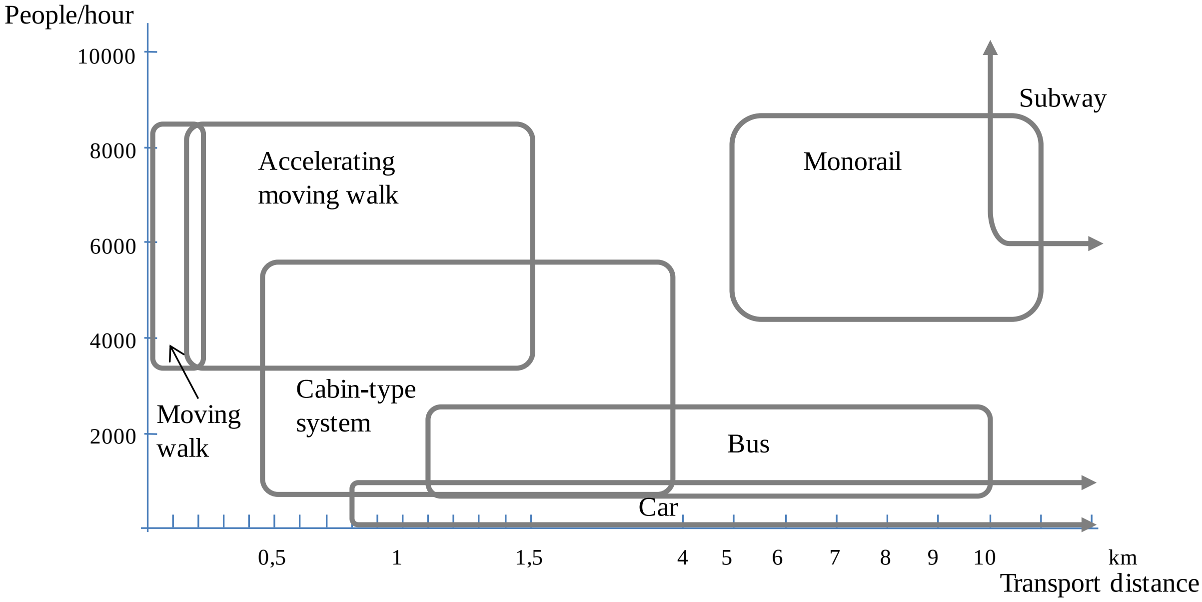

Fig. 2. Passenger flow and urban travel distance comparison of different people transportation systems (Source: internal research)

Variable speed moving walks are horizontal continuous transportation systems with the purpose of covering this identified gap in a continuous way and travel speeds around 3 to 4 times higher than conventional moving walks. Several moving walk manufacturers have tried to develop a system that can successfully give response to this need, but there are several technical challenges that need to be solved.

3. APPLICABLE STANDARDS

Variable speed moving walks have not been commercially available until mid 1990's and their application has been very limited. Subsequently, standards have not considered them specifically until very recently and yet there are very few references in current moving walk legislation. The main critical risk for passengers using a moving walk related to travel speed is the transition between the fixed part of the moving walk and the movable part if the relative speed is too high. Variable speed systems in which there is only one discrete speed change between fixed surface and maximum speed surface are considered safer in a similar way to conventional moving walks; given that the continuous speed increase occurs with a low acceleration value.

Regarding the most common applicable standards, "EN-115:2008+A1:2010 [1]" includes a brief reference to variable speed moving walks in chapter 5.4.1.2.3. Speed of conventional moving walks is limited typically to 0.75 m/s although speeds up to 0.9 m/s are accepted in some situations. However such limitations do not apply to moving walks with acceleration paths or with systems travelling at different speeds. "ASME A17.1-2010/CSA B44-10 [2]" standard also limits the maximum treadway speed for moving walks depending on the usable surface slope to 0.7 m/s or 0.9 m/s. The tenth edition of the Code (1981) incorporated Appendix G, Recommended Practice for Accelerating Moving Walks. This appendix was removed in subsequent editions so variable speed moving walks are not mentioned anymore.

Several studies identify the possibility of loss of balance depending on the acceleration. For instance, De Graaf, B. and Van Weperen, W [9] state that balance is maintained in a standing position with acceleration values lower than 0.5 m/s^2. Other studies recommend maximum jerk values of 0.5 to 0.6 m/s^3 for public transportation systems. Standards already state safe maximum acceleration values. Accelerating moving walks using such values should be as safe as conventional moving walks regarding speed increase. ASME A17.1-2010/CSA B44-10 [2] allows an acceleration and deceleration rate of up to 0.3 m/s^2 in conventional moving walks start-up. EN-115:2008+A1:2010 [1] allows acceleration rates up to 0.5 m/s^2.

Variable speed systems usually are based on a modification of the usable surface of the pallet and handrail. Any usable surface modification should be addressed regarding safety. The use of slotted surfaces and combs is usually considered the safest configuration in a similar way to the entry and exit areas of conventional moving walks. Ergonomic studies are carried out to increase passenger comfort and avoid any possible uncomfortable perception due to the higher speed compared to conventional moving walks.

Specifically for European legislation the harmonized standard identifies all potential safety risks according to EN ISO 14121-1:2007 [3]. Fulfilling such standard is a condition which assures the assessment of all identified machinery risks applied to moving walks. As some new risks may appear due to the specific characteristics of variable speed moving walks an individual risk assessment according to ISO 14798:2009 [4] is needed.

Due to the acceleration and higher speed values, the impact of passenger whole body vibration taking into account comfort but also health, motion sickness and perception in all three directions is filtered and evaluated according to ISO 2631-1:1997 [5], ISO 18738-2:2012 [6] and ISO 8041:2005 [7]. As a general rule pallet vibration values lower than 0.315 m/s^2 are considered not uncomfortable. Regarding hand vibration, standard ISO 5349-1 2001 [8] establishes the general rules to evaluate health impact due to vibrations on hand but there is no specific assessment regarding comfort. Noise values should also be evaluated according to ISO 18738-2:2012 [6]. EN-115:2008+A1:2010 [1] does not consider noise as a significant nor relevant hazard while emission sound pressure level is expected not to exceed 70 dB(A) for conventional moving walks.

4. STATE OF THE ART

First attempt to have a variable speed people transportation system was developed at the end of 19th century and finally constructed to start operation during the 1900 Paris Universal Exposition (Figure 3). The concept was based on two parallel conveyors running at different speeds and located adjacent to the fixed floor so that the passenger could move laterally from the slow speed surface to the high speed surface. The unit ran for a few months and several minor accidents were registered. The machine was finally closed and no attempt was made to improve the system.

At the end of the 1960’s, G. Bouladon and P. Zuppiger patented a new concept for a variable speed transportation system (US3580182) [10] (Fig. 4). It was based on moving platforms with rhomboid shapes which move laterally in a certain relative position to the boarding and landing areas. The result was an “S” shaped moving walkway which had wide areas in the slow speed sections and narrow ones in the high speed sections.

Based on the concept from G. Bouladon and P. Zuppiger, Dunlop initially and Mitsubishi some years later, developed driving systems resulting in real prototypes. The main disadvantages of this concept were the high space required for installation, the complexity of the driving systems and the difficulties to find a variable speed handrail synchronized with the moving platforms.

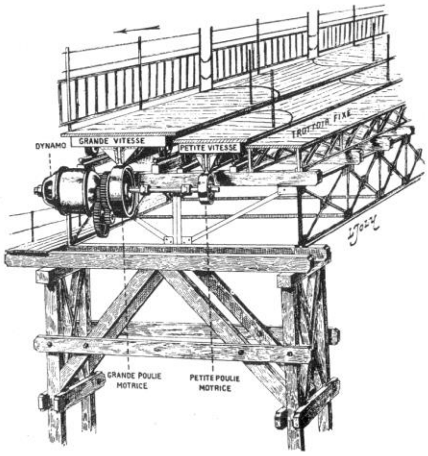

Fig. 3. L.Joly, Illustration, 1900 Paris Universal Exposition two speed moving walk diagram [15]

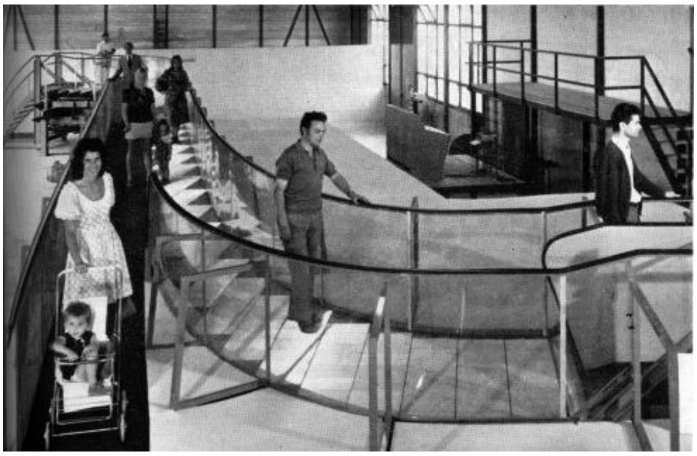

Fig. 4. G. Bouladon and P. Zuppiger variable speed moving walk using rhomboid platforms

Based on an invention from the Loderway company (J.L. Loder - EP0352968) [11] a variable speed transportation system unit was installed in Brisbane airport during the 1990's. The working principle consisted on a succession of closed belts running at different constant speeds. In parallel to the running belt, several running handrails synchronized with the moving floor, giving the user an area to hold the handrail. The main disadvantage of this type of conveyor is the speed leap between the different belts running at different speeds. Loderway moving walkway was opened to public for some months showing the feasibility of variable speed conveyors.

Up to date, the most ambitious attempt to install a commercial variable speed conveyor was carried out by the company CNIM [14] at Montparnasse metro station in Paris. The concept (Fig. 5) was based on closed treaded belts running in constant speed areas while the acceleration between them is achieved by a succession of small rollers running at different speeds. Transition between the acceleration and constant speed areas is achieved by means of free rotating elements covering the total surface of the transition. CNIM also implemented the first variable speed solution for the handrail. The concept was based in a rigid moving area and a flexible one acted by a mechanism with a guiding system which changed its length accordingly to achieve the required kinematics' behavior. Due to some accidents registered, most of them located in the variable speed transitions, the units were closed to public after some months of operation.

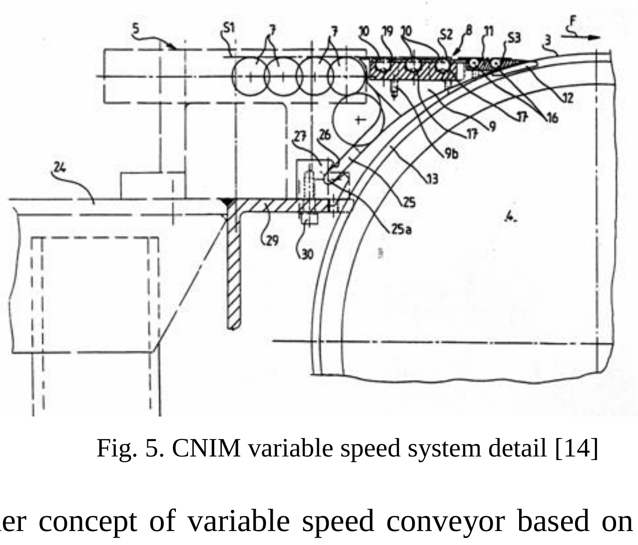

Fig. 5. CNIM variable speed system detail [14]

Hitachi patented another concept of variable speed conveyor based on a retractile pallet which is completely folded in the low speed section while a treaded surface is exposed to the users between adjacent pallets as the speed increases. Maximum speed of this concept is limited to 1.8 times boarding speed, which is below the potential speed increase of the other variable speed concept systems. In addition, in the invention (GB 2264686) [12] it is not mentioned how a smooth transition between the treaded surface and the rest of the areas is achieved when the treaded surface disappears in the area where the speed is reduced.

5. ARCHITECTURE OF THYSSENKRUPP VARIABLE SPEED MOVING WALK

Currently there are only two variable speed moving walk units in operation in a public environment, which have been developed by ThyssenKrupp and commercially named as TurboTrack[R]. The first related patent was published in 2003 (M. Alemany et al. - EP1253101) [13]. Since then several more patents were published describing the different subsystems of the overall conveyor and several possible solutions proposed. The transportation system is based on a principle of a succession of overlapped pallets (Fig. 6) which form the moving surface. Each pallet consists of a short body pallet and a long body pallet with a hinge joining them. In the high speed area, both the short and long pallets are accessible to passengers while as the speed is reduced long pallets start to move underneath the adjacent short pallet. When the conveyor reaches the minimum speed, long pallets are not accessible to passengers and the usable surface is formed only by the succession of short pallets.

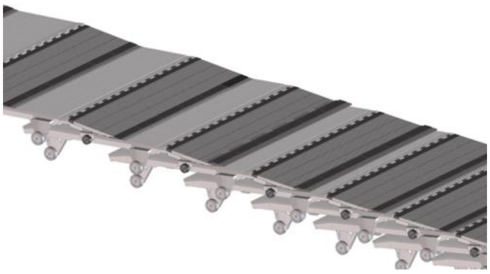

Fig. 6. ThyssenKrupp TurboTrack pallet system

Fig. 7. Grasps and covers distribution of the handrail system

During acceleration and deceleration, there is a relative movement between the short and the long pallets. Combs are located in the short pallets to mesh into the adjacent long pallet and assure a smooth transition for the users in case they stand in the long pallet in the deceleration area. This pallet concept is a continuous and variable transportation system that has been safely working at Pearson Toronto airport since April 2009.

From a user point of view, the TurboTrack handrail system is similar to the pallet. The moving area consists of a succession of two parts, grasps and covers (Fig. 7). In the low speed sections only grasps are accessible to the user while as the moving walk accelerates covers appear below between adjacent grasps. Small treads in the grasp intermeshing into the cover reduce the potential risk of entrapments between both components due to relative movement.

In the high speed areas, the pallets are moved by a chain drive system (Figure 8). When the pallets reach the variable speed area, they are mechanically disengaged from the chain and engaged to a variable pitch screw located longitudinally to the conveyor. As the pitch of the screw decreases the speed of the pallet assembly is reduced proportionally. When the pallets reach the comb level at low speed, the pallet speed is increased again by changing the pitch of the screw and is mechanically engaged to the chain when it matches the chain constant speed. With this system a continuous speed profile is achieve between the boarding low speed areas and the central high speed areas (Fig. 10)

For driving the handrail (Figure 9) the cover is connected directly to the drive chain and it is running all along the moving walk at high speed. In the high speed areas the grasp is mechanically engaged to the drive chain and moved by it. When the grasp reaches the variable speed area it is mechanically disengaged from the chain and driven by a variable pitch screw synchronizing the grasp with the short pallet below. The power to move the handrail drive is transmitted from the main drive shaft with a chain.

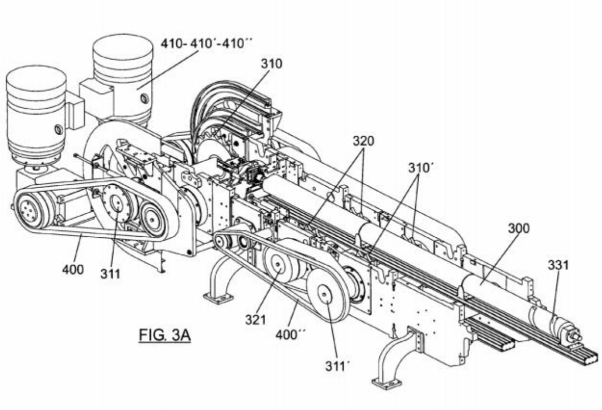

Fig. 8. Pallet band drive and transmission systems

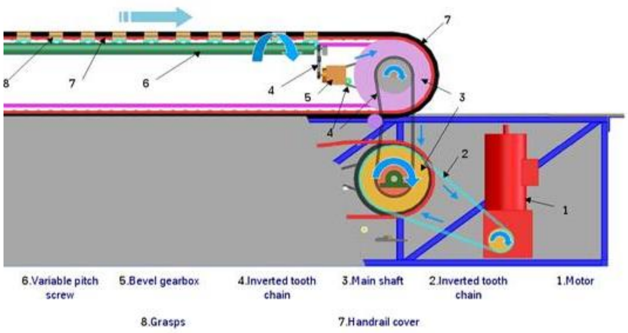

Fig. 9. Handrail drive and transmission

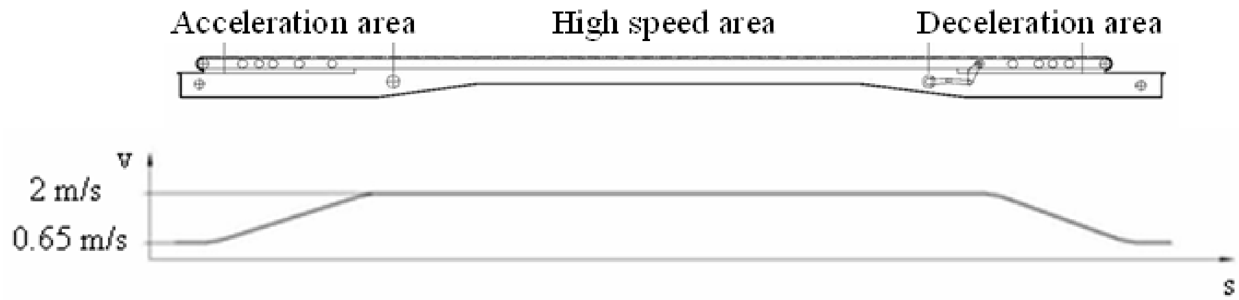

Fig. 10.Variable speed moving walk speed profile, speed (v) vs. distance (s)

The synchronization of the different drive systems of the moving walk is carried out completely mechanically by means of gears, wheels and chains. The application of alternative technologies like linear motors to electronically control the variable speed and drive any of the TurboTrack subsystems could potential simplify the architecture of the system.

6. APPLICATION OF LINEAR INDUCTION MOTOR TECHNOLOGY IN VARIABLE-SPEED SYSTEMS

Up to now all variable speed moving walk systems have used centralized drives to achieve pallet band movement. However it would be possible to drive pallets individually provided that the required speed profile is achieved independently. The most effective way is to drive pallets linearly in the direction of motion but there is a challenge on how to provide such power to each pallet. This may be possible using Linear Induction Motor (LIM) technology.

A linear motor is an electric motor with its stator and rotor distributed so that instead of rotating produces a linear force along its length. The applied force is linearly proportional to the electric current and the magnetic field (Lorentz-type actuator) (Eq.1)

$$\vec{F} = q * \vec{v} \times \vec{B} \qquad \text{(Eq. 1)}$$

where $\vec{F}$ is the applied force, q is charge of the particle, $\vec{v}$ is the velocity and $\vec{B}$ the magnetic field, Linear synchronous motors (LSM) are linear induction motors with a three phase winding on one side of the air-gap and a set of magnets with alternating poles on the other side. These magnets might be permanent or electromagnets. The operating principle of the linear motor allows obtaining an energy conversion form with clear advantages for translation purposes as the linear motor provides propulsion force with only electromagnetic link between the fixed and mobile parts without the need of any additional mechanical transmission from rotational movement.

In rotational motors a fixed distance between inductor and inductive (rotor and stator) parts is easily achieved as the movement uses always the same reference. One challenge when working with linear motors for horizontal motion is to maintain the gap when the moving part is changing its position. To control this gap it is critical to have low values of the inducted magnetic field.

Two types of linear motors exist depending on the nature of the armature: iron-core and iron-less. In iron core (Fig. 11) motors there is a unidirectional non-compensated force between the inductor and the inductive. This force is variable and depends more on the nature of the armature rather than on the air gap. In order to avoid excessive friction a robust guiding system is then required. The magnetic attraction is weaker with mixed induced because the magnetic gap will be greater than in other types of armature, as it comprises the thickness of the conductive plate. It must be considered that this magnetic attraction is harmful for the application to moving walks, even as iron-core linear motors are typically cheaper.

With a strictly symmetrical system and a configuration with two inductors, one at each side of the inductive, or with two inductives, one at each side of the inductor, the attraction forces are compensated. The differential force will be weaker than the unidirectional attraction.

For iron-less motors the inductive is made of isotropic non-magnetic conductor material like copper or aluminum. The configuration of the motor can be with two inductors or one inductor and a yoke closing the flow. Because the design is balanced and the coil section contains no magnetic material the motor has no attraction force and there is absolutely no cogging. The only force generated is the thrust force. Due to the high magnetic resistance the coil inductance is relatively low allowing high change rates for very fast movements and reactions to the disturbing forces. These features provide very short reaction times and high speed to this highly dynamic motor which will require accurate control by means of a fast and a precise controller and amplifier. One disadvantage of this type of motor arises from the fact that it is necessary to have two rows of magnets within the sandwich therefore increasing the cost of the magnet yokes.

This type of motor is the most adequate one to drive pallets in order to achieve variable speed. The magnet yoke which does not require power is the one installed in the moving part (the pallet) while the motor windings are the path through which the magnet yoke will run.

One requirement is that only one pallet can coexist in the same motor as it is not possible to have different control through one motor. Motors must be as close as possible, even side by side, so there is not transition between them, although due to the expansion effect a small gap is needed. This is crucial in the acceleration and deceleration areas where high accuracy is required as it is necessary to react as fast as possible to any change in the pallet load. In order to reduce the number of motors, in the central area they are grouped together leaving gaps between groups.

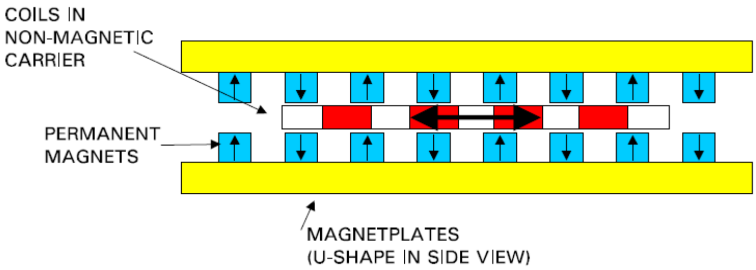

Fig. 11. Iron core motor schematic [16]

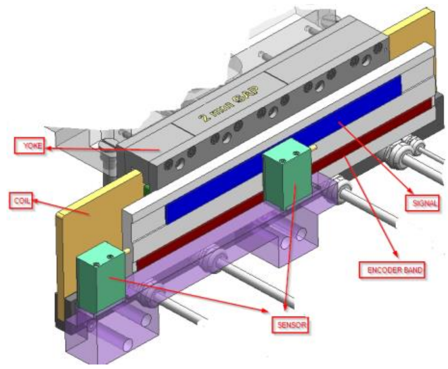
Fig. 12. Location of the encoder and sensor

Linear applications require a sophisticated motor position and velocity feedback. To achieve accurate control of the motors it is necessary to have a position sensor (Fig. 12). A linear encoder and a servo controller are used in the positioning system. The ideal solution would be to have an absolute encoder so the location of each pallet is known at anytime. This requires having a measuring device in the floor and a reading sensor in each pallet; since this solution requires the wiring of moving parts, the solution must be reversed. The problem then is how to build a continuous measuring device. To solve this, a double sensor solution is considered: the incremental encoder signal indicates the position and an additional signal indicates when the magnet yoke enters the motor. A single sensor developed for this application provides encoder pulses only when a magnet yoke is detected. Sensors are placed every short distance in the area of acceleration and deceleration while in the central area a small group of sensors can cover longer distances.

To handle synchronization of all drives in real time a master computer is used. The main feature of the system is that every single motor performs exactly the same specific movement depending on the position and speed. This allows splitting the complete kinematics of the moving walks in small portions and each portion is assigned to one motor which can work mainly autonomously as the information is stored. The control system (Fig. 13) is then more decentralized and as a result simpler. Only a central master is required to synchronize the clock of each motor with a fast execution cycle. To assess the feasibility of the linear motor configuration maximum needed motor force are defined by considering different load scenarios, distributing passengers along the moving walk areas.

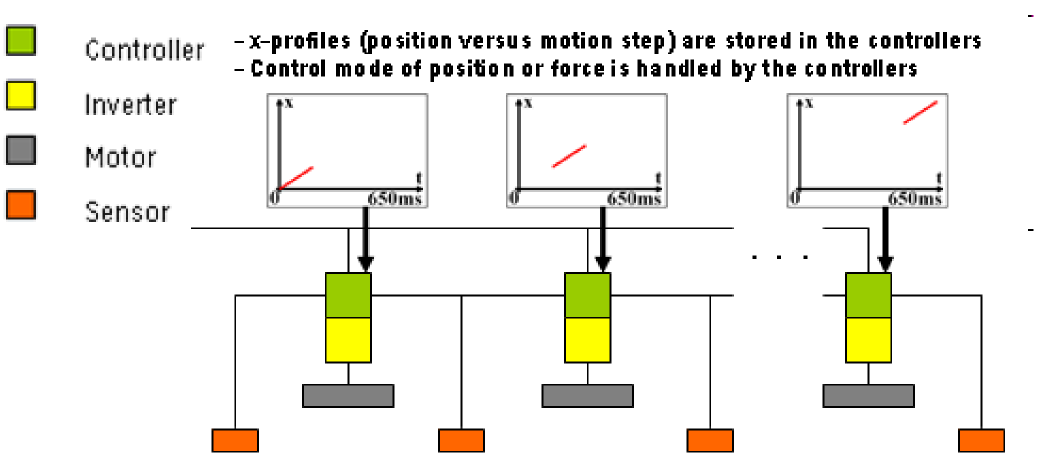

Fig. 13. Decentralized control system scheme

7. CONCLUSIONS

Variable speed moving walks are identified as a possible sustainable and accessible solution to present and future transportation needs in urban environments as city population increases and mobility becomes more complex. Travel distances from 200 m to 1000 m may be covered continuously with higher capacity, low commuting time and reduced costs. Continuous acceleration systems are safer than discrete speed increase systems, provided than acceleration values are low.

Many technical challenges need to be solved to achieve variable speed in moving walks and some manufacturers have developed different concepts during the past years.

Currently two units of Thyssenkrupp variable speed moving walk TurboTrack^{R} are installed and in operation. The continuous acceleration speed profile system is based on a two-body pallet design mechanically driven by gears, chains, rollers and variable pitch. The application of alternative technologies like linear motors to drive and electronically control the variable speed is identified to potentially simplify the architecture of the system.

Linear synchronous motors have a three phase winding on one side of the air-gap and a set of permanents or electromagnets with alternating poles on the other side and can drive pallets individually to achieve the needed speed profile, as force can be applied directly in the direction of travel. Air gap control is critical to have low values of the inducted magnetic field.

For iron core motors there is a non-compensated force while iron-less motors are made of isotropic non-magnetic conductor materials and have no attraction force and there is no cogging. This type of motor is the most adequate one to drive variable speed pallets. The magnet yoke is installed in the moving part while the motor windings are the path through which the magnet yoke will run. A double position sensor is used for accurate motor control position and velocity feedback for the overall position and when the magnet yoke enters the motor. A master computer is used for synchronization of all drives in real time, as every motor performs the same movement depending on its position and speed mainly autonomous as the information is stored.

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