Contribution to microfactory technologies: A flexible conveyor and its dedicated control system

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KEYWORDS : Micro-conveyors, planar electromagnetic actuator, flexible micro factory conveyors, control systems

In this paper, a flexible conveyor system for microfactory applications is presented. The proposed conveyor allows the automated transportation of micro objects to the desired location within a microfactory. The conveyor system is based on electromagnetic actuation principle. It consists of a fixed coils platform and a moving pallet which regroups several permanent magnets. The fixed conveyor platform is composed of mesh of 2D coils based on matrix arrangement where each cell of the matrix can be independently controlled to form a flexible conveying path for the moving pallet. The matrix design ensures low energy consumption, flexibility, reconfigurability and robustness of the system. Furthermore, a dedicated control system is being developed. It ensures minimum energy consumption, manages potential failures of elementary cells and avoids collision between the moving pallets. The control system is used to simulate the global platform behavior and manage the communication with it .

NOMENCLATURE

2D =	Two dimensional
DOF =	Degree-Of-Freedom
p =	Pitch of the coil
d =	Distance between two coils
I_1, I_2 =	Current carried on conducting coils
l, w, h =	Length, width and height of a permanent magnet

1. Introduction

In recent years, the concept of microfactory has been widely described for micro manipulation and assembly purpose [1, 2]. The microfactory concept aims at miniaturizing the production systems to match the size of the small objects, they are producing or manipulating. It leads to the development of modular, flexible and reconfigurable systems [3]. The economic and environmental significance of this concept include reduced need for capital investment, low running cost such as energy consumption, efficient use of space etc., [4].

Microfactory usually is an integration of miniaturized machining units to produce the objects, a small manipulator, a transfer arm or a conveyor system to transport the objects and a small size assembly unit to assemble the objects with manual or automated control [5]. Currently, the primary focus is on the development of modular microfactory platforms. These platforms provide reconfiguration in a short time span of time which is essential for the production of highly customized micro objects.

In these perspectives, automated transportation system is a basic requirement for micro factories. The design of a specific conveyance system with high reconfigurability and flexibility is crucial for the conveyance of micro objects within the microfactory. In literature, different approaches for the conveyance of micro parts have been proposed depending on the applications. A modular microfactory for high volume assembly of watch mechanism has been developed. Belt conveyors have been proposed that pass through the micro factory process modules for a single chain of assembly process

[6]. Numerous multi dimensional micro conveyors have also been developed in the past. Delettre et al. have introduced a contactless conveyor based on aerodynamic traction principle [7]. The device is capable of conveying flat objects such as silicon wafers, glass sheets or food stuff. Zeggari et al. have developed a 2D pneumatic conveyor for micro chips manipulation which levitates and moves flat objects to the desired location [8]. Piezoelectric vibratory conveyor based on micro slide principle which allows the positioning and orientation of the objects of different shapes and geometries has been developed by Fleischer et al. [9]. Denkena et al. presented a new fluid dynamic drive principle based conveyance mechanism where the force is generated by controlling injection of free fluid jets on periodic structures that integrates drive and guiding functions [10].

At the Roberval Laboratory of the Université de Technologie de Compiègne, a planar flexible electromagnetic conveyor with a dedicated control system is being developed in order to control and manage the motion of micro-objects. The conveyor is based on a 3DOF long stroke electromagnetic *xy* positioning system developed at the laboratory [11]. The aim of this work is to develop a flexible smart conveyor platform able to carry a micro object on a pallet within a microfactory. The smart conveyor surface is based on a matrix structure that allows local activation to ensure low energy consumption. In addition, it allows the possibility to independently manage several mobile pallets on the same conveyance surface.

The matrix configuration based design of the smart surface ensures flexibility and reconfigurability but it induces control complexity. Thus, a dedicated control system is proposed using a grid based map technique which is able to compute the displacement of several pallets on the smart surface. It is able to find the shortest path to minimize the energy consumption and adapts the pallet path while considering elementary cells failures and manages several pallet paths in order to avoid collision between them. Moreover, it is used to simulate the global platform and manage its communication.

In this paper, the conveyance system is presented in details. Section 2 describes the working principle of the micro conveyor platform based on matrix configuration and its design layout. The organization of the platform as flexible conveyance device for the mobile pallet is presented in section 3. The control system of the conveyor platform is described in section 4 of this paper. The experimental setup is presented in section 5 and its initial characteristics are discussed in section 6.

2. Micro-conveyor technology

The actuation principle of the conveyor is based on Lorentz force law. Motion of a Permanent Magnet Array (PMA) occurs when two currents I_1 and I_2, with the relative phase shift of $\pi/2$, are supplied into the two fixed Planar Electric Drive Coils (PEDCs) situated underneath the PMA [11]. The interaction between the magnetic field from the PMAs and currents in the coils leads to the generation of electromagnetic forces that produces motion. The actuation principle of a Linear Motor (LM) along a single axis is illustrated in Fig. 1 (a).

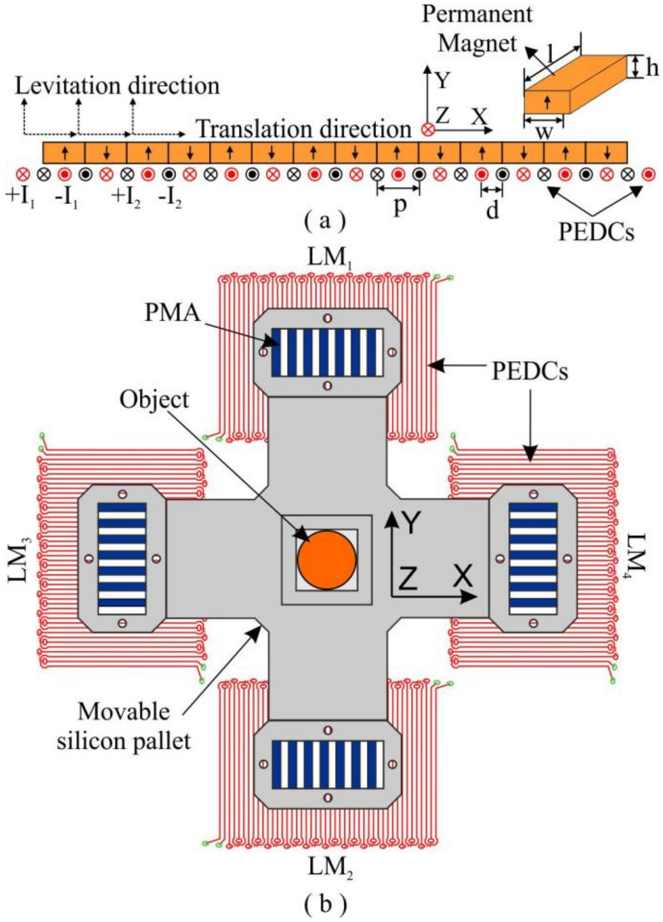

Fig. 1 (a) Single axis linear motor. (b) Planar electromagnetic positioning system.

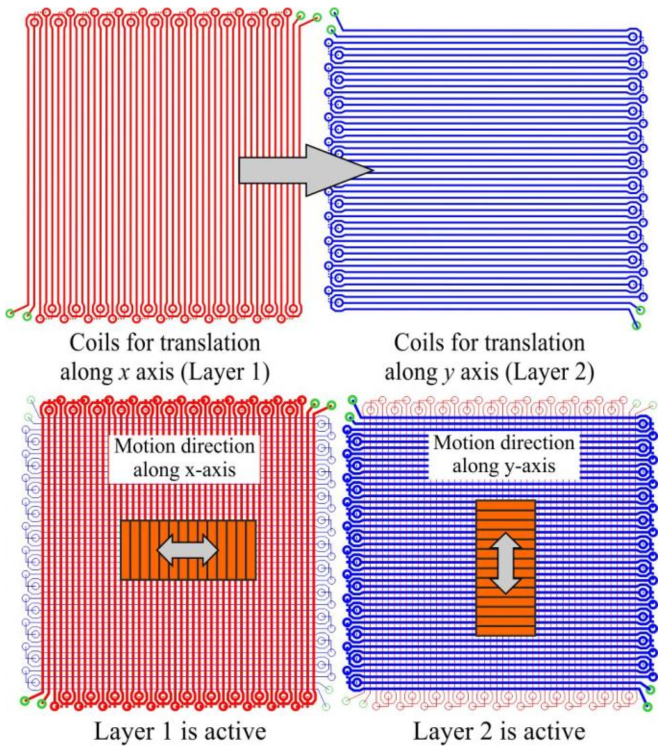

Fig. 2 Two layer coil design layout.

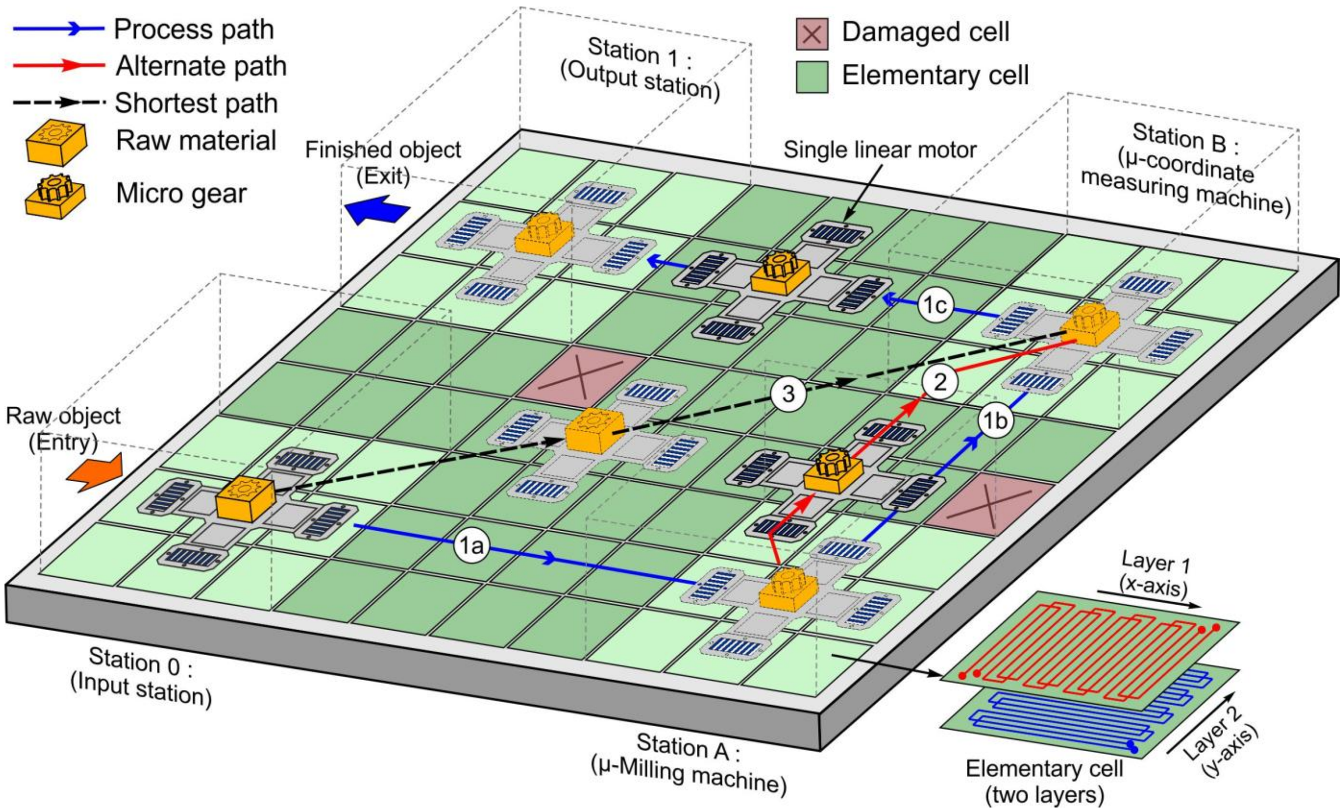

Fig. 3 Flexible smart conveyor platform and its control mechanism.

Based on this principle, a 3DOF planar *xy* electromagnetic positioning stage has been developed [11]. The positioning stage is able to perform planar motions along *x*- and *y*-axis and rotation along *z*-axis. It consists of fixed PEDCs assembly and a moving silicon pallet that regroups several Permanent Magnets (PMs) (see Fig. 1(b)) [12]. Four LMs (LM_1, LM_2, LM_3 and LM_4) are used for the positioning.

Each LM consists of a fixed pair of PEDCs and a PMA composed of 14 PMs. Only two motors are required to be activated in order to perform motions along single axis. LM_1 and LM_2 ensure motion of the silicon pallet along *x*-axis while LM_3 and LM_4 move the pallet along *y*-axis. Planar motions can be achieved by injecting currents in all four motors at the same time. Further, a planar electromagnetic actuator based on two layer coil assembly design for micro applications has been developed [13]. In this case, 2D coils are overlapped to form two layers of coils (see Fig. 2). PEDCs in Layer 1 and Layer 2 arranged orthogonally with respect to each other are used for the translations along *x*- and *y*-axis respectively. Both layers can be used together to achieve planar motions.

The 2D planar actuator based on two layer coil design is further expanded to develop a smart conveyor platform that allows long displacements of the moving silicon pallet for the automated transportation of micro objects to the desired location on the microfactory floor. In order to achieve this target, one possible approach is to enlarge the surface area of two layer coil assembly by increasing lengths of the PEDCs. This ensures planar long stroke motions of the pallet. However, this configuration is not adapted to independently control several moving pallets at the same time. Also, if one of the PEDCs is damaged or deteriorated the whole conveyor platform stops functioning and need to be replaced. To overcome these problems, another approach to increase the motion stroke is by adapting smart surface approach where displacement of several pallets is possible. In this work, a smart conveyor surface is designed and developed by using matrix design configuration where each cell of the matrix is a 2D layer coil (elementary cell) as shown in Fig. 3. Each elementary cell of the matrix can be managed and controlled independently by locally activating the coils in the neighborhood of the mobile silicon pallet. For each cell, two currents I_1 and I_2 with a relative phase shift of $\pi/2$ are simultaneously injected into two opposite LMs (as described in Fig. 1(b)) in Layer 1 (Layer 2) of the cell that generates motion of the pallet along *x*-axis (*y*-axis). This shows that specific cells of the platform (i.e., cells underneath the PMAs) are required to be energized in order to generate motion while the remaining cells do not need to be energized. The electrical resistance of the supplied coils is reduced and hence the energy consumption is low especially over large surfaces.

In addition, the conveyor has a guidance function which helps in reducing the straightness error during motion. This function can be used by supplying constant currents to the two opposite LMs in Layer 2 (i.e., guidance along *y*-axis) while sinusoidal currents are supplied to the two opposite LMs in Layer 1 (i.e., actuation along *x*-axis). Similarly, guidance function can be used in *x*-axis while actuation along *y*-axis. It improves the motion characteristics by aligning the mobile pallet relative to the PEDCs during motion.

3. Platform and organization system

Flexibility and reconfigurability are the crucial parameters of any microfactory. To achieve this, a specific information and organization system is required to access the micro scale requirements of the micro world [14]. Specifically the conveyors used for the transportation of micro objects within the microfactory require control and management to acquire specific characteristics adapted to the micro scale requirements.

The conveyance system presented in this paper is complex. It is composed of several elements in terms of physical parts such as mobile pallets, elementary cells and in terms of organization i.e. manufacturing tasks in order to manage complex trajectories. Also high performances (robustness to cell failures, minimization of energy consumption, prevention of pallets collisions etc.) are needed. An example of manufacturing a micro gear is presented in Fig. 3. A block of raw material is placed above the mobile pallet which follows a particular process path for machining. The raw material block is machined by the milling machine and then its dimensions are verified by the micro-coordinate measuring machine. For this, a machining station and measuring station are fixed on the conveyor platform (see Fig. 3).

In Fig. 3, Station 0 is the input station of the raw object and Station 1 is the output station of the finished object. At start, the mobile pallet takes path (1a) to reach Station A for micro-milling machine task. Once the gear is machined, the pallet moves to the micro-coordinate measuring machine located at Station B for the dimension measuring task. After the dimensions of the object are verified, the finished object takes exit from Station 1 (output station). Thus, the whole process path of the mobile pallet in order to successfully complete all the manufacturing tasks is path (1a)→(1b)→(1c) (see Fig. 3). In order to avoid damaged cells, the mobile pallet is able to automatically change its path and follows an alternative path for the smooth functioning of the pallet, for example; path (1a)→(2)→(1c). In this way, all the tasks are finished without any manual intervention and replacement. If only one task is required to be done, such as the raw object has to be moved directly to Station B for the dimension measuring task, instead of following the whole process path, the pallet takes the shortest possible path i.e., path (3)→(1c). By doing this, the minimum consumption of energy can be achieved and the process is much faster. The conveyance system can also be configured to control the trajectories of several pallets moving at the same time to avoid collisions. To achieve these tasks, a dedicated control system is presented in the next section.

4. Control and monitoring system

As presented in the previous section, the conveyor platform is composed by a certain number of cells. Hence, a platform could be designed with different forms by installing side by side a number of 3 by 3 cell matrix. The control system management needs to take into consideration the modification of the platform dimensions. On the other hand, this control system allows users not only to monitor or obtain desired information, but also to reconfigure the platform via a Human Machine Interface (HMI). It is also a software environment, which has the potential to provide support to: (1) design for manufacture in line, (2) select a product, (3) request modifications to a particular specification of a product, and (4) send feedback to the platform.

A conceptual model for the software has been developed. which integrates four main function as described below, (see Fig. 4):

- Platform configuration process/start up: Modeling of the basic physical processes with the essential parameters such as the form and dimension of the platform, the number of cells and pallets, etc.
- Layout/production planning: Production simulation, collecting the manufacturing process data.
- Path generation: Trajectory calculation of all the pallets, which is optimized while satisfying some requirements on the performance criteria such as the energy consumption or the reliability.
- Results (command/execution): Coordination of the execution of the pallets, updates, stores and records information.

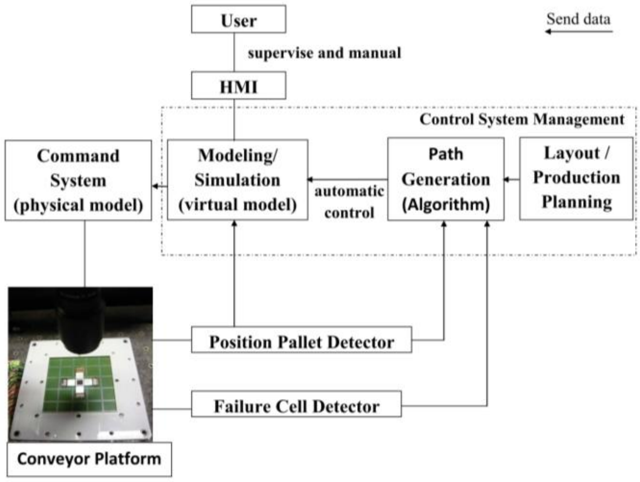

Fig. 4 Conceptual model of the control system management.

The goal is to map the application software (see Fig. 5) with the platform. The simulation model is executed through the real-time environment. It allows applying scheduling workflow applications onto a target platform in order to optimize predefined criteria.

A uniform grid, which is the simplest possible spatial subdivision, is used for modeling the conveyor platform. It subdivides the simulation platform into a grid of uniformly sized cells that have the same size as the real elementary cells. Each cell is indexed. This method allows us to calculate the cell index where a pallet is located in via the pallet position and command the next cells that will be energized. Furthermore, it simplifies the collision pallet check method by looping over the neighboring 9 grid cells (3 × 3 cells). If 2 pallets have common neighboring cells, it is possible that they may collide.

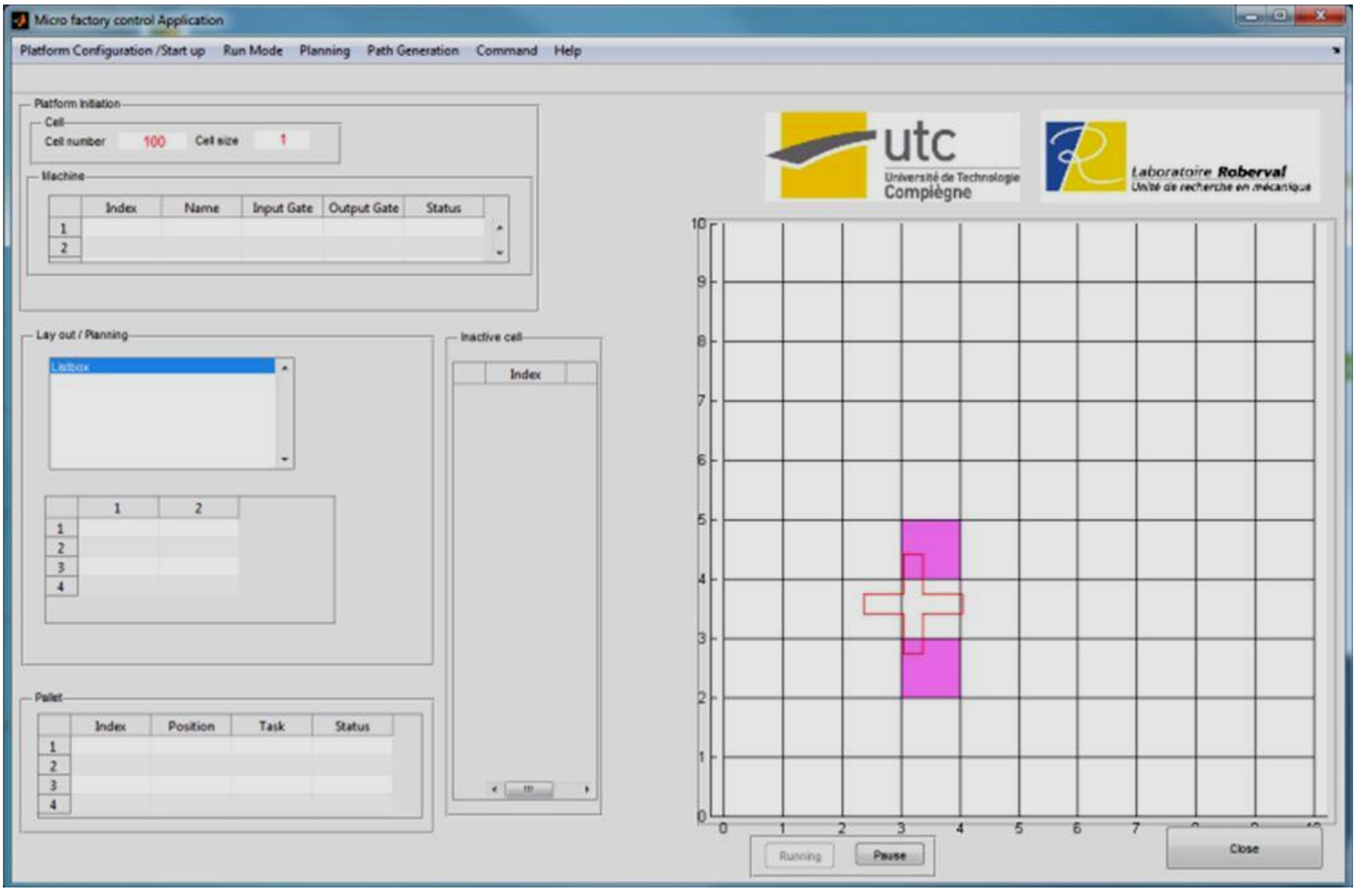

Fig. 5 Control demonstrator interface.

For calculating the trajectory of the pallets, different algorithms that will be implemented in path generation module are being studied and compared such as dijkstra's algorithm, A* search algorithm, and Floyd–Warshall algorithm. For the moment, the cost function is considered to be depending on the displacement distance and the energy consumption. However, thanks to the failure cell detector, the cost function can easily be recalculated. From the results, it is concluded that the path generation module works well for computing a pallet path using Floyd–Warshall algorithm. This algorithm allows the pallet to avoid the entire damaged cells in the conveyance platform and determines the shortest path. In future, advance algorithms will be developed and analyzed to avoid collision between multiple pallets.

5. Experimental setup

In order to test the planar motion, a prototype conveyor platform of 5 × 5 matrix square design has been developed. The overall surface dimensions of the conveyor platform are 130 mm × 130 mm. This platform which has been fabricated on a commercially available four layers Printed Circuit Board (PCB). PCB prototype is a sandwich structure of four copper layers of coils. Layer 1 and Layer 2 form two overlapped layers of coils arranged in a matrix configuration for two axes motions. Each cell of the matrix is composed of two layers of coils, each consisting of a pair of PEDCs. Through vias are fabricated to connect the coils to the external power source via Layer 4 (routing layer).

Four thin glass layers (130 µm thickness) are glued to the bottom of each edge of the cross shaped pallet and then the PMAs are placed above each glass layer. This insulation layer between the PMAs and the PCB reduces friction which occurs due to mechanical contact and hence, provides smooth motion of the pallet. In Table 1, the synthesis of the conveyor platform characteristics are presented.

Table 1 Conveyor platform characteristics.

Prototype dimensions (mm)	
Overall dimensions	130 × 130
Elementary cell dimensions	25 × 25
Pitch of each PEDC, p	1
Distance between PEDCs, d	0.5
PM dimensions	6.0 × 1.0 × 0.5
No. of PMs in each LM	14
Glass layer thickness	0.13
Materials	
Printed circuit board	FR4
PEDCs	Copper
PMs	NdFeB
Platform support	PMMA
Experimental parameters	
Experimental stroke	68 mm
Nominal current for layer 1	0.40 A /coil
Nominal current for layer 2	0.74 A /coil
Remanent magnetization of each PM	1.4 T

In Fig. 6, the experimental setup has been realized in order to demonstrate long stroke displacements along *x*- and *y*-axis.

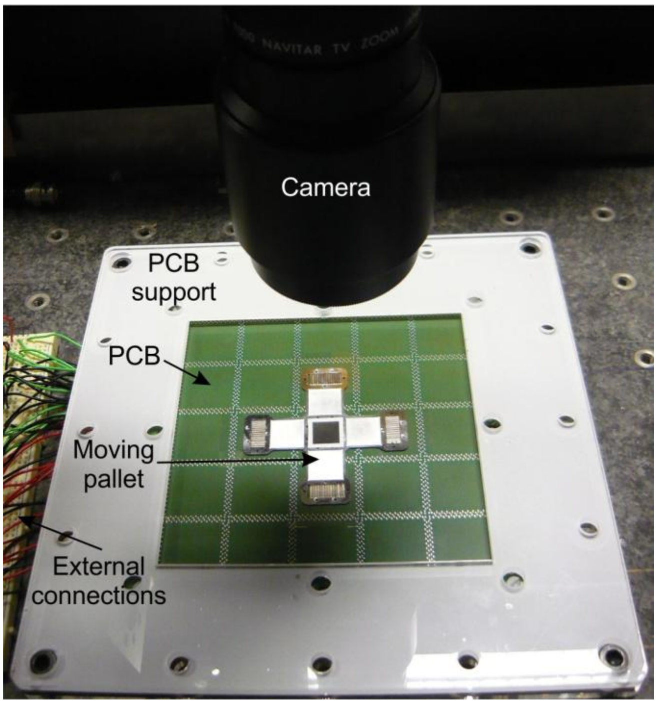

Fig. 6 Experimental setup.

The four layer PCB has been mounted on a table using a mechanical PMMA support which has been fabricated using laser cutting machine. Two controlling voltages are generated for each axis using a computer equipped with a data acquisition board (NI PCI-6733) and then converted into currents using voltage-to-current converters. The voltage input and current output of both the converters are in the range of [-10V, 10V] and [-3A, +3A] with the bandwidth of 50 KHz.

A camera has been installed above the PCB in order to capture images of the platform during the functioning. These images are then used to measure the displacement realized by the pallet using image processing algorithm. A Labview interface has been developed to control the pallet motion.

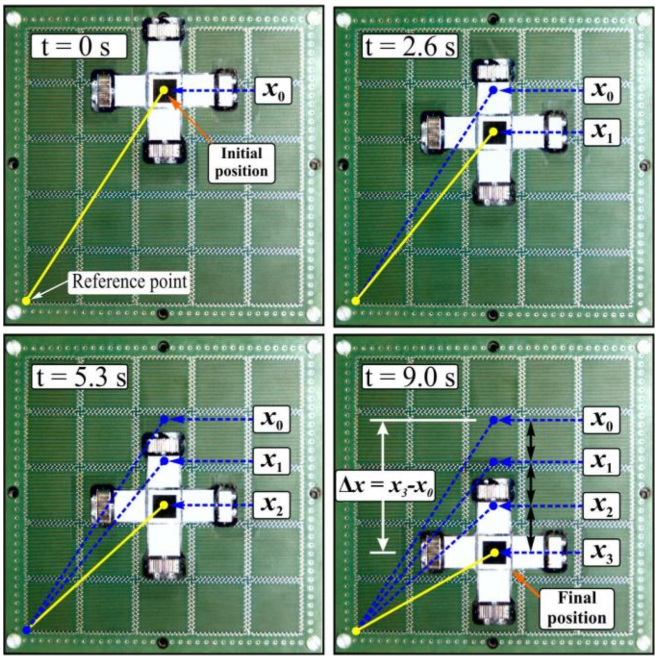

Fig. 7 Images along *x*-axis for forward motion.

6. Results and discussions

An analytical model has been developed to design the conveyance device. The model computes the electromagnetic forces exerted on the PMAs and the displacement of the pallet in function of the controlling currents. The experimental tests of the device have been performed in open loop that has validated the working principle of the conveyor. Displacements along both axes have been obtained using nominal current values (see Table 1) with the actuation speed of 1mm/s. Higher currents have been used for the motions along *y*-axis due to the large distance between the PMAs and Layer 2. The nominal current values are selected such that equal forces are generated during the motion along both axes and similar motion characteristics can be achieved. The experiments have been performed in the guidance mode i.e. constant currents are injected in the axis which is not used for the actuation. One displacement cycle (i.e. forward and backward motion) of 68 mm for each axis has been performed. The images have been captured by the camera during the functioning of the conveyor and the displacement has been measured using image processing algorithm. From the images, the displacement resolution has been computed and is equal to 0.195 mm (1 pixel) in both horizontal and vertical axis. Several images have been for each axis with a time delay of 0.13 s between two images.

At first, the displacements along *x*-axis have been performed by injecting nominal current of 0.4 A per coil in the required PEDCs of Layer 1. Fig. 7 represents the images taken by the camera along *x*-axis motion. Different positions of the pallet are shown where x_0 is the initial position at time, t = 0 s. After displacement along *x*-axis, the final position is at x_3 at time, t = 9.0 s (see Fig. 7). The displacement curve is presented in Fig. 8. The total displacement measured along *x*-axis is 67.7 mm with the displacement loss of 0.3 mm due to friction. Similarly, the nominal current of 0.74 A per coil has been injected to the required cells in Layer 2 for a *y*-axis displacement. The displacement loss along *y*-axis due to friction is equal to 0.8 mm that results in a total displacement measured equal to 67.2 mm.

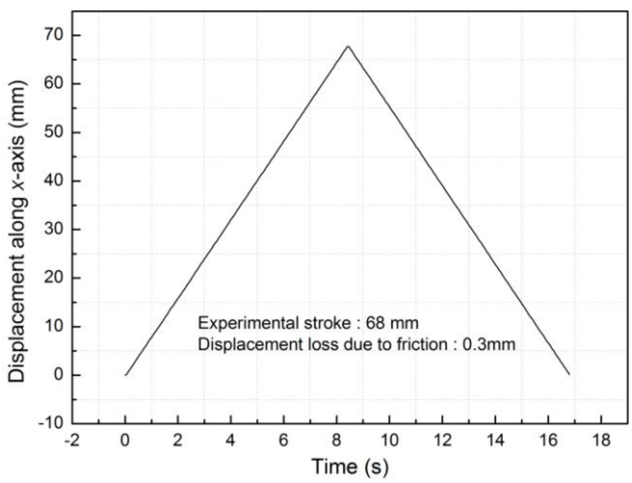

Fig. 8 Displacement curve along *x*-axis for one cycle

7. Conclusion

An automated micro conveyor based on electromagnetic actuation principle has been developed for the conveyance of micro objects within the microfactory in order to perform various micro manipulation or micro assembly tasks. The design of the conveyor platform based on matrix configuration allows the independent controlling of several mobile pallets. This technology allows obtaining complex trajectories of several mobile pallets to perform various manufacturing tasks on the same surface without manual intervention. The matrix design ensures low energy consumption, flexibility, reconfigurability and robustness of the system.

To validate the concept, an experimental prototype of 5×5 matrix square design has been developed using a four layer PCB. The prototype has been manufactured and experimentally tested. Long displacements strokes have been successfully obtained along *x*- and *y*-axis. Using image processing, the displacements of the mobile pallet have been computed and presented in this paper. Furthermore, a dedicated control has been developed. It minimizes the energy consumption, manages potential failures of elementary cells and avoids collision between the mobile pallets. The control system is used to simulate the global platform behavior and manage the communication with it.

Experimental tests have shown the possibility of wide area of planar displacements. Numerous experimental tests (control in open loop and closed loop performance characterization as straightness of movement, position repeatability, movable load, etc.) are currently in progress in order to qualify the performances of the conveyor system. In future works, the surface area of the conveyor platform will be increased in order to control and manage several moving pallets at the same time. Then the control and monitoring system presented in this work will be integrated to experimentally validate the control model of the platform.

REFERENCES

1. G. Fontana, S. Ruggeri, I. Fassi and G. Legnani, Calibration strategies for a micromanipulation workcell, 8th International Workshop on Microfactories IWMF 2012, Tampere (Finland), 8 pages, 2012.
2. C. Löchte, C. Behring ,A. Burisch, and A. Raatz, Design Principles for a Tool Changing System for Flexible Micro Assembly in Desktop Factories, 8th International Workshop on Microfactories IWMF 2012, Tampere (Finland), 8 page, 2012.
3. D. Gendreau, M. Gauthier, D. Hériban, P., Modular architecture of the microfactories for automatic micro-assembly, Robotics and Computer-Integrated Manufacturing, Vol. 26, pp. 354–360, 2010.
4. Y. Okazaki, N. Mishima, and K. Ashida. (2004, November). Microfactory-Concept, History, and Developements. Journal of Manufacturing Science and Engineering, 126 (no. 4), pp. 837-844, 2004.
5. R. Tuokko, R. Heikkila, E. Jarvenpaa, A. Nurmi, T. Prusi, N. Sitala and A. Vuola. Micro and Desktop Factory Roadmap, Tampere University of Technology, Department of Production Engineering, Tampere, 2012.
6. E. Jarvenpaa, R. Heikkila and R. Tuokko. Microfactory concept for Highly Flexible Volume Assembly of Watch Mechanisms. 7th International Workshop on Microfactories IWMF 2010, Daejeon, Korea (Finland), 6 pages, 2010.
7. A. Delettre, G. J. Laurent and N. Le Fort-Piat. (2010, October 18-22). A new contactless Conveyor System for Handling Clean and Delicate Products Using Induced Air Flows. IEEE/RSJ International Conference on Intelligent Robots and Systems. Taipei, Taiwan. pp- 2351-2356, 2010.
8. R. Zeggari, R. Yahiaoui, J. Malapert, J.F. Manceau. (2010). Design and fabrication of a new two-dimensional pneumatic micro-conveyor. Sensors and Actuators A. 164, pp. 125-130, 2010.
9. J. Fleischer, S. Herder, U. Leberle. (2011). Automated supply of micro parts based on the micro slide conveying principle. CIRP Annals - Manufacturing Technology. 60, pp. 13-16, 2011.
10. B. Denkena, H. C. Mohring, H. Kayapinar. (2013, March). A novel fluid-dynamic drive principle for desktop machines. CIRP Journal of Manufacturing Science and Technology. 6, pp. 89-97, 2013.
11. M.U. Khan, N. Bencheikh, C. Prelle, F. Lamarque, T. Beutel, S. Büttgenbach, A long stroke electromagnetic XY positioning stage for micro applications, IEEE/ASME Transactions on Mechatronics, Vol. 17, Issue 5, pp 866-875, 2012.
12. M. U. Khan, N. Bencheikh, C. Prelle, F. Lamarque, T. Beutel and S. Buttgenbach. Silicon conveyor based electromagnetic device for linear displacement (July 2010). IEEE/ASME International Conference Advanced Intelligent mechatronics Association Information and Management, Vol. 13, no. 2, Montreal, QC, Canada, 2010.
13. N. Arora, M. U. Khan, L. Petit, C. Prelle, A planar electromagnetic actuator based on two layer coil assembly for micro applications, IEEE/ASME conference on Advanced Intelligent Mechatronics, July 8-11, Besançon (France), 6 pages, 2014.
14. M. Bosch-Mauchand, C. Prelle, J. Daaboul, T. A. T. Dang, S. D. Labato, Preliminary contributions of industrial management methods to microfactory context: Case of microfactory conveyors integration, Proceedings of joint conference on mechanical, design engineering and advanced manufacturing, Toulouse, June 18-20, 6 pages, 2014.