High Performance Linear and Surface Motors for Advanced Flexible Manufacturing Systems

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Abstract* – Precise linear or planar motion is required in highly developed manufacturing systems. To achieve these accurate motions usually rotary motors are used combined with rotary-to-linear conversion mechanisms. This method has several disadvantages as low accuracy, complex mechanical adjustments, high cost, and low reliability. A novel modular machine construction will be presented in this paper. The modules can be used to build up several linear and surface direct-driven motors. Using these motors high accuracy positioning tasks can be fulfilled in flexible manufacturing systems. Results obtained by means of digital simulations prove the ability of these motors to be used in such advanced systems.

***Keywords:* flexible manufacturing system, linear motors, surface motors, simulations.**

I. INTRODUCTION

The most typical Flexible Manufacturing System (FMS) is composed of many different assemblies:

- load/unload stations
- workstations (processing tools)
- a common buffer

All of these must be linked together with a so called Material Handling System (MHS).

The load station consists of a storage buffer at which raw part arrive. Each workstation consists of a limited input buffer, one or more processing machines, robots, etc., and a limited output buffer. The common buffer is a temporary storage unit which is used when a part is blocked due to the limited local buffer capacity when it is moved to a workstation, but cannot enter the workstation. Finished products leave the system through the unload station.

The MHS has to ensure the movement of the parts within the FMS according to the process paths required by the parts. This is one of the key units of the entire manufacturing system. All the manufacturing process's performances depend on their part handling speed capability and precision [1].

The classical solution for the MHS are the conveyors driven by rotating electrical machines. Their main drawback is due to the need of rotary-to-linear conversion mechanisms (such as leadscrews, belt drives, and rack & pinions), which converts the rotational movement into a linear one. These conversion mechanisms add inertia, friction, compliance, backlash, and wear, all of which compromise the overall system performance of the classical conveyors.

An other possibility is to use high force and high precision linear or surface motors for these purposes, which offer to the system designer an elegant alternative, hence they produce linear, respectively planar motion directly, and therefore eliminate the need for conversion mechanisms.

If the complexity of the FMS is great it should be possible that the part handling linear paths should be changed in a planar trajectories, increasing this way the possibilities of the part's movement between the different workstations, load and unload stations and buffers [2].

For these purposes the modular hybrid linear [3] and surface stepper motors [4] should be an excellent solution, due their high force developing capability combined with high positioning accuracy.

II. THE MODULAR LINEAR AND SURFACE HYBRID STEPPER MOTORS

As it was stated out previously in order to achieve the high positioning accuracies required in the advanced flexible manufacturing systems linear or surface stepper motors seems to be one of the best solutions.

Several linear and surface stepper motors are cited in the literature. Most of them have some drawbacks: high attracting forces between the armatures, braking forces, etc. These disadvantages can be diminished by a novel modular construction of these motors. The mover of the linear and surface hybrid stepper motors is built up of modules, like the one presented in Fig. 1.

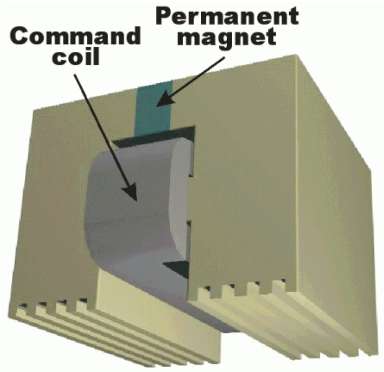

Fig. 1. The mover module

Each module has a rare earth permanent magnet, two salient teethed poles and a command coil.

The working principle of the motor can be followed in Fig. 2.

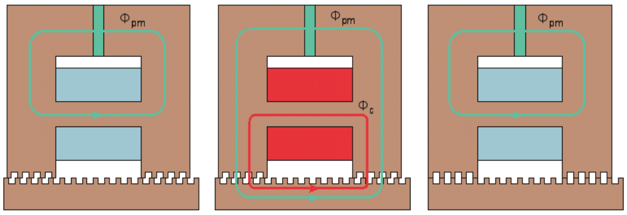

Fig. 2. The working principle of the modular motor

If the command coil of the module is not energised the magnetic flux generated by the permanent magnet (Φ_{pm}) passes through the core branch parallel to the permanent magnet due to its smaller magnetic resistance compared to the air-gap's one. In this case practically there is neither tangential, nor normal force produced.

If the coil is energised (the case of an active module) the command flux produced by it (Φ_c) directs the flux of the permanent magnet to pass through the air-gap and to generate significant force.

Due to the tangential component of the generated force in an active module the mover (forcer) moves one step in a position where the air-gap magnetic energy is minimum.

Displacement in both directions can be achieved by energising the modules in a adequate sequence

Several motor structures having linear or planar movement can be built up using the modules like that shown in Fig. 1.

From the various possible linear motor structures a three-phase variant is presented in Fig. 3. Its main advantage is that it can be controlled from a three-phase commercially available power converter. The three-phase construction still can assure the high accuracy required in flexible manufacturing units or in other high precision industrial applications.

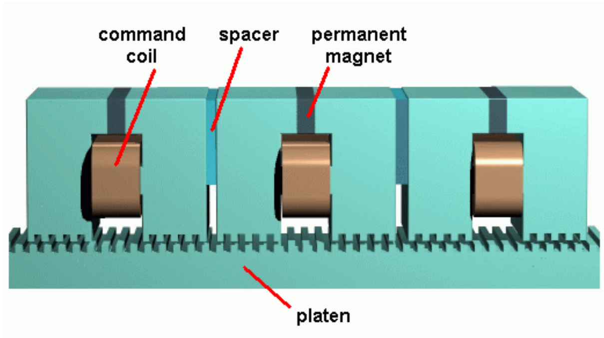

Fig. 3. The three-phase modular linear motor

From the same modules also planar (surface) motors can be built up. The mover of the simplest (three-phase) modular surface hybrid stepper motor is presented in Fig. 4.

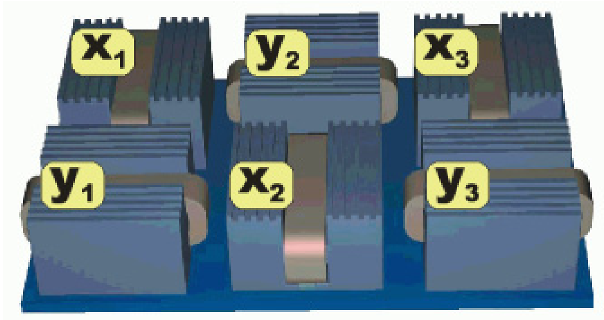

Fig. 4. The mover of the modular surface motor

The mover of the surface motor has six modules, three for each direction. The three modules that ensure the displacement in x direction (x_1, x_2 and x_3) are mounted ortogonally to those three modules for the y direction displacement (y_1, y_2 and y_3).

All the modules are fixed in a common housing. The air-gap between this mover and the fixed platen is assured by air bearing. One set of three command coils drives the mover in the x direction, and the other in the other direction.

The entire modular surface motor can be seen in Fig. 5.

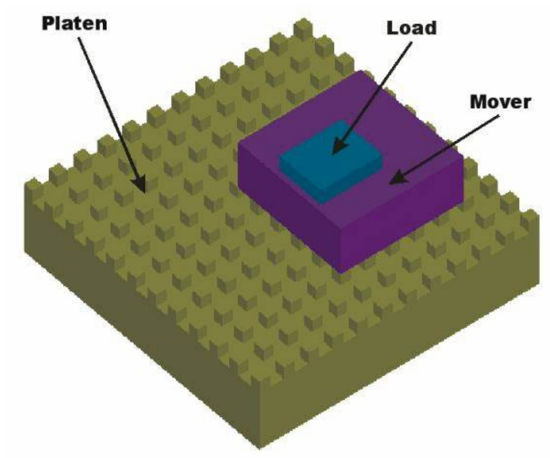

Fig. 5. The modular surface motor

The control system of the motor is not very complicated, and can be built up from well-known components.

The block diagram of the entire control system is given in Fig. 6.

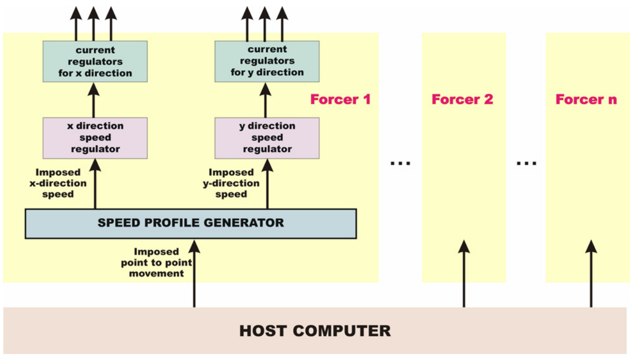

Fig. 6. The block diagram of the surface motor's control system

A host computer co-ordinates the whole movement task of the surface motor. It can control several forcers moving on the same platen. It computes the point to point imposed movement for each forcer. Based on this a speed profile generator calculates the two imposed speeds on the two orthogonal directions. PID type speed controllers are used to prescribe the imposed currents through the command coils.

The commutation of the phases of the motor was optimised in order to obtain the lowest possible force ripple [5].

The usefulness of applying linear and surface modular hybrid stepping motors in flexible manufacturing systems will be demonstrated by means of simulation [6].

III. THE SIMULATION PROGRAM

The program for simulating modular surface motors was written in MATLAB/Simulink, the best environment considered for these purposes.

The program is built up modularly. All its main components (as the common trajectory generator, respectively the control unit, the frequency converter and the motor part for each axis, etc.) are grouped in separate user-defined blocks. The main computations tasks are performed using MATLAB functions called from the SIMULINK program [5].

The magnetic flux, the developed normal and tangential forces of the motor for several possible mover positions, respectively command currents, were computed previously via a FEM based program (MagNet v.6.10) [7]. The results are stored in easy-to-use look-up tables. Hence the computations were drastically reduced, and of course also the running time of the simulation program.

The main window of the simulation program is given in Fig. 7. The two parts of the motor, each producing the movement in one of the two orthogonal directions, can be clearly distinguished.

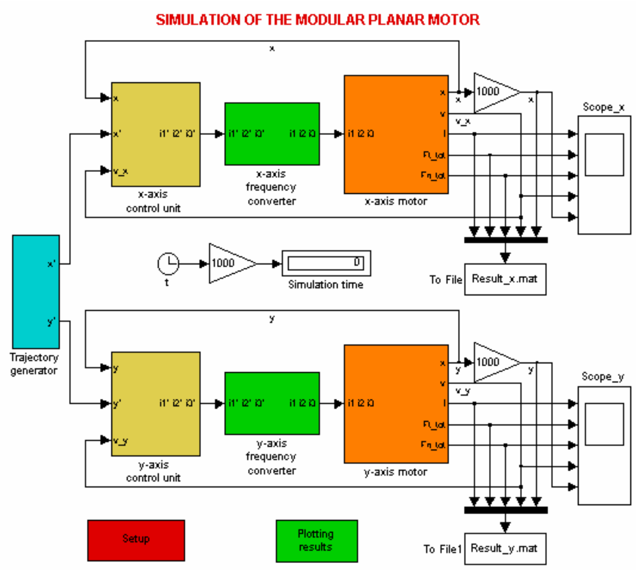

Fig. 7. The main window of the simulation program of the modular surface motor

Several possibilities are included into the program to visualise the obtained results: scopes and digital displays.

All the results are saved in files for future data processing and visualisation. The results (plots) given in section V were performed using the advanced graphical possibilities of MATLAB [8].

From the numerous blocks (sub-systems) of the program here only two will be presented in detail.

In Fig. 8 the block called "*x-axis motor*" is given. It models that part of the surface motor, which ensures the movement on the *x*-axis. The blocks corresponding to the three modules can be easily distinguished in Fig. 8. An identical block is used for the other component of the motor.

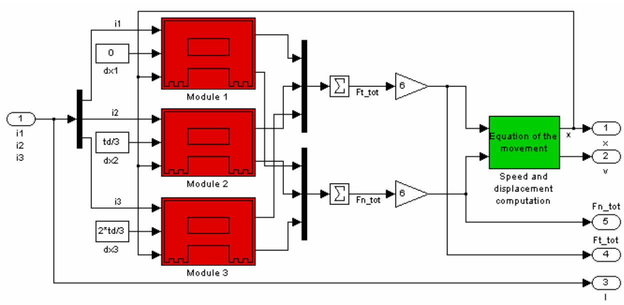

Fig. 8. The sub-system of t the surface motor that ensures the movement on the *x*-axis

The inputs in the block are the three currents of the command coils. In the block the total tangential and normal forces developed by the three modules are computed and added, respectively upon these the speed and the displacement of that mover part are calculated.

The sub-system of a mover module of the surface hybrid stepper motor is given in Fig. 9.

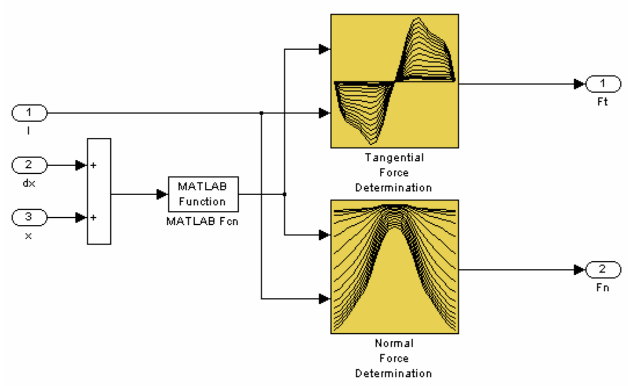

Fig. 9. The sub-system containing the model of one forcer module

On the mask of the two look-up tables ("*Tangential Force Determination*" and "*Normal Force Determination*") the static characteristics of the motor can be clearly seen. In the block the developed tangential and normal forces are obtained function of the actual command current and displacement of the mover.

The above presented program with minor changes can be used also for the simulation of other surface motor structures built up of the modules given in Fig. 1, and also of the linear variants of the motor.

IV. THE SIMULATED TASK

A work-cell of a flexible manufacturing system in which the modular surface motor in discussion was integrated is shown in Fig. 10 [9].

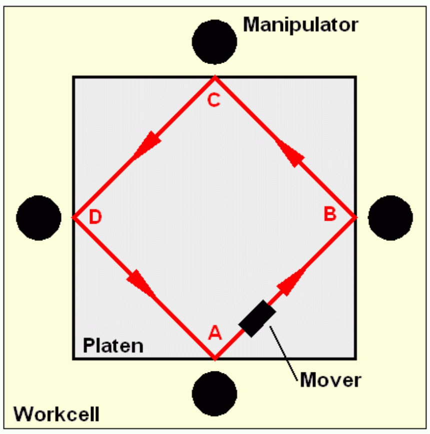

Fig. 10. A work-cell in which the proposed surface motor is used

The platen on which the mover of the surface motor carrying the part in work can move is surrounded by four universal manipulators, which processes the part.

The mover has to start from point *A*, and to reach sequentially the points *B*, *C* and *D*, and to arrive back to the initial point *A*. At each point the mover has to wait still the processing of the carried part is finished.

The sample motor simulated is the simplest surface motor that can be built up from the modules given in Fig. 1. It has only the minimum of 6 modules displaced in the forcer in a manner as shown in Fig. 11.

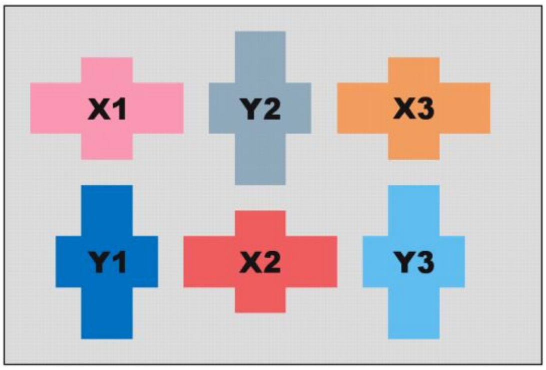

Fig. 11. The placement of the forcer modules within the sample surface motor

The most important data of the sample surface hybrid stepper motor are:

- Number of mover modules: 6
- Number of teeth per pole: 5
- Tooth width: 0.84 mm
- Slot width: 1.16 mm
- Tooth pitch: 2 mm
- Rated command current: 0.5 A
- Rated tangential force 75 N
- Motor width: 83 mm
- Air-gap: 0.1 mm
- Permanent magnet type: VACOMAX148
- Residual flux density: 0.9 T
- Coercive force: 650 kA/m

The main dimensions of a module are given in Fig. 12.

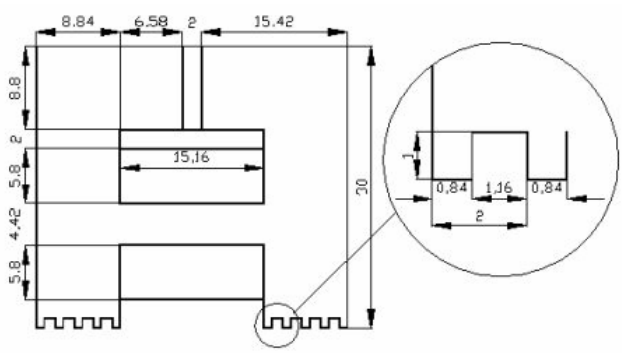

Fig. 12. The main dimensions of a module

The mover of the motor is carrying a 3 kg load during its displacement. In each point where its load is processed the motor is stopped 0.5 s.

V. SIMULATION RESULTS

Using the simulation program the above presented task for the modular surface hybrid stepper motor was performed. From the obtained results only the most significant ones will be presented here.

As the imposed task was a prescribed planar movement, the most important result should be the performed displacement of the mover. In Fig. 13 the variation of the mover's displacement versus time are given. Both the displacements of the two surface motor components (corresponding to the *x*-axis, respectively *y*-axis movement) are given.

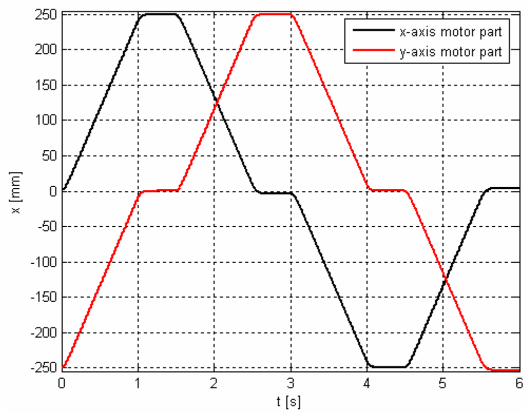

Fig. 13. The plots of the displacements versus time

In Fig. 13 the straight line movements of the two motor components, as well as the movers' stopping states can be clearly distinguished. The imposed positions of the mover carrying the part to be processed were reached as fast as possible.

In Fig. 14 the variation of the total tangential forces versus time are given. Also in this case both the tangential forces developed by the surface motor are plotted.

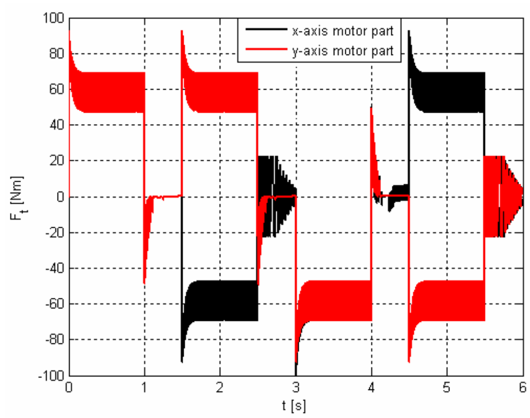

Fig. 14. The plots of the tangential forces versus time

In Fig. 14 it can be observed what amount of tangential force was required to accelerate the mover, to keep it at a constant speed, respectively to decelerate it in order to fulfil the prescribed simple manufacturing task.

For a better view two sequences of these plots are zoomed in Fig. 15.

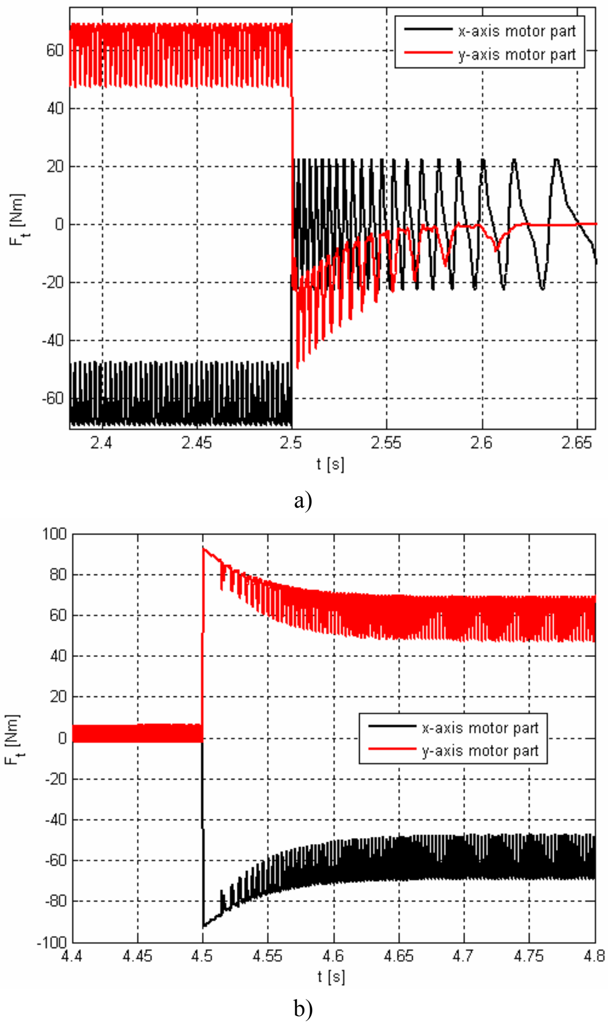

Fig. 15. Two zoomed views of the plots of the total tangential forces given in Fig. 14

In Fig. 15a the variation of the total tangential forces are given during a period when both motor components are braked before to be stopped in the point *C*.

In the other figure, Fig. 15b, the plots of the tangential forces are given during the restarting of the mover from point *D*. The high tangential forces assure a fast acceleration for the motor.

As it can be seen from these figures the tangential force ripples are quite small due to the advanced control strategy adopted.

The speeds corresponding to the displacements presented in Fig. 13 are shown in Fig. 16.

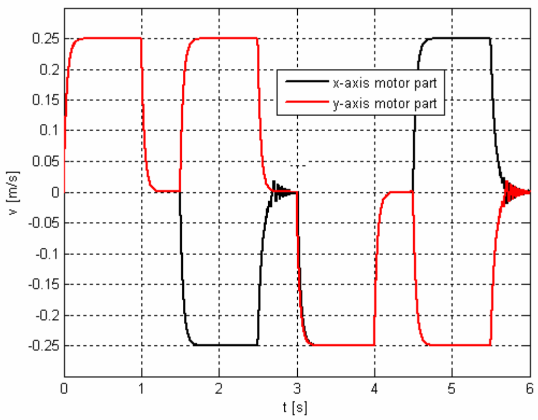

Fig. 16. The plots of the velocities versus time

In Fig. 16 how the two speed controllers imposed the velocities of the two motor components in order to achieve the required movements can be followed.

Finally in Fig. 17 the obtained planar displacement, y=f(x), is given.

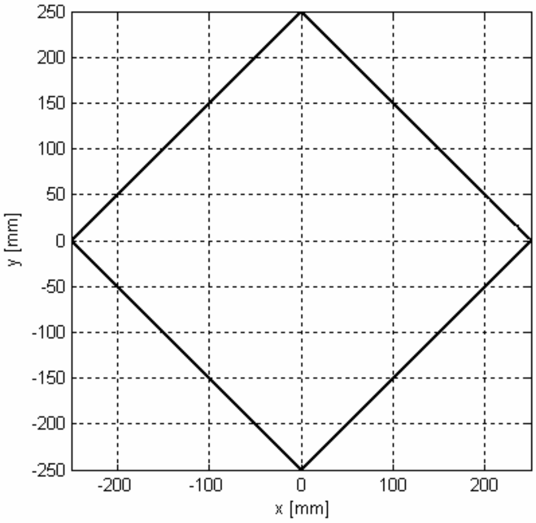

Fig. 17. The performed planar movement of the surface motor

As it can be clearly observed in Fig. 17 the imposed planar movement was very precisely fulfilled.

VI. CONCLUSIONS

Upon the simulated results it can be clearly stated out that the proposed modular surface hybrid stepper motor is well suited to be integrated in modern flexible manufacturing cells. The linear variants of this motor also can be used in such applications in which only precise linear movements are required.

The flexible manufacturing systems using the proposed linear and/or surface modular hybrid stepper motors have several advantages:

- Precision: assuring joint and link flexibility
- Throughput: conveyers and couriers (practically the movers of the linear, respectively the surface modular motors) can proceed to different manipulators while the current one is picking a part and preparing for the arrival of a different courier.
- Floor space: the combination of the variable linear motor driven conveyers or couriers and of the manipulator occupies much less space than a conventional assembly robot for the same size product.
- Flexibility: mechanical and electrical modularity allows easy integration of any overhead processing elements (e.g. screwdrivers, orbital head formers, glue dispensers, laser processors, etc.).

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