Optimal Trajectory Generation for a Modular Planar Motor Used in Flexible Manufacturing Systems

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Abstract - Modular planar motors can be used in flexible manufacturing systems due to their high forces and accurate positioning capabilities. The desired efficiency of the manufacturing process can be achieved only when the displacements are precisely performed upon a well-planned imposed trajectory. In this paper different trajectory generation possibilities are studied by means of simulation.

I. INTRODUCTION

Flexible manufacturing systems are widespread in modern factories [1]. A flexible multi-purpose minifactory unit can be built up also by using surface motors.

In this paper a variable reluctance type surface motor will be presented. Its movable armature can be used as a two-DOF courier moving over a high-precision platen surface. The mover is connected to its control unit via a tether, which carries both control currents for the mover and the air for the air bearings. On a single platen several couriers can move in the same time.

The most typical displacements to be applied for the couriers in such flexible manufacturing cells are:

i.) point to point movements, used typically in pick and place type applications, when the mover has to be moved from an initial position to a target position as fast as possible,

ii.) imposed path based movements, used commonly in cutting and welding applications, where the mover has to follow as close as possible the imposed trajectory.

Both of them require very precise motion and a good synchronization of the two mover parts of the surface motor, each assuring the displacement on one of the two orthogonal directions.

In this paper the positioning capability of the variable reluctance surface motor will be studied. The fulfillment of the different displacement tasks will be analyzed by means of digital simulations.

The simulation program is based on a coupled multi-level mathematical model of the motor. The program models also the power converters feeding the motor.

Both kinds of the required tasks were simulated and the obtained results will be presented in this paper.

All of the simulated results confirm that the proposed modular variable reluctance surface motors are good solutions both for point to point and for imposed trajectory based movements.

Therefore the variable reluctance modular surface motors are well suited to be integrated in modern high performance flexible manufacturing cells.

II. FLEXIBLE MANUFACTURING CELLS

The most widely used solution for manipulator positioning purpose is that shown in Fig. 1.

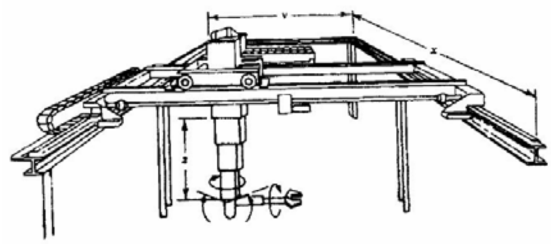


Fig. 1. Manipulator positioning system

The manipulator is guided by rotary motors moving on rails above the part to process. The need of applying rotary-to-linear converting mechanisms decreases the efficiency and the precision of the entire drive system because they have several disadvantages, as low accuracy, complex mechanical adjustments, high cost, and low reliability [2].

In a more advanced concept the direct-driven motors, such that to be presented in the next section are used, which can eliminate almost all of these disadvantages [3].

The main assembly in such an advanced flexible manufacturing cell is a set of platens which serve as the factory floor. On the platens, couriers float on air bearings and move around in the factory with subassemblies on their backs (see Fig. 2).

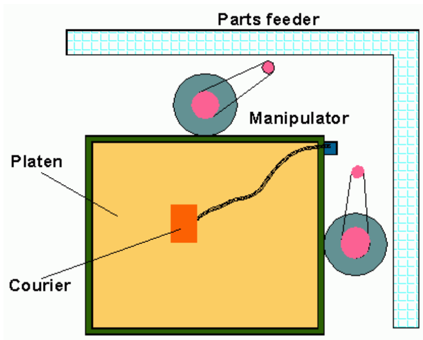


Fig. 2. Advanced flexible manufacturing cell

The couriers can navigate the platens with high accuracy. Round the platens various types of manipulators and parts feeders are placed, which can insert parts and perform other simple operations on the subassemblies, being carried about by the couriers. Each courier is controlled separately by its real time command system. The couriers can replace the conveyer belts in a traditional factory,

allowing for fewer restrictions on the paths of subassemblies between the manipulators [4].
The couriers can provide precise two-dimensional planar motion for the products, both for gross movement from point to point in the factory and for fine positioning based on an imposed trajectory. This means that they are one of the most critical parts of the manufacturing unit. The attached manipulators and part feeders can be of a great variety in complexity and in task to fulfil [5].
As all the other advanced fabrication systems the above-presented flexible manufacturing cells require precise 2D surface motion for several purposes, as material transfer, packaging, assembly, electrical wiring, welding, cutting, etc.

III. THE VARIABLE RELUCTANCE SURFACE MOTOR

The variable reluctance surface motor shown in Fig. 3 was presented in several previous papers [6]. It has a relatively simple modular construction.

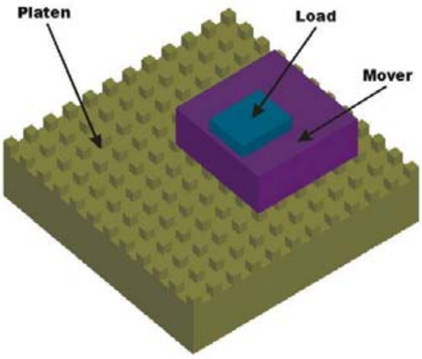


Fig. 3. The modular planar motor

The motor consists of a moving forcer being air bearing preloaded, that can translate in two orthogonal directions along a passive steel platen stator surface. This is a waffle-iron type pattern planarized using epoxy. The load (the part to be processed) can be fixed directly on the forcer. The forcer, the active part of the motor, is built up of high force modules, just like the modular double salient permanent magnet linear motor presented in detail in [7].

The basic arrangement of the modules in a three-phase forcer is given in Fig. 4.

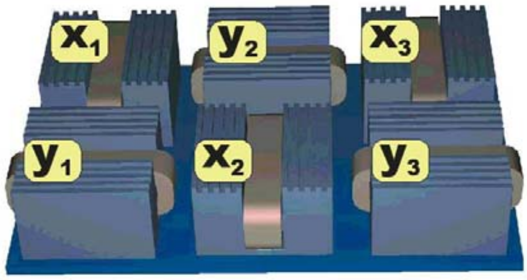


Fig. 4. The mover of the surface motor

The forcer can be considered as composed of two linear motors, each ensuring the movement in one of the two orthogonal directions (x and y). Thus one set of three command coils drives the forcer in the x direction and the other in the y direction.

IV. TRAJECTORY GENERATION

The trajectory generation of the courier in a flexible manufacturing cell is function of the type of the required displacement.
The first basic movement to fulfil by the surface motor's forcer is from an initial point to the target point (point to point type displacement).
Both points must be very precisely defined. The 2D movement of the forcer must be optimized. This can be made by considering different aspects, such as minimum time, minimum power, minimum length, etc. When minimum time is imposed for the displacement the forcer has to be moved at the maximum speed of the motor.
The displacements on the two 2D orthogonal directions must be very well co-coordinated. The movement of the courier must be also co-coordinated with the manipulators in order to carry out successfully their manufacturing tasks.
When more than a single forcer is moving on the same platen the trajectories of the different couriers must be also co-coordinated in order to avoid their collision.
The control unit of the planar motor used in such cases is given in Fig. 5.

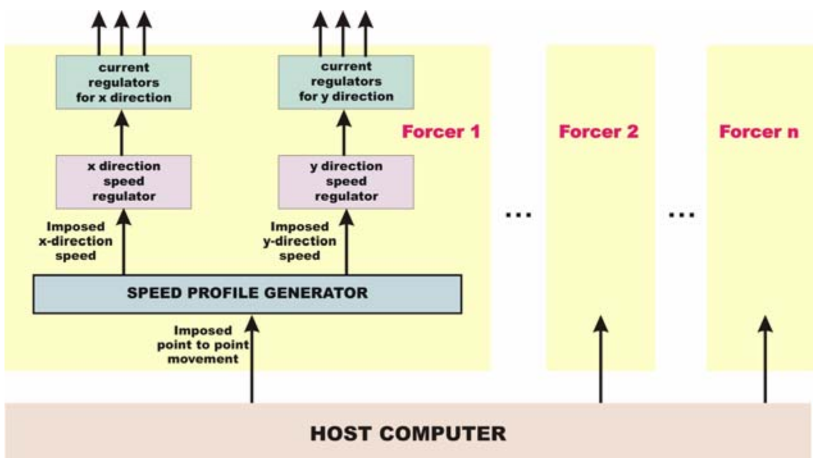


Fig. 5. The control system of the couriers

All the forcers moving on the common platen have their own control unit, composed of a trajectory generator, which computes the imposed speeds on both axes, two speed regulators and the current regulators for each motor phase. The trajectory generators of the different forcers are communicating through the host computer, which co-ordinates all the assemblies of the factory (couriers, manipulators, etc.). The control unit has to take the forcer from any starting position to the required target position without violating the velocity and acceleration limits of the assemblies to be manufactured, or exceeding the motor's dynamic possibilities [8].

Next the algorithm of the two speed profile generators will be presented in detail for the case when the time of the motion is optimized.

In most of the cases the simplest and most widely used trapezoid speed profile will be applied (see Fig. 6).

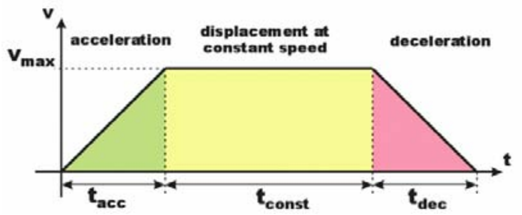


Fig. 6. The trapezoidal speed profile

Of course, if the loads to be carried require more smooth motions also other velocity profiles can be used.

During the required displacement (x_{total} and x'_{total}) the mover has three stages: it is accelerated at constant acceleration, it is moved with a constant speed, and at the end of the movement it is stopped after a constant deceleration. In order to simplify the computations the acceleration and deceleration times are taken to be equal ($t_{acc} = t_{dec}$).

During the total time of the movement ($t_{total} = t_{acc} + t_{const} + t_{dec}$) the mover performs the required displacement: $x_{total} = x_{acc} + x_{const} + x_{dec}$.

It is very important to define correctly the maximum speed and acceleration of the motor ($v_{\max}$, $a_{\max}$) which depends of the thrust and load. Upon these parameters the times needed to accelerate and to break the motor can be easily computed:

$$t_{acc} = t_{dec} = \frac{v_{\max}}{a_{\max}} \tag{1}$$

which leads to the displacements performed during this two stages of the motion:

$$x_{acc} = x_{dec} = \frac{a_{max}\, t_{acc}^2}{2} \tag{2}$$

Now the displacement performed at constant speed and the required time for it are given by:

$$x_{const} = x_{total} - x_{acc} - x_{dec}\,, \quad t_{const} = \frac{x_{const}}{v_{max}} \tag{3}$$

Using the above equations all the parameters of the imposed trapezoidal speed profile can be computed.

The motion on the two axes must be precisely co-coordinated, because the total time of the motions on the two orthogonal axes obviously must be the same. Hence first the longer displacement must be taken. The displacement on that axis will be performed with the maximum velocity and the corresponding speed profile can be computed using the above-presented equations.

Upon these parameters the other speed profile can be computed. As it was stated out previously, the duration of the motion on the two orthogonal directions must be the same ($t'_{total} = t_{total}$). In this case the maximum velocity of the second speed profile is given by:

$$v'_{max} = \frac{x'_{total}}{t'_{total}} = \frac{x'_{total}}{t_{total}} \tag{4}$$

Using this equation the maximum acceleration will be:

$$a'_{max} = \frac{v'_{max}}{t'_{acc}} = \frac{v'_{max}}{t_{acc}} \tag{5}$$

As the maximum acceleration and speed being set the rest of the parameters of the speed profile can be easily computed using equations similar to (2) and (3).

Imposing the two speed profiles the load fixed on the forcer can be moved in the target position in the shortest time possible.

In the case of the other type of displacement to fulfill the courier must follow a previously planned trajectory (path) [9, 10].

The block scheme of the control unit used in this case is given in Fig. 7.

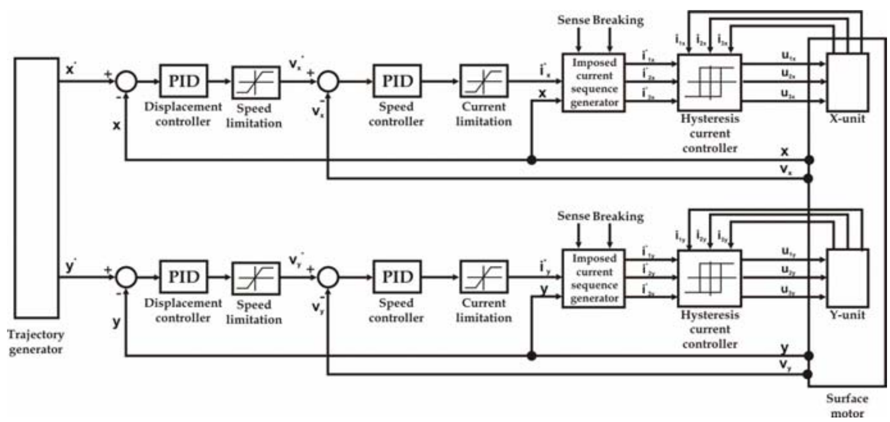


Fig. 7. The block scheme of the control system

In this case the control unit has for both parts of the surface motor 2 PID controllers (a displacement controller and a speed controller), respectively a hysteresis current controller. Based on the required trajectory the two imposed displacements (x^* and y^*) must be generated.
The control system requires several feedback signals from the surface motor: the measured currents of the six phases, and the displacement, respectively the speed on the two axis of the motor. The last signals can be obtained in several ways: from transducers fixed on the mover, or by applying sensorless speed and displacement estimation techniques [11].

V. SIMULATIONS

The positioning capability of the proposed variable reluctance surface motor was analyzed by means of simulation.
The applied simulation program, presented in detail in [12], has three coupled units. Each unit is implemented in different analysis and simulation platform. Hence for all the simulation tasks almost the best software environments are used. This way the accuracy of the entire simulation program is as high as possible.
The main simulation program is built up in SIMULINK. The forces developed by the motor for given command currents and relative displacements were previously computed very accurately using the 2D Finite Element Method (FEM) based analysis.
The power converter was simulated in SIMPLORER and integrated in the SIMULINK program by an S-type function.
The main window of the simulation program is given in Fig. 8.

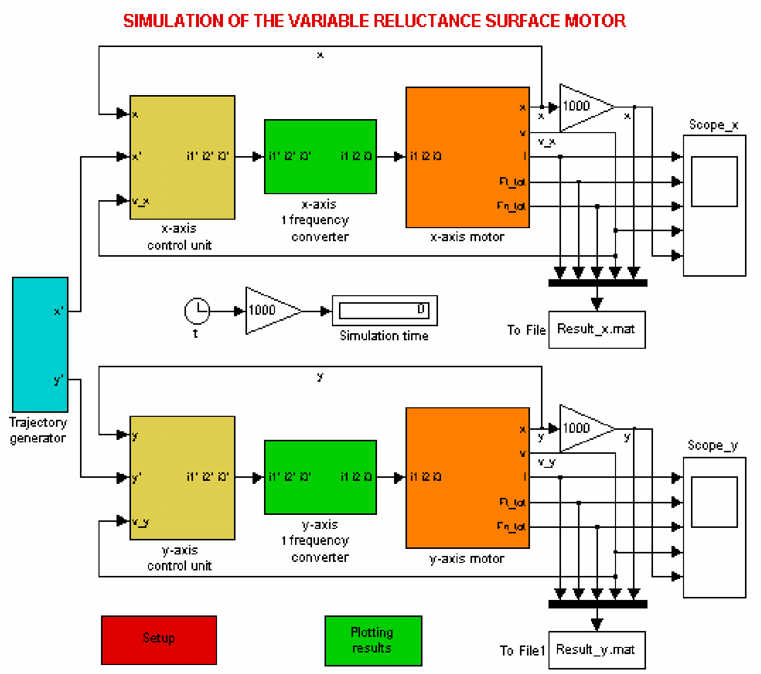


Fig. 8. The main window of the simulation program

A very simple task was imposed to fulfil: the forcer was started from its initial position, A, and was moved into position B where the load was put on it and it was displaced in C. Here the load was taken down and the courier returns to its initial position. The imposed task is given in Fig. 9.

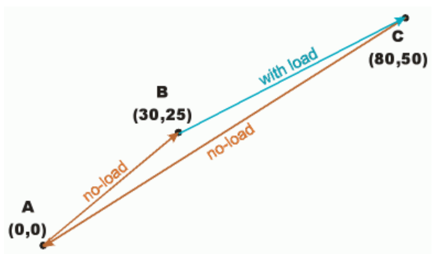


Fig. 9. The imposed positioning task

This simple task is composed of three different motion stages for each direction of the movement (A→B, B→C and C→A), having distinct imposed trapezoidal speed profiles.
The main data of the two speed profiles are given in Table 1.
The speed profiles with the corresponding variations of the accelerations and of the displacements versus time are given in Fig. 10.
From the results obtained by the simulation of the given task here only those for the x-axis motor part will be given. The plots of the command currents, of the total tangential and normal forces, of the speed and of the displacement versus time are shown in Fig. 11.
The results for the y-axis motor part are similar to those given in Fig 11.

TABLE 1
THE MAIN DATA OF THE SPEED PROFILES

	Stage 1. (A→B)		Stage 2. (B→C)		Stage 3. (C→A)	
	x motor	**y motor**	**x motor**	**y motor**	**x motor**	**y motor**
load [kg]	0		5		0	
t_{acc} [ms]	12		14		12	
t_{const} [ms]	13		57.43		54.7	
t_{dec} [ms]	12		14		12	
a [m/s^2]	100	71.43	50	25	100	62.5
v_{max} [m/s]	1.2	1	0.7	0.35	-1.2	-0.75
x_{acc} [mm]	7.2	6	4.9	2.45	7.2	4.5
x_{const} [mm]	15.6	13	40.2	20.1	65.6	41
x_{dec} [mm]	7.2	6	4.9	2.45	7.2	4.5

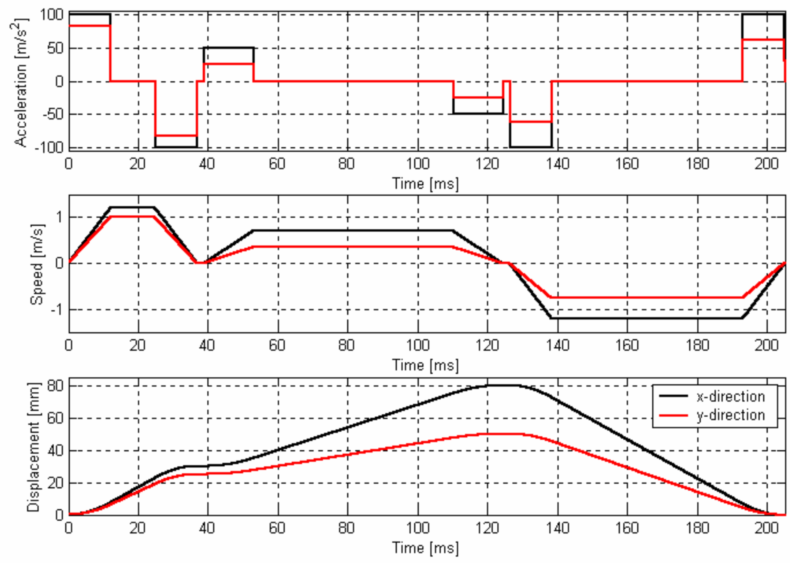


Fig. 10. The imposed characteristics of the motion task

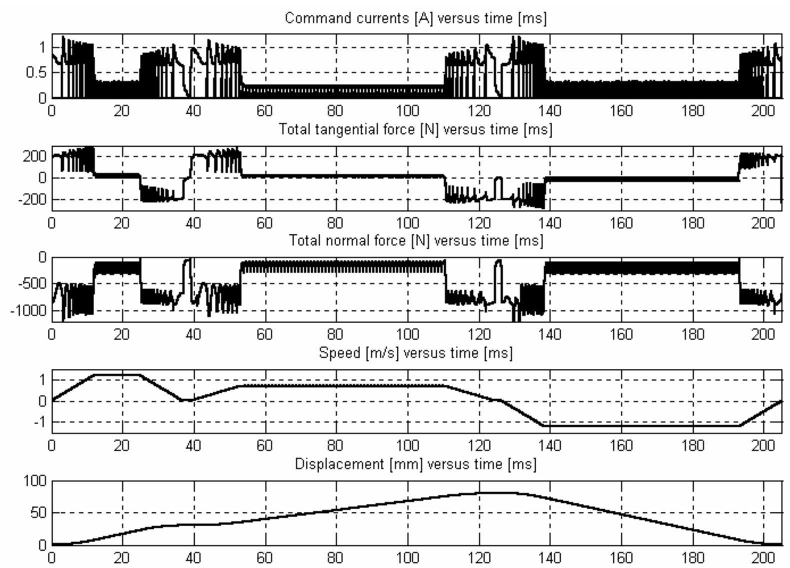


Fig. 11. Results of the simulation for the x-axis motor part

The obtained planar displacement of the courier is given in Fig 12.

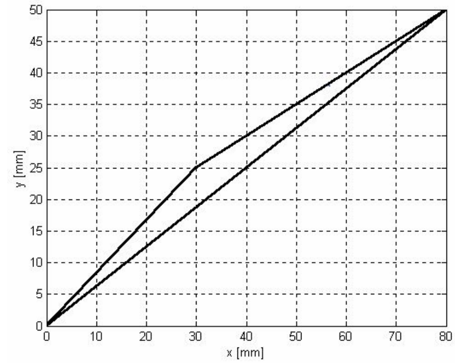


Fig. 12. The obtained planar displacement

As it can be seen the imposed task was perfectly fulfilled.

Next the results of the simulation of the variable reluctance surface motor moving upon an imposed trajectory will be presented.

The imposed trajectory was a quite complicated one, having a snail form.

The trajectory is defined by the following parametric system of equations:

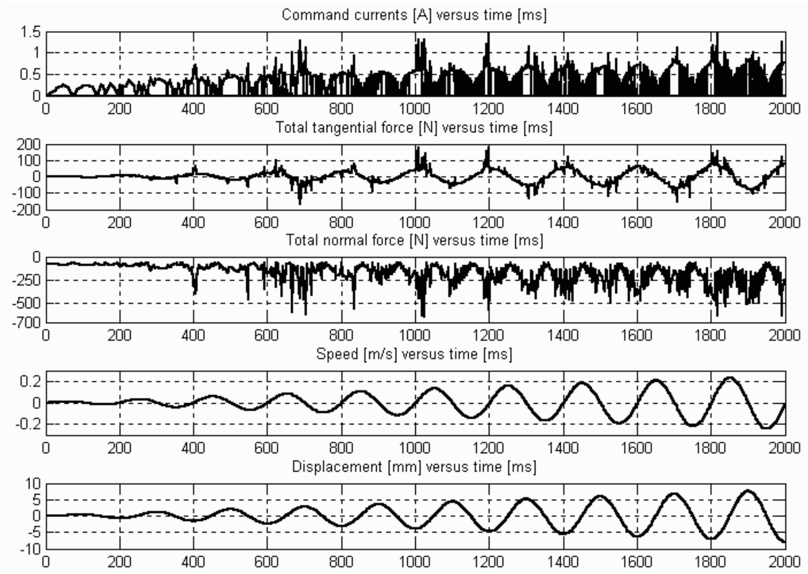
$$\begin{cases} x(t) = -r(t)\cos(\omega t) \\ y(t) = r(t)\sin(\omega t) \end{cases} \tag{6}$$

where:

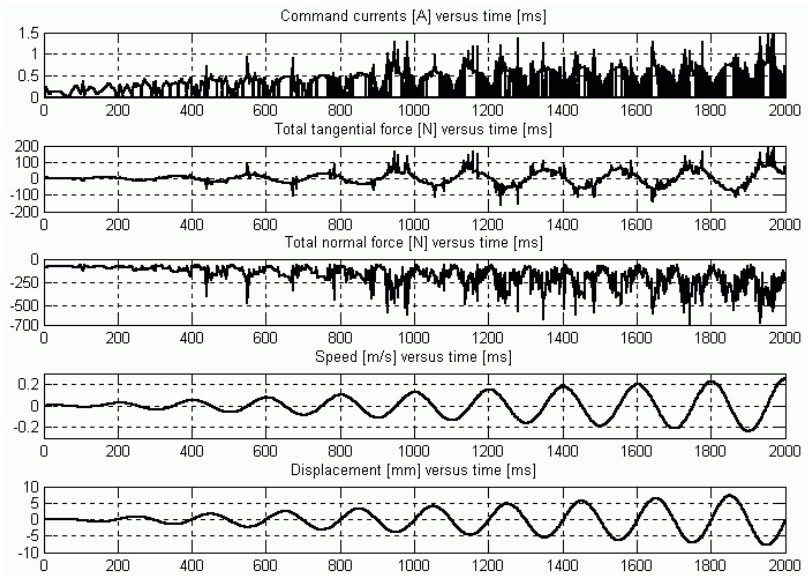
$$r(t) = c \cdot t \tag{7}$$

The parameters of the snail were be selected to be c=4, ω=10π and duration of the motion is t∈[0, 2] s.

The results obtained for this imposed trajectory are given in Fig 13.



a) the x-axis motor part



b) the y-axis motor part

Fig. 13. Results of the simulation for the imposed snail form trajectory

The planar trajectory obtained by the surface motor is given in Fig 14.

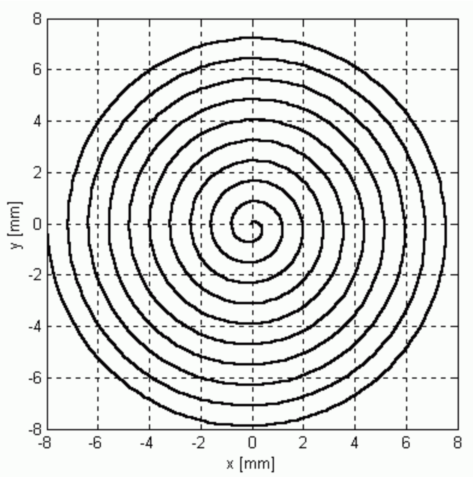


Fig. 14. The obtained planar displacement

Studying the obtained results it comes clearly out, that also this kind of positioning task is done with high accuracy by the variable reluctance surface motor in discussion.

VI. CONCLUSIONS

As it can be seen from all the obtained results the modular planar motor is well suited for any application required in a flexible manufacturing system.

The trajectory generated to achieve the given task was computed correctly and this way the task can be fulfilled in the shortest possible time.

Both the motor and its control unit are well-suited for these tasks and also for several other industrial applications, which demands fast and accurate plain movements.

Finally it can be stated out that only a well-planned trajectory together with the planar motor's high dynamic capabilities can assure the desired efficiency for the manufacturing process.

ACKNOWLEDGMENT

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