Using Dynamic Vector Force Fields to Manipulate Parts on an Intelligent Motion Surface[1]

Murilo G. Coutinho, Peter M. Will, IEEE Members,
USC Information Sciences Institute
Marina del Rey, CA
(310)-822-1511
coutinho@isi.edu

Abstract: *In this paper we will introduce the use of* ***dynamic vector force fields*** *as a means of moving parts between work cells on an Intelligent Motion Surface (IMS). The idea is to put a force field around a part and move the force field in a continuous or discrete way, dragging the part along with the field. Here, we are not interested in determining in what stable position the part finds itself after the movement, but rather, we are interested in deriving the capture condition in order to guarantee that the part will not be lost during the movement. We will derive a realistic and accurate model of the movement of dynamic vector force fields taking into account the discrete placement of the micro-manipulators on the IMS. Using this model, we will show how dynamic vector force fields can be implemented by analyzing the special case of a squeeze vector force field moving a part (assumed to be a particle) along a straight line path. Dynamic control algorithms considering the discrete nature of the IMS have not yet been explored by the research community and to the best of our knowledge, this is the first time a sensorless manipulation strategy for moving parts on an IMS is derived taking into account the discrete placement of the micro-manipulators and the dynamics of the part.*

1. Introduction

The Intelligent Motion Surface (IMS), an array of micro-manipulators that in aggregate form a programmable motion surface capable of manipulating small, MEMS parts placed on it, is being used as the basis for a new class of precision positioning and feeding devices. In an industrial environment, the IMS would be used as an intelligent feeder, moving parts between work cells and accurately positioning and orienting the parts within each work cell (see Figure 1). Each work cell would comprise a sub-region of the IMS (called the working area of the work cell) and a mesoscopic robot for parts assembly.

Current modeling and analysis of the several hardware variations of IMS micro-manipulators ([1-5; 8-11]) share the same approximation of assuming that the micro-manipulators induce a continuous vector force field on the parts being manipulated. The vector force field can be programmed to change its direction and possibly its strength (up to a maximum value) on a time-varying basis. This flexibility has been explored by the research community to generate sensorless manipulation algorithms to orient parts placed on the vector force field [7, 12] using techniques borrowed from sensorless manipulation using the well-known parallel-jaw gripper [3, 6].

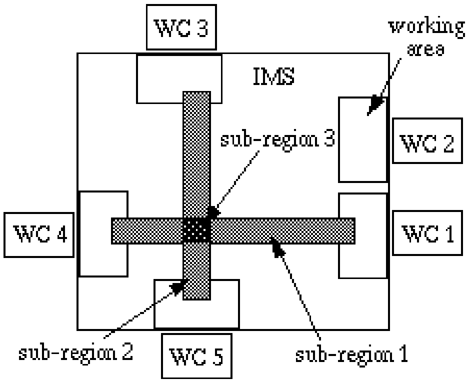

Figure 1: Typical IMS configuration with several work cells (WC).

In this paper we will introduce the use of **dynamic vector force fields** as a means of moving parts between work cells. The idea is to put a force field around a part and move the force field in a continuous or discrete way, dragging the part along

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with the field. We believe the use of dynamic vector force fields to activate moving sub-regions of the IMS (and not the entire IMS) can be used to optimize the power consumption as well as the feeding throughput (independent manipulation tasks can be executed in parallel).

A *dynamic vector force field* is a sub-region of the IMS that has its shape and/or position within the IMS changed on a time-varying basis. A static vector force field is a special case of a dynamic vector force field with a constant shape and position. Although static vector force fields can be used to manipulate parts within a work cell they are inappropriate to move parts between work cells. Consider the case shown in Figure 1, where sub-assembly tasks involve moving parts from work cell 3 to work cell 5 and from work cell 2 to work cell 4. These sub-assembly tasks could not be performed simultaneously using static vector force fields since this would require the activation of sub-region 3 with two different (incompatible) vector force field directions.

2. Modeling the movement of dynamic vector force fields

Consider two consecutive instances of a dynamic vector force field being moved along the x-direction of the IMS (see Figure 2). Moving the dynamic vector force field from position 1 to position 2 implies activating micro-manipulators 5 and 6, and deactivating micro-manipulators 1 and 2. This is equivalent to shifting the dynamic vector force field to the right by the length of the micro-manipulators along the x-direction. (We are assuming all micro-manipulators have the same dimensions.) Note that the overall movement of the dynamic vector force field is **not continuous.** In fact, the maximum possible resolution of the movement is limited by the length of the micro-manipulators along the direction of the movement. Therefore, in a realistic model, we cannot move dynamic vector force fields by any desired amount: the possible amounts are limited to be integer multiples of the length of the micro-manipulators along the direction of the movement. This will affect the dynamics of parts being placed on dynamic vector force fields and how fast we can move them without losing the part. This last problem is defined as the *capture condition*.

A feasible dynamic control algorithm is one that enforces the capture condition for a given dynamic vector force field moving along a given path. Depending on the path and the dynamic vector force field, a feasible dynamic control algorithm may not exist. For instance, in the case of a smooth curved path, depending on the curvature of the path and the velocity and acceleration of the movement, the dynamic vector force field may not be strong enough to resist the centrifugal force acting on the part, and the part may be thrown out of the dynamic force field sub-region.

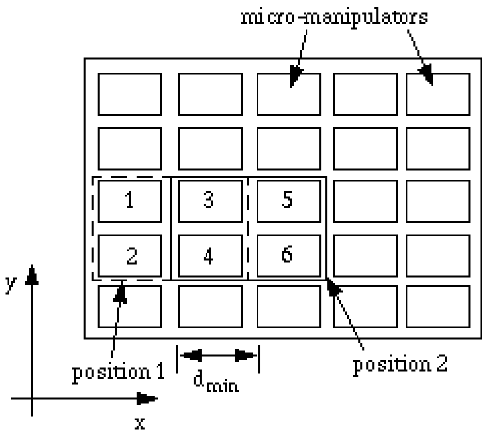

Figure 2: Two consecutive instances of a dynamic vector force field moving along the x-direction.

In this paper we will derive a sensorless dynamic control algorithm that enforces the capture condition while moving parts along straight line paths. The more general characterization and derivation of sensorless dynamic control algorithms that enforces the capture condition for a given family of smooth curved paths will be published elsewhere.

3. Moving parts along straight line paths using a squeeze vector force field

Given a part to be moved between different work cells on an IMS, and a straight line path to be followed, the most intuitive dynamic vector force field configuration to be used, that may be able to enforce the capture condition in the direction of movement is the squeeze vector force field (see Figure 3(a)).

Initially, the part is stabilized at the center line of the squeeze vector force field. Since the movement of dynamic vector force fields is not continuous, moving the squeeze vector force field by a distance *d* along the direction of the straight line path will instantaneously place the part the same distance *d* away from the center line (see Figure 3(b)). The squeeze vector force field will act on the part, pushing it back to a stable position, not necessary the same as the previous one. Here, we are not interested in determining in what stable position the part finds itself after a sequence of pushes, but rather, we are interested in deriving the capture condition in order to guarantee that the part will not be lost during the movement. This is crucial for sensorless manipulation strategies.

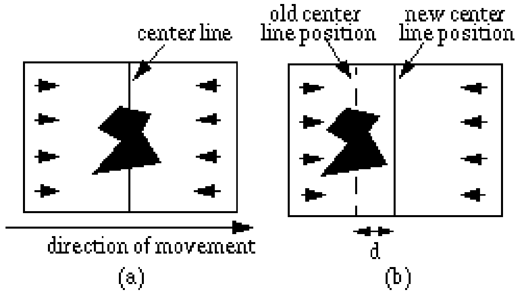

Figure 3: (a) The squeeze vector force field and a part initially stabilized; (b) At the next time step, the squeeze vector force field is moved by a distance *d* (not continuously), instantaneously placing the part at a distance *d* from the center line.

Note that the net force induced by the squeeze vector force field acting on the part will be maximum whenever the part is totally contained inside one of the squeeze vector force field regions (see Figure 4(a)).

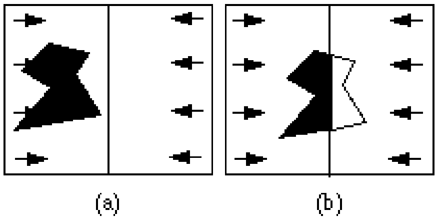

Figure 4: (a) The part is totally contained inside one sub-region of the squeeze field (case of maximum induced force); (b) The part intersects the center line. In this case, the net force will be the difference between the forces acting on each of the two subdivisions of the part.

Here, we will simplify the problem by considering the part to be a particle[2] coincident with its center of mass, and analyze the dynamics of the capture condition for the particle. This is a reasonable assumption as long as we keep the part totally inside one of the force field regions during the movement. Doing so, we can assume that the squeeze vector force field will induce its maximum squeeze force on the particle at all times the particle is not on top of the center line and is inside one of the two squeeze regions.

3.1 The differential equation that governs the movement of a particle on a squeeze vector force field along a straight line path

Since the dynamic vector force field is moving along a straight line, the particle's movement can be described as a one-dimensional movement along the direction of the straight line path. Without loss of generality, lets assume that the direction of the straight line coincides with the x-axis direction. Let *x(t)* be the position of the particle relative to the center line. So, *x(t)* will be negative (positive) if the particle is positioned to the left (right) of the center line (*x(t)* is zero at the center line). Let F be the maximum possible squeeze force acting on the particle and let f be the dynamic friction coefficient between the particle and the IMS. The differential equation governing the particle's movement will be:

$$-F\frac{x}{|x|} - f\frac{\dot{x}}{|\dot{x}|} = m\ddot{x} \qquad \text{(eq.1)}$$

Instead of solving (eq.1) directly, we will break it up into all four possible situations that can occur, and rewrite (eq.1) for each one of them. This is particular interesting since we are going to derive a dynamic control algorithm that will move the particle in a controlled way, that is, we will know in what situation the particle finds itself at anytime during the movement and therefore we will be able to apply the correct equation. Figure 5 shows all four possible situations that a particle can find itself just after the dynamic squeeze vector force field moves one more time step along the straight line path. Let the current time step be t_n. Let v_{n-1} (the final velocity at time step t_{n-1}) be the initial velocity of the particle at time t_n. Let x_{n-1} (the final position at time step t_{n-1}) be the initial position of the particle at time t_n. Following is the solution of the differential equations for each situation for $t_{n-1} \le t \le t_n$.

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[2] From now on, the words "part" and "particle" will be used interchangeably.

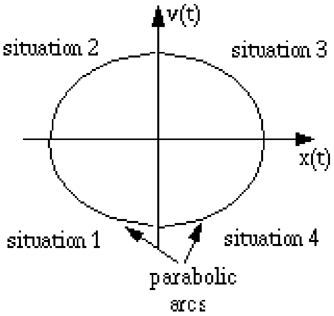

Figure 5: Phase diagram of equation (eq.1).

Situation 1: $v_{n-1} < 0$ and $x(t) < 0$. (eq.1) can be reduced to: $F + f = m\ddot{x}$. We have:

$$x(t) = \frac{(F+f)}{2m}t^2 + v_{n-1}t + x_{n-1}$$
$$v(t) = \frac{(F+f)}{m}t + v_{n-1} \qquad \text{(eq.1.1)}$$

Situation 2: $v_{n-1} \geq 0$ and $x(t) < 0$. (eq.1) can be reduced to: $F - f = m\ddot{x}$. We have:

$$x(t) = \frac{(F-f)}{2m}t^2 + v_{n-1}t + x_{n-1}$$
$$v(t) = \frac{(F-f)}{m}t + v_{n-1} \qquad \text{(eq.1.2)}$$

Situation 3: $v_{n-1} \geq 0$ and $x(t) \geq 0$. (eq.1) can be reduced to: $-F - f = m\ddot{x}$. We have:

$$x(t) = -\frac{(F+f)}{2m}t^2 + v_{n-1}t + x_{n-1}$$
$$v(t) = -\frac{(F+f)}{m}t + v_{n-1} \qquad \text{(eq.1.3)}$$

Situation 4: $v_{n-1} < 0$ and $x(t) \geq 0$. (eq.1) can be reduced to: $-F + f = m\ddot{x}$. We have:

$$x(t) = -\frac{(F-f)}{2m}t^2 + v_{n-1}t + x_{n-1}$$
$$v(t) = -\frac{(F-f)}{m}t + v_{n-1} \qquad \text{(eq.1.4)}$$

3.3 How the dynamic squeeze vector force field is moved along the straight line path

Since we want to maximize throughput, we need to move parts reliably and fast between work cells. Reliably implies that we will enforce the capture condition at all times. Fast implies that we will move the dynamic squeeze vector force field in such a way that the particle will gain as much velocity as possible, that is, it will be accelerated as much as possible during the movement. The maximum acceleration can only be achieved if the part remains inside the squeeze vector force field region that has its force vector pointing on the same direction of the movement. Without loss of generality, lets assume we are moving along the positive x-direction.

In this paper we assume there is no upper limit to the maximum possible velocity the part can gain during the movement. The idea will be to move the dynamic squeeze vector force field by a fixed distance *d* using *non-uniform time steps*. The time steps will be chosen such that the particle will never have enough time to travel the distance *d* and move into the right side region of the squeeze vector force field. In the next sections, we will derive the capture condition that must be satisfied at all times. In this paper we will consider the case of abruptly stopping at the final goal position.

3.4 Computing the velocity of the particle after *n* non-uniform time steps

Figure 6 shows the situation at the beginning of time step *n*. The particle is at a distance *d* from the center line and with initial velocity v_{n-1}. This corresponds to situation 1 described in section 3.1. Lets compute how much time the particle will take to reach the center line. According to section 3.3, this time will be the time step t_n.

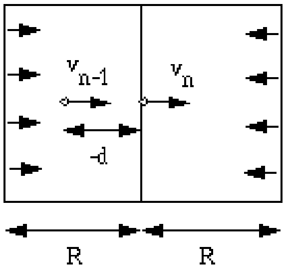

Figure 6: Initial configuration of the particle at the beginning of time step n.

When the particle reaches the center line its position will be zero, that is, $x(t) = 0$. Using (eq.1.1) we have:

$$x(t)=0 \quad \Leftrightarrow \quad \frac{(F-f)}{2m}t^2+v_{n-1}t-d=0$$

Solving for *t*, we have:

$$t=\frac{-v_{n-1}+\sqrt{\Delta}}{(F-f)}m, \qquad \Delta=v_{n-1}^2+\frac{2d(F-f)}{m} \qquad \text{(eq.2)}$$

So, the velocity of the particle at the end of the *n-th* time step can be recursively computed as:

$$v_n=\sqrt{v_{n-1}^2+\frac{2d(F-f)}{m}} \qquad \text{(eq.3)}$$

Since initially the particle is assumed to be stabilized, its initial velocity is zero ($v_o=0$.) Substituting into equation (eq.3), we can compute the final velocity after *n* time steps as:

$$v_n=\sqrt{\frac{2d(F-f)}{m}n} \qquad \text{(eq.4)}$$

3.5 Computing the n-th non-uniform time step

Using (eq.2) and the fact that the initial velocity is zero, we can also derive a recursive formula for computing the *n-th* non-uniform time step used to move the dynamic squeeze vector force field. We will have:

$$t_0=0, \quad t_1=\sqrt{\frac{2dm}{(F-f)}},$$

$$t_2=\frac{-mv_1}{(F-f)}+\sqrt{\frac{m^2v_1^2}{(F-f)^2}+\frac{2dm}{(F-f)}}=$$

$$=(\sqrt{2}-1)\sqrt{\frac{2dm}{(F-f)}}, \qquad \ldots$$

$$t_n=(\sqrt{n}-\sqrt{n-1})\sqrt{\frac{2dm}{(F-f)}} \qquad \text{(eq.5)}$$

Note that as *n* increases the corresponding time step decreases. On the limiting condition, we have $n\to\infty\Rightarrow t_n\to 0$.

3.6 Deriving the capture condition for the abrupt stop case

In the abrupt stop case, the dynamic squeeze vector force field will stop moving as soon as its center line is on top of the goal position. Lets assume that this will happen at time step *n*. Using (eq.4), we know the final velocity v_n of the particle at time step *n*. Since the dynamic squeeze vector force field will not move anymore, the particle will enter the right side region of the squeeze field after the time step *n*. The penetration depth will depend on the initial velocity v_n. This case corresponds to situation 3 of section 3.1 (see Figure 5). Using (eq.1.3), we will compute the time it takes to reduce the particle's velocity to zero. Note that the initial position of the particle will be zero, since it will be positioned on top of the center line at the end of time step *n*. We will have:

$$x(t)=-\frac{(F+f)}{2m}t^2+v_nt+0,$$

$$v(t)=-\frac{(F+f)}{m}t+v_n$$

$$v(t)=0 \quad \Leftrightarrow \quad t=\frac{mv_n}{(F+f)}$$

The penetration depth of the particle will be:

$$d_{depth}=\frac{mv_n^2}{2(F+f)} \qquad \text{(eq.6)}$$

The capture condition will be satisfied if and only if the penetration depth is less than the length *R* of the squeeze vector force field region (see Figure 6), that is:

$$R\geq\frac{mv_n^2}{2(F+f)} \qquad \text{(eq.7)}$$

Substituting (eq.4) into (eq.7), we have:

$$R\geq\frac{nd(F-f)}{(F+f)} \qquad \text{(eq.8)}$$

Therefore, given the distance *L* between the start and final goal position (that is, the total distance we should move the dynamic squeeze vector force field), and the maximum squeeze force *F*, we want to determine *R*, *d*, and *n*, such that the capture condition will be satisfied during the movement. Since the dynamic squeeze vector force field is moved by a fixed distance d at each time step, the total distance moved after n time steps will be nd. So, we must have:

$$L = nd \qquad \text{(eq.9)}$$

Substituting in (eq.8), we have:

$$R \geq \frac{L(F-f)}{(F+f)} \qquad \text{(eq.10)}$$

We use (eq.10) to choose R, the length of the squeeze region along the direction of movement (see Figure 6). (eq.10) gives a lower bound to the possible values of R, in order to enforce the capture condition for time step n. By construction the capture condition is already satisfied during the movement if the distance d is less than R. Note also that from the discussion on section 2, the distance d has a minimum value equal to the length of the micro-manipulators along the direction of movement. That is, d must satisfy:

$$d_{micro-manipulators} \leq d < R \qquad \text{(eq.11)}$$

After choosing d satisfying (eq.11), we can substitute it on (eq.9) to obtain n, the total number of time steps. The non-uniform time steps can be computed using (eq.5). For completeness, lets compute the total time spent to move the particle. The total time will be:

$$total\ time = \sum_{n=1}^{L/d} (\sqrt{n} - \sqrt{n-1}) \sqrt{\frac{2dm}{(F-f)}} =$$
$$= \sqrt{\frac{L}{d}} \sqrt{\frac{2dm}{(F-f)}} = \sqrt{\frac{2Lm}{(F-f)}}$$

That is, the total time is independent of the total number of steps n and the distance d! Of course, it depends on the distance L that we have to travel from the start to the final goal positions.

4 Conclusion

Dynamic control algorithms considering the discrete nature of the IMS have not yet been explored by the research community and to the best of our knowledge, this is the first time a sensorless manipulation strategy for moving parts on an IMS is derived taking into account the discrete placement of the micro-manipulators and the dynamics of the part. However, this paper still assumes that the micro-manipulators induce a continuous vector force field on parts placed on top of them, and treated the part as a particle. Also, we did not considered the discrete placement of the micro-manipulators to compute the force induced by them on parts placed on the IMS. This is still subject of future research.

5 References

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