Parcel Manipulation and Dynamics with a Distributed Actuator Array: The Virtual Vehicle

Jonathan E. Luntz, William Messner, and Howie Choset
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213
jl9f@cmu.edu, bmessner@cmu.edu, choset@cs.cmu.edu

Abstract *We are developing a materials handling system where many small simple actuators cooperate to transport and to manipulate large objects in the plane. A discrete set of cells, each comprising two actuators, are fixed in a planar array. By coordinating the actuators in the cells on which an objects rests, an object can be transported and manipulated. In essence, this system is an improvement over traditional conveyor systems in that objects can be re-oriented, as well as conveyed. Such an array provides flexible materials handling in which many objects independently can be manipulated and transported at the same time. The array is coordinated in a distributed manner where each cell has its own controller and each controller communicates with its neighbors. Towards the goal of motion planning, in this paper we consider the dynamics of parcel transport and manipulation. The parcel dynamics are based on an exact discrete representation of the system, unlike other methods where a continuity assumption is made. Two types of contact models are considered.*

1 Introduction

Many applications require objects to be transported and manipulated in the plane. Two such applications are flexible manufacturing and package handling. Flexible manufacturing requires that working part paths be arbitrarily specified and that these paths be readily updated by a "factory programmer." Package handling systems, such as airport baggage handling, require parcels to be sorted, oriented, and transported to one of several locations.

Two existing methods of material transfer are conveyor belts and robotic manipulators. The conveyor belts are able to transfer many large heavy objects for long distances, but lack the ability to orient precisely and to re-order the objects. Furthermore, while conveyor belts allow objects to be diverted to different destinations, they are not well suited to merging objects from different sources. Robots, on the other hand, are able to precisely position and orient objects, but are limited by strength and reach. Furthermore, the robot can only re-orient one object at a time. The Virtual Vehicle system, described below, combines the benefits of conveyor and robotics transport systems while overcoming their limitations.

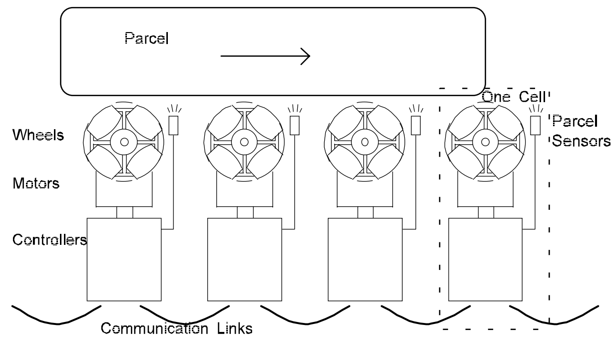

Fig. 1. A few manipulator cells carrying a parcel.

We are developing an alternative method for manipulating objects in the plane, where many small manipulation cells fixed in a planar array cooperate to handle objects. In our system, each cell consists of a pair of actuators whose combined action can effect force in any planar direction to a parcel resting on top of the array. Furthermore, each cell contains up to five binary sensors which detect the presence of an object. See Figure 1.

In our system, the parcels are significantly larger than each cell; several cells handle a single object. Through proper coordination, parcels which ride on top of the array can be made to translate and rotate in the plane. Since sensing and actuation are distributed, each of many parcels can be manipulated independently, appearing as if each parcel were carried by a separate vehicle (Figure 2). Hence, the name *Virtual Vehicle.*

For many applications, a dedicated robot or conveyor is the simplest and most appropriate solution. There are cases, however, where features, such as additional flexibility and reconfigurability, are required. In these cases, the Virtual Vehicle possesses many advantages, including

- **Flexibility.** Since the actuation is distributed, multiple parcels can be manipulated independently. This allows for parcels to be sorted, re-ordered, and re-directed quickly. Furthermore, objects of many sizes and shapes can be passed along easily. Finally, multiple object pathways can be invoked in

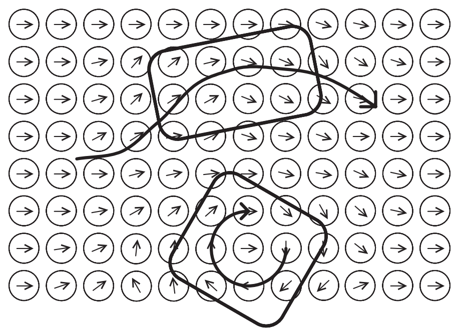

Fig. 2. The Virtual Vehicle: Several parcels can be translated and rotated, independently.

parallel.

- **Redundancy.** Since the Virtual Vehicle System is a massively parallel array of cells, if one cell breaks, the neighboring cells work around the broken cell by either diverting parcels around the broken cell or simply passing parcels over the it.
- **Modularity/Reconfigurability.** Many cells can be produced at a low cost because of their small size and relative simplicity. The cells are designed to "snap" together to form an array. This modularity allows the cells to be arranged in any configuration. The array can be easily reconfigured by moving cells and adding new cells. The modularity also enables easy repair because a broken cell is simply replaced with a new one.
- **Scalability.** Cells can be designed to carry objects of all sizes. For example, micromachined actuators can carry near-microscopic objects such as integrated circuit components, whereas small plastic wheels can carry suitcases (of many sizes) through airports and large truck tires can carry box cars around a ship/train yard.

The Virtual Vehicle can be used in conjunction with traditional robots and conveyor belts to form hybrid systems. For example, in airport baggage handling, long conveyors can be used to transport parcels over long distances while Virtual Vehicle arrays can be installed at conveyor junctions to sort and to re-direct parcel traffic. In flexible manufacturing, the Virtual Vehicle can be used to transport objects between robot workspaces where simple robots are used for object fixturing.

2 Prior Work

The notion of cooperative motion has been examined in the past. For example, Reynolds (1987) has emulated the flocking motion of birds using simple rules between independent agents which react to their surroundings. An overview of work in cooperating agents has been compiled by Mataric (1995a). Among these concepts presented, the idea of cellular robotics described by Wang and Beni (1988, 1991) is somewhat similar to our system in that a fixed array of robots cooperates to manipulate parts for manufacturing with the main difference being that the parts are smaller than the robots such that only one robot handles one part at a time. Much of the other work in cooperative distributed agents has been concerning the cooperation of multiple mobile robots (Deneubourg, et. al., 1990, Mataric, et. al., 1995b) such as a robotic ant colony. Such a system, however, does not have a fixed spatial arrangement as does the Virtual Vehicle.

The idea of an array of actuators carrying an object on top is described by Bohringer, Donald, et. al. (1994) where microelectromechanical actuators are used to manipulate very small objects. Their system is different in that it is on a small scale, the control is centralized, and the manipulation is entirely sensorless. It is worth noting that Bohringer, Donald, et. al. consider kinematics and ignore dynamics because of their small scale application.

The Virtual Vehicle concept was introduced in (Luntz and Messner, 1995a) where a continuous medium model of the system was used. This idea says that a regularly distributed array of interacting dynamic systems can be treated as a continuous medium, rather than a collection of discrete elements. This was demonstrated by assuming a simple control law for each cell in a row of cells based on the speeds of the neighboring cells. The equation of motion for each cell contains a finite difference term which is recognized as the approximation of a second partial derivative with respect to distance along the array. The resulting equation is equivalent to the transient heat conduction equation, with actuator velocity analogous to temperature. Physical analogies such as these are useful to understand the dynamics and to design behavior for such distributed systems. Simulations were performed to demonstrate these ideas.

More recently, prototype hardware was built and tested (Luntz, et. al., 1995b, Luntz and Messner, 1996a). Simple tests, such as passing a cardboard box back and forth along a row of cells were performed. A distributed network and a communication language were developed (Luntz and Messner, 1996b) which enables the cells to communicate effectively with each other. The network is briefly described in the next section. The language involves the construction of short "sentences" which are made up of labeled pieces of data, or words, punctuated by a checksum. Such a sentence may be translated, for example, as "I know a parcel which is three cells away and which should go at a speed of 20."

In this paper, we take a first step in examining the dynamics of a parcel carried by the Virtual Vehicle. The ultimate goal of this work is to be able to predict and

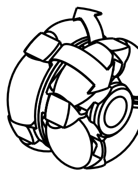

Fig. 3. Roller wheel.

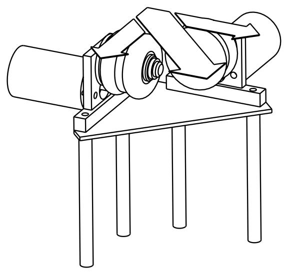

Fig. 4. Prototype cell.

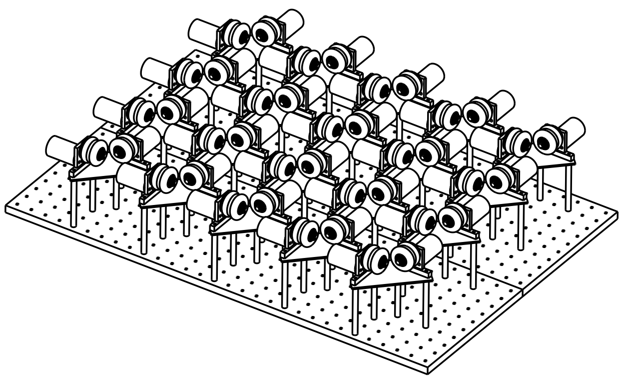

Fig. 5. Two-dimensional array of cells.

control the motion of one or more parcels with two-dimensional translation with rotation in the plane.

3 System Architecture

Mechanical Configuration. We have built a prototype system consisting of a small array of cells capable of transporting objects about the size of a bread box. Each cell consists of a pair of orthogonally oriented motorized roller wheels (Figures 3 and 4) which are capable of producing a force perpendicular to their axes, while allowing free motion parallel to their axes. Each wheel is driven through a gear reduction by a small DC motor.

Each of these cells is connected to a large breadboard style base (Figure 5) to create a regular array of manipulators. Currently, we have only 20 cells which are arranged in single row. The mounting system allows us readily to reconfigure the array to a small 2-D grid. Currently, we are studying the 1-D row to develop analytical solutions, which will later be generalized to a 2-D system. Furthermore, we can analyze communication issues among cells with the 1-D row.

Electronic Configuration We are exploring the use of distributed control on the Virtual Vehicle because it is a relatively underdeveloped and interesting control paradigm, and because we believe that it would become impractical or impossible for a single computer to control hundreds or possibly thousands of cells. The controller of each cell is a single-board computer based on the Motorola MC68HC11 microprocessor. The capabilities of this processor allow it to control more than one cell. In application, either multiple cells would be controlled by one processor, or a simpler processor would be used in each cell in order to build a more cost effective system.

The speed of the wheels is measured by a quadrature encoder. The presence of a parcel is sensed by a phototransistor which detects the shadow from the overhead lights. The motor is driven by pulse width modulation using an H-bridge circuit.

Network Configuration An important aspect of our control scheme is the communication between cells. Each controller has an RS232 serial communications port. This port is multiplexed between each of the four neighboring cells, conceptually equivalent to a one-of-four BCD switch controlled by the processor. For a cell to send a message to or receive a message from a neighbor, it must actively select the neighbor with the multiplexer. Handshaking lines are necessary to alert a neighboring cell that a message is pending since only one neighbor can be selected at once. A hell's processor polls through all four neighbor's handshaking lines to look for pending incoming messages.

The above described communication may seem awkward compared to standard local area network schemes where each cell would have an address, and all cells share a data bus. We require many communications to occur simultaneously on the array which cannot be accomplished with a shared data bus. Also, we would like our network not to be limited by a maximum address space, or to require any particular cell to know its location relative to the rest of the array. Each cell need only be aware of its immediate surroundings. If any information needs to be sent further than one cell away, it can be passed along the array, from cell to cell.

4 Dynamics

Towards the goal of representing the dynamics of handling a parcel in the plane with an array of actuators, first consider the dynamics of a single row of cells transporting a parcel along a line. Each cell consists of just one wheel oriented along the row. We are examining the situation where all of the wheels in the row spin clockwise (effecting right-wise motion to a parcel), except the right most wheel which spins counter clockwise (effecting left-wise motion to a parcel) This right most wheel acts as a restoring force that prevents a parcel from falling off of the edge of the linear array.

In the methodology of Bohringer, Donald, et. al. (1994), each cell (i.e., wheel) would exhibit a constant force in the direction of the the wheel's motion. Such methodology would result in a horizontal force field as shown in Figure 6. This simple force law is easy to cal-

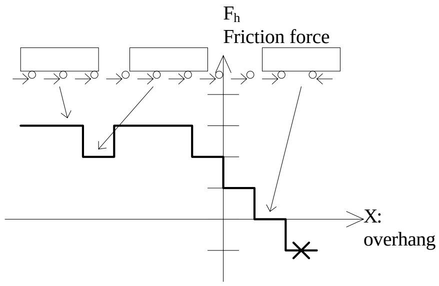

Fig. 6. Force vs. Position for Constant Force Cells. Three typical positions are indicated along graph. Positive distance measures how far the parcel overhangs the last cell. Arrows under each wheel indicate the direction of force from that wheel. The $\times$ means the parcel falls off of the linear array.

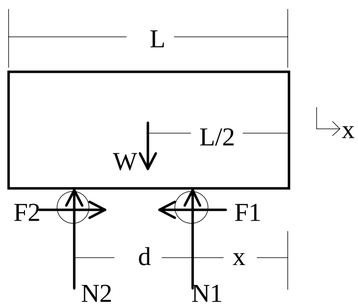

Fig. 7. Free body diagram of parcel in two-cell case.

culate, but does not demonstrate the dynamics observed in our system. With this methodology, a parcel traveling along the above described linear array would fall off the edge of the array because there is no *net* force pushing it back onto the array. Nevertheless, our observations show that the parcel finds a stable equilibrium when it "overhangs" the last reversed spinning wheel. (The x in Figure 7 and in Figure 8 is the "overhang" of the right most cell.)

In order to better represent the dynamics of the system, a more accurate approximation of the forces between the wheels and the parcel is necessary. Forces and moments are balanced to get a more realistic representation of the load balance on the wheels. Initially, we look at the dynamics of a parcel supported by two cells with simple coulomb friction between the wheels and the parcel. Then, we examine the more general case of many cells supporting the parcel with both coulomb and velocity-dependent friction models.

4.1 Two-Cell Case

We are modeling the parcel as a simple inertia that rests on two point contacts (Figure 7). The wheels are assumed to be both spinning inward (trying to keep the box centered, with the velocity of the wheel surface faster than that of the box, so that a simple coulomb friction model can be used.

The normal forces acting on the box are obtained from static equilibrium, balancing moment about one wheel and total vertical force, as follows

$$\begin{aligned} \sum F_y = 0 &\quad = N_1 + N_2 - W \\ \sum M_1 = 0 &\quad = W(\tfrac{L}{2} - x) - N_2(d) \end{aligned} \tag{1}$$

Note that N_2 can be determined from the moment equation and substituted into the force equation, yielding

$$\begin{aligned} N_1 &= W(1 - \tfrac{L}{2d} + \tfrac{x}{d}) \\ N_2 &= W(\tfrac{L}{2d} - \tfrac{x}{d}) \end{aligned} \tag{2}$$

These equations show that as the parcel's overhang past wheel 1 increases, more of the load is supported by wheel 1. The dynamics of the parcel can be derived by obtaining the horizontal forces from the coefficient of friction, μ. Since $F_1 = \mu N_1$, $F_2 = \mu N_2$, and $W = mg$, the horizontal motion of the parcel is

$$m\ddot{x} = F_2 - F_1 = \mu N_2 - \mu N_1$$

$$\ddot{x} = \frac{\mu W}{m}(-1 + \frac{L}{d} - \frac{2x}{d})$$

$$\ddot{x} + \frac{2\mu g}{d}x = \frac{\mu g}{d}(L - d) \tag{3}$$

This is a simple harmonic oscillator. As the parcel hangs over one end, that wheel's normal force increases, increasing the friction force on the parcel which acts as a restoring force. The parcel will oscillate around $x = \frac{L-d}{2}$ which corresponds to the center of the two wheels.

4.2 Many-Cell Case

Now we consider an array where n cells support the parcel. We consider the the coulomb friction model, as we did with the two-cell case. Then, we introduce a viscous-like velocity-dependent friction model. Before we can do that, we first must look at the normal forces in the linear array.

4.2.1 Normal Forces

In general, when the parcel is supported by n cells, the normal forces, and hence the friction forces, cannot be found through static equilibrium because there are only two equations (y-forces and moments) and n unknowns. That is, the multiple support problem is statically indeterminant, and depends upon mechanical flexibility in the system to supply the remaining $n - 2$ equations. A simple model of the flexibility in the system is shown in Figure 8. Each support is assumed to be a spring, with Hooke's Law ($N = k\Delta y$) representing its compression under a normal load. Physically, this flexibility can be thought of as a flexible suspension under each wheel, as will be included in the next generation of our hardware array. In the current system, the flexibility is apparent in the bottom of the parcel, particularly when a rubbery material is used under the parcel to increase friction.

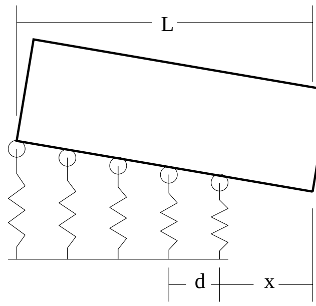

Fig. 8. Flexible supports in many-cell casee.

Assuming that the bottom of the box, without elastic deformations, is straight, the difference in spring compression between the ith and the $i+1$st cells must be equal to the difference in compression between the $i+1$st and $i+2$nd cells in order to maintain a straight line between all of the contact points. Hooke's Law asserts that for $0 < i < (n-2)$,

$$N_i - N_{i+1} = N_{i+1} - N_{i+2}$$

$$N_i - 2N_{i+1} + N_{i+2} = 0, \qquad (4)$$

which says the discretized second derivative is zero, i.e., the box is linear.

This constitutive law supplies the remaining $n-2$ equations needed to solve for the normal forces, i.e.,

$$\underbrace{\begin{bmatrix} 1 & 1 & 1 & 1 & \dots & 1 \\ 0 & d & 2d & 3d & \dots & nd \\ 1 & -2 & 1 & 0 & \dots & 0 \\ 0 & 1 & -2 & 1 & & 0 \\ & & & \ddots & & \\ 0 & \dots & 0 & 1 & -2 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ \vdots \\ N_n \end{bmatrix}}_{\bar{N}} = \underbrace{\begin{bmatrix} W \\ W(\frac{L}{2}-x) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{\bar{W}} \qquad (5)$$

The first two rows of the equation represent the equilibrium of vertical forces and moments about the first point of contact, respectively. the remaining $n-2$ rows represent the constitutive laws from Equation 4. A is a constant matrix (for a given value of d) and can be inverted so that the normal forces can be determined.

4.2.2 Coulomb Friction

In the case of coulomb friction, where the wheels are assumed to be be spinning faster than the parcel is moving, the force from friction will always be equal to μN_i in the direction of wheel rotation. In this case, the horizontal dynamics of the parcel can be represented as

$$m\ddot{x} = \mu \begin{bmatrix} -1 & +1 & +1 & \dots & +1 \end{bmatrix} \bar{N} \qquad (6)$$

where the $+1$ and -1 represent the direction that the wheel is spinning and thus the direction of the friction force. Note that in the case of coulomb friction, the relative velocity of the surfaces in unimportant.

Since the normal force vector can be expressed in terms of the matrices from Equation 5, Equation 6 can be written as

$$m\ddot{x} = \mu \underbrace{\begin{bmatrix} -1 & +1 & +1 & \dots & +1 \end{bmatrix}}_{\bar{F}} A^{-1} \begin{bmatrix} W \\ W(\frac{L}{2}-x) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

$$\ddot{x} = \mu \frac{W}{m} \bar{F} A^{-1} \underbrace{\begin{bmatrix} 1 & 0 \\ \frac{L}{2} & 1 \\ 0 & 0 \\ \vdots & \vdots \\ 0 & 0 \end{bmatrix}}_{B} \left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} - \begin{bmatrix} 0 \\ 1 \end{bmatrix} x \right)$$

$$\ddot{x} + \mu g \bar{F} A^{-1} B \begin{bmatrix} 0 \\ 1 \end{bmatrix} x = \mu g \bar{F} A^{-1} B \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad (7)$$

Equation 7 represents a simple harmonic oscillator with the frequency and offset constants determined by the parameters of the 5

system, L, d, μ, and by the number of cells supporting the parcel.

4.2.3 Velocity-Dependent Friction

The coulomb friction model gives a system with no damping, and thus there will be oscillations about an equilibrium point. A large enough oscillation may result in the parcel falling off of the edge of the array, particularly because the equilibrium location is near the end of the array. This differs from our experimental observation in which the parcel slows down and nearly stops after oscillating around the equilibrium position. Therefore, some damping must be added to the model.

Damping is added to the model with a velocity-dependent friction force which is proportional to both the normal force and the relative speed between the wheel and the parcel, such that $Ff_i = k(V_i - \dot{x})N_i$, where V_i is the velocity of the ith wheel, and k is a friction constant. This is basically viscous damping where the damping constant is proportional to the normal force. The horizontal dynamics of the parcel then becomes

$$m\ddot{x} = k(V_1 - \dot{x})N_1 + k(V_2 - \dot{x})N_2 + \dots + k(V_n - \dot{x})N_n$$

$$m\ddot{x} = k \overbrace{\begin{bmatrix} V_1 & V_2 & \dots & V_n \end{bmatrix}}^{\bar{V}} \bar{N} - k\dot{x} \begin{bmatrix} 1 & 1 & \dots & 1 \end{bmatrix} \bar{N}$$

$$\ddot{x} = k\frac{W}{m}\bar{V}A^{-1}B\left(\begin{bmatrix}1\\0\end{bmatrix} - \begin{bmatrix}0\\1\end{bmatrix}x\right)$$
$$- k\frac{W}{m}\begin{bmatrix}1 & 1 & \dots & 1\end{bmatrix}A^{-1}B\left(\begin{bmatrix}1\\0\end{bmatrix} - \begin{bmatrix}0\\1\end{bmatrix}x\right)\dot{x}$$

$$\ddot{x} + kg\begin{bmatrix}1 & 1 & \dots & 1\end{bmatrix}A^{-1}B\begin{bmatrix}1\\0\end{bmatrix}\dot{x} + kg\bar{V}A^{-1}B\begin{bmatrix}0\\1\end{bmatrix}x = kg\bar{V}A^{-1}B\begin{bmatrix}1\\0\end{bmatrix} \quad (8)$$

In the final equation, the cross term $(x\dot{x})$ does not appear because it can be shown that this term is identically zero. The algebra is omitted due to space limitations, but the intuition is as follows. The cross term can be represented as the sum of n constants times x times $\dot{x}$. These n constants come from $WA^{-1}B\begin{bmatrix}0 & 1\end{bmatrix}^T$ which is equal to the x terms in $\bar{N}$ (the monomials in $\bar{N}$ containing x). Therefore, for the cross term to equal zero, the sum of the x terms of the normal forces must add up to zero. The sum of the forces in $\bar{N}$ must be constant (in fact, it is equal to W) in order to satisfy the vertical equilibrium condition. The contribution of the x to this sum is equal to $x\sum\alpha_i$, where $x\alpha_i$ is the x contribution to N_i. Since the only variable in $\bar{N}$ is x, the sum of the x coefficients must be identically zero for the sum of the forces to be constant. This sum is the same sum which makes up the cross term, so the cross term must be identically zero.

It is worth noting that the horizontal dynamics are just that of a damped harmonic oscillator. The damping ratio, natural frequency, and offset are again just functions of the system parameters and of the number of cells supporting the parcel.

4.3 Motion Prediction

The dynamics of the parcel in both the coulomb and velocity-dependent friction models are linear second order. When the number of cells supporting a parcel is changed, the the constants of the differential equation are simply altered. The overall motion of the parcel can be predicted easily by calculating the number of cells under the parcel at the start, and determining, from the second order dynamics, when and where the number of supporting cells changes. (In some cases, computing the normal forces results in negative values, particularly when the parcel overhangs the end of the array and thus the cell at the other end may require a negative force to balance moments and forces on the parcel. Since the wheels can only push up on a parcel, a negative force means that wheel loses contact with the parcel, and the forces should be recomputed with one fewer support.)

It is interesting to examine the force as a function of position for this type of arrangement. Figure 9 shows this relationship for $L = 12$ and $d = 5$ in the case of coulomb friction. The equilibrium position of the parcel is where the force equals zero. Since there is a continuous negative slope of force through the equilibrium, this equilibrium is stable, unlike the constant-force case equilibrium.

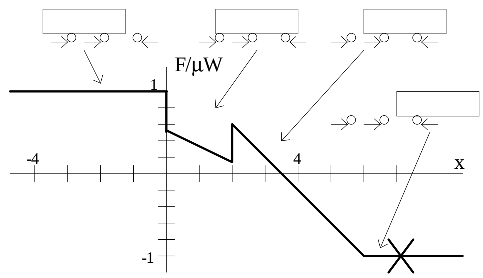

Fig. 9. Force vs. position for coulomb friction model. Four typical positions are indicated along graph. Positive distance measures how far the parcel overhangs the last cell. Arrows under each wheel indicate the direction of force from that wheel.

5 Conclusion and Future Work

We have shown that the dynamics of a parcel carried by the Virtual Vehicle can be modeled as a second order harmonic oscillator. We derived the equation of motion for a linear array with a particular arrangement of motor velocities where all motors spin clockwise and the right-most spins counter-clockwise. This motion is specified by the row vector $\bar{F}$ which is equal to $\begin{bmatrix}-1 & +1 & +1 & \dots & +1\end{bmatrix}$. This row vector can be changed without affecting the previous derivations; therefore, the dynamics derived in this paper are applicable to *any* arrangement of wheel velocities.

The next step of this work is to extend this type of calculation to 2-D and to 3-D (actually, $SE(2)$: 2-D plus rotation). It is hoped that a similar low-order model can be obtained for both translation and rotation. Allowing for rotations complicates the calculations, particularly in determining the distribution of cells under the parcel.

Another direction in motion prediction is to discretize the dynamics in time and space. The dynamics over a particular range of positions (where the parcel is supported by a constant number of cells) are known. Given the position and velocity when the parcel enters this range, the velocity and position where it leaves this range and enters the next can be computed directly. (The motion within the range becomes unimportant.) A set of discrete-space state transition equations can be computed, similar to those for discrete-time systems. This would allow for predictions of overall motion all at once, rather than in a piecewise manner.

Once the dynamics can be predicted, control laws will be generated so that parcels can be positioned and oriented as desired. Some work in this area has been done by Bohringer, Donald, et.al. (1994, 1996) for a similar system without parcel dynamics (just kinematics) with sensorless manipulation. This work could be extended for sensored systems with dynamics. Also, control laws can be distributed so that several parcels can be handled simultaneously.

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