On Large Scale Planar Manipulation*

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I Introduction

Autonomy may be thought of as a capacity to independently make logical decisions and take appropriate actions based on interpretation of particular circumstances perceived. For a robot, this typically means providing it with sensing and a set of predefined responses to particular sensed conditions. Consider a mobile robot (e.g. a security robot or a helper robot) with a mission of wandering around an office environment. The robot can detect the proximity of obstacles with a ranging sensor. Whenever a range reading is detected which is less than a predefined minimum value the robot stops and takes range measurements while rotating in place. When an open space is detected (i.e a range reading greater than some predefined value) it proceeds towards the open space. The robot can thus continue its "wandering" misson without human intervention. A fundamental goal of research in machine autonomy is to remove or reduce the necessity for human intervention when unexpected or unplanned for circumstances are encountered.

Robots should perform useful tasks prescribed by human masters. To a certain extent, such capability has been achieved within the traditional domain of fixed manipulation in structured environments. Robots can be programmed to spray paint, spot weld and perform basic assembly strategies such as inserting a peg in a hole. The successful outcome of such tasks relies heavily on careful control over the environment. Parts to be manipulated must be fed to the manipulator in a prescribed manner. Special fixturing and grippers must be designed to suit the task geometry. Collisions must be avoided by ensuring that the workspace is free of unexpected obstacles. We see that all of these restrictions detract from our notion of a robot as a general purpose manipulation device and increase the cost of adapting a particular manipulator to perform new tasks. The desire to remove this reliance on strict environmental control is a strong argument favoring the development of autonomous robots.

Rigorous environmental control is one approach towards uncertainty. Uncertainty results from errors in sensing and control, misallignment of parts, errors in initial positions etc. Uncertainty can be reduced by developing more accurate sensing and control schemes. However, this approach is ultimately restrictive and costly. An alternative, is to accept the presence of uncertainty and seek manipulation strategies which are robust in the face of uncertainty. Erdmann [22] states that *work in uncertainty can be interpreted as the search for primitive actions and methods of combination of these actions which extend the class of tasks solvable in the presence of uncertainty.* Consider a peg insertion task where the goal is to insert the peg in a hole. A naive position controlled strategy might be to move the peg directly downwards into the hole. Uncertainty in the initial position of the peg may cause the insertion to fail because the peg contacts either to the left or right of the hole. We seek manipulation *strategies* which will achieve a goal if it is achievable even in the presence of uncertainty. For instance, we can make the peg insertion strategy more robust by introducing force sensing which detects contact with the edge of the hole. Subsequent motion of the peg to the left or right can thus allow the peg insertion to succeed. This strategy is implemented using control software with conditional branching and provides a measure of autonomy for a stationary arm manipulator.

An additional motivation for developing autonomous machines is to understand the nature of intelligence. Brooks [2] and Moravec [13] argue from an evolutionary viewpoint that there is a strong correlation between mobility and intelligence. The traditional approach to developing artificial intelligence is to decompose the problem into specialized subproblems such as knowledge representation, recognition, vision, and language understanding. Human level intelligence is felt to be far too complex and ill understood to allow such simple decompositions. Mobile robot builders [1,2,3,33,34,13,26] argue that a true understanding of human level intelligence will evolve after much experience with creating simpler level intelligent systems that operate in the real world. Brooks suggests that complex behavior does not necessarily imply great complexity in the system exhibiting the behavior. He has investigated this idea by constructing mobile robots, from simple components with simple connections between components, which exhibit complex insect-like [3] behavioral patterns driven by sensed conditions in the real world.

The approach of researchers, in addressing the high-level issues outlined above, is to select an interesting class of tasks and to develop strategies which allow the robot to accomplish these tasks. Tasks pertaining to robot navigation have received the greatest deal of attention. Autonomous mobile robots operate in highly uncertain environments and have no easy method for determining their location. Referencing off an initial starting point is generally futile due to cumulative errors in odometry based sensing. A proposed solution is to provide sensing which allows the robot to construct maps [?,32,25] of its environment and locate itself within these maps. Various types of sensors such as shaft encoders [10], laser range finders, ultrasonic transducers [5,24,9], and cameras [8,7,11] can be used in a complimentary fashion to aid map construction and navigation. Research covers the physical characterization of individual sensors [4,5] and the development of techniques for combination of noisy data derived from fundamentally different sensors [24]. Probabilistic frameworks [11,34,25] for data combination have been proposed. Moravec [11] proposes the notion of "occupancy grids" where occupancy grid peaks represent regions where the probability of finding an obstacle is high. Conversely, valleys in the occupancy grid represent regions likely to be empty and local robot path planning can be implemented by searching for routes through valleys. Techniques [10,25] from state estimation theory (e.g. Kalman Filter) are also used in probabilistic approaches towards uncertainty.

Other work deals with architectural implementation. Brooks [1] proposes a multiprocessor based control architecture (subsumption architecture) where independent layers of control are built to let a robot operate at increasing levels of competence. Layers may be considered as simple input/output boxes which generate a *fixed* response to a given input. Higher level layers can suppress the outputs of lower level layers. For example, a sonar module (sensor-processor arrangement) provides adequate information for navigation in unconfined regions where the sensor's lack of angular resolution is not a critical factor. When greater accuracy is required, say as the robot attempts to enter a doorway, locomotion commands generated by the sonar module are suppressed in favor of commands generated by an infra-red module which provides good short-range angular resolution. These ideas are similar to those of Arkin [34] and Noreils [9]. Noreils [9] suggests a more complex interconnection scheme between control/processor layers where an overall system manager *surveillance monitor* monitors status information associated with all layers before initiating a consistent action on an individual layer.

The robot's internal representation of its environment is an important issue. High-level "world-models" [32,27] attempt to describe the relationship between environmental features such as doors, rooms and hallways. Chatila [32] proposes a representation in terms of connectivity graphs. Lower level "world-models" deal with the construction of geometric representations from sensor data. Flynn [24] uses a configuration space approach and one based on a generalized cone version of free space to construct models suitable for path planning. Tsuiji [?] represents a building environment in terms of an apriori data base of horizontal and vertical edges extracted from video images corresponding to particular locations. During navigation the robot extracts edges from a detected image and interpolates its location by comparison with data base images.

In the preceding paragraphs, we have attempted to describe some of the primary motivations driving the development of autonomous robots. We have given a brief flavor for the breadth of issues involved. While navigation is an intrinsicly interesting and rich domain in which to develop autonomous capability, we feel that other classes of tasks should be explored.

II On a Mobot as a Manipulator

There exists no significant body of work on the utilization of mobile robots for manipulation. We propose to initiate the *development of strategies to autonomously perform useful manipulative tasks.* Clearly, the set of "useful tasks" is very wide. Our approach is to select a suitable subset and endeavor to achieve autonomous manipulation capability for this subset. We choose to restrict our domain to the manipulation of objects in the plane. The characteristics of allowable objects and their allowable interactions with the robot are:

- All objects will maintain dry frictional contact with the plane
- All motions will be dominated by frictional effects i.e. essentially quasi-static
- All interactions between manipulator and object will endeavor to maintain quasi-static motion of the object
- All objects may be approximated as truly planar i.e. laminar extrudates with low center of gravity

Candidate objects might be boxes or trash cans. Consider a robot with the prescribed task of " pushing a box down the hallway ". What faculties are required to achieve this task ? A speculative decomposition of the requirements is that the robot should have:

- Notions of what a box and a hallway are
- Faculties for locating the box
- A notion of what we mean by "push"
- An ability to find its way down the hall
- An ability to effect controlled pushing as it moves

It is the last of these abilities with which we are concerned. Note that our subset does not include objects which exhibit rolling contact with the plane such as castored trolleys or bowling balls. Although these are an interesting class of manipulatable objects, the strategic and hardware requirements to effect their manipulation are perceived to be quite different from those for the class we consider. A long term goal would be to extend our framework to encompass such tasks. For instance, a bowling ball could be manipulated by imparting a sequence of impulses and providing a sensor arrangement to track resultant motions whereas a simple pushing strategy might be sufficient for a box. In efforts to preserve simplicity, we also exclude strategies where an object is grasped by a manipulator and lifted from the plane. Although, this is a perfectly viable strategy for moving small objects from one location to another, we are concerned with objects which are typically large compared to the size of the manipulator. We also wish to avoid getting sidetracked into areas, such as grasping, which are the subject of intensive research in their own right. Other issues initially outside the scope of this work are: (a) recognition of a particular object (b) communication of a particular task request to the robot (c) possible interactions of robot and object with other obstacles in the planar world. These will eventually be incorporated in an overall framework if a useful and generally applicable planar manipulator is to be created. Our problem statement is simply this:

- Given that an object from the above subset is presented to the robot, can a system (hardware/strategy combination) be constructed which will allow the robot to independently effect controlled motion (i.e rotation-constrained motion) of the object in the plane ?

Fig (1) shows a mobile robot with two passive effectors A and B The robot is effecting translation of the laminar object in a direction specified by the velocity vector $\vec{V}_{mobot}$. The pushers A and B are contacting the object boundary at points C_A and C_B. We state, without proof, that no relative rotation between the object and the manipulator is possible if the Center of Friction (COF) is bounded by the two *lines of pushing* shown. A line of pushing is a line through the *boundary* contact point parallel to the velocity vector of the contact point. The COF is defined as that point on the *planar* contact surface of the body, about which the frictional reaction forces resulting from a pure *translation* of the object yield a zero resultant moment. We wish to develop a strategy which will result in the robot achieving such a configuration. Note that there are many acceptable contact points corresponding to different relative orientations that result in no relative rotation subject to motion. The robot's goal is to achieve any one of these configurations. During a search for such a configuration the robot is permitted to reorient the object. The outcome of a search is a reduction in the relational uncertainty between the robot and the object.

At this stage, we are not particularly concerned that our manipulator should effect purposeful motion of a given object, only that it should effect motion and that it should be controlled. Our goal is to identify the system requirements implied by such a capability. System requirements include sensors, effectors, electronic controllers, and intelligent manipulation strategies.

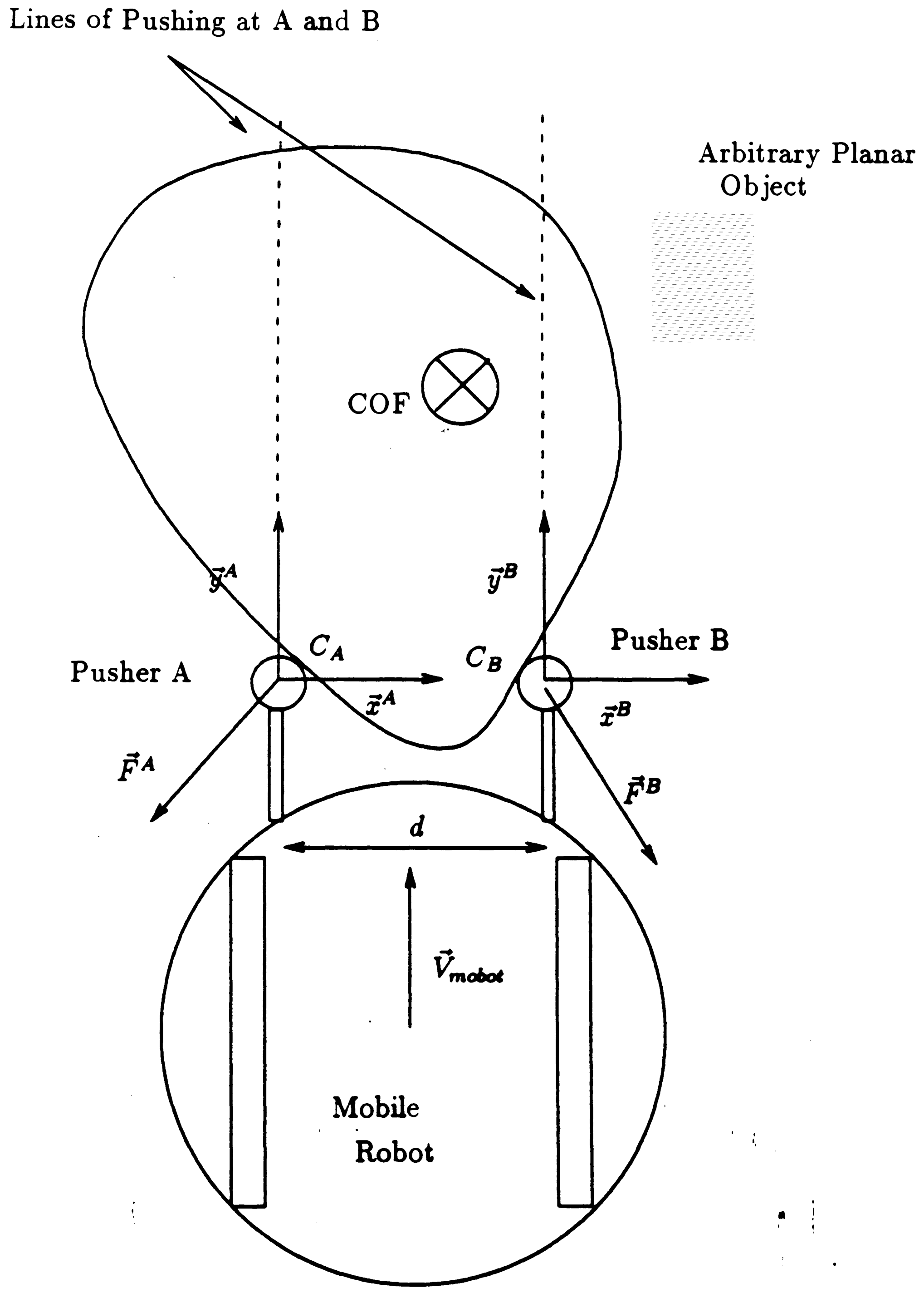

Figure 1: Mobile robot in stable manipulation configuration with arbitrary object

III Methodologies for Mechanics based manipulation

Three methodologies will be used in our efforts to develop planar manipulation strategies and are given as:

- Error Detection and Recovery (EDR)
- A Geometric Approach to Task Mechanics
- Matching Control to Mechanics.

Each of the above addresses different aspects of the planar manipulation problem. EDR provides a high-level definition of the characteristics of "good" manipulation strategies and an outline of the necessary steps for their construction. The geometric approach is a specific methodology for the implementation of EDR strategies while matching control to mechanics address dynamical aspects of the manipulation process.

III.1 Error Detection and Recovery

Error Detection and Recovery (EDR) proposed by Donald [19,20] is a formal framework for the synthesis and analysis of motion plans which are guaranteed to succeed or fail in a recognizable way. It has evolved from work on automatic strategy synthesis for assembly tasks performed by fixed-base manipulators. Assembly was originally viewed as a motion planning problem (i.e. moving an object from an initial configuration to a goal configuration through a collection of obstacles, while avoiding collisions with obstacles). Lozano-Pérez [18] proposed a representation, namely that of moving a point from a start location to a goal location in a higher dimensional *Configuration Space.* The basic idea is that objects can be shrunk to a point while obstacles may be grown to account for the shrinking. Configuration space approaches have been extended to incorporate dynamical models (e.g. generalized damper) and models of other physical constraints such as friction [21]. This proves useful in modeling *compliant motions*, i.e. interactions where objects slide along obstacle surfaces. LMT [17] outline an extended framework for synthesis of multi-step *guaranteed* strategies where position sensing and control uncertainties are explicitly accounted for.

Donald's work addresses the issue of model uncertainty. Model uncertainty refers to errors in the geometric models of the object and its environment. He shows that uncertainties can be parameterized as additional degrees of freedom in a higher dimensional configuration space. Strategies can be composed from a repertoire of simple actions such as sensor based gross motions in free space, compliant motions and simple pushing motions. Donald relaxes the restriction of demanding guaranteed strategies and considers multi-step strategies which might successfully achieve a goal configuration if it exists and is recognizably reachable but fail in some reasonable way when it does not. He shows that configuration space can be categorized into regions: (a) A goal region where a termination predicate can signal success (b) EDR regions where failure of a termination predicate can be recognized and an appropriate recovery action taken and (c) Bad regions from where it is impossible to recover from. A termination predicate is a function which asserts that a goal or subgoal has been achieved. There are three fundamental types of termination predictate: (1) position termination (2) force termination (3) time termination. A fourth type is derived from any combination of these. Donald defines [19] an EDR strategy as follows:

- An EDR strategy should attain the goal when it is recognizably reachable and signal failure when it is not
- It should permit serendipitous achievement of the goal
- No motion guaranteed to terminate recognizably in the goal should be prematurely terminated as a failure
- Finally, no motion should be terminated as a failure while there is any chance that it might serendipitously achieve the goal due to fortuitous sensing and control events

These are the EDR axioms and define the characteristics of good manipulation plans.

The peg insertion task mentioned earlier is an example EDR strategy. The initial downward motion of the peg resulted from an assumption of perfect position control. Force sensing allowed detection of the failure of this assumption and triggered recovery actions (i.e. lateral motions of the peg). On achieving the bottom of the hole, the termination predicate signals success. If the insertion failed, perhaps due to too small a hole diameter, the termination predicate would have signalled failure.

The theory underlying EDR is generally difficult to apply. However, Donald [20] has developed an automated EDR planner for simple planar assembly tasks such as meshing gears or inserting a peg in a hole. Generated plans have been implemented [30] on a Puma 560 robot and demonstrated to work. Automatic planning for wider classes of tasks is a subject of ongoing research. Currently one approach is to manually develop such plans using EDR as a set of guiding principles. In this respect, we believe that EDR will prove to be a fruitful tool in our efforts to construct planar manipulation strategies. However, a set of less abstract task specific tools is required to construct EDR plans. This leads to a geometric mechanics based methodology.

III.2 A Geometric Approach to task Mechanics

The geometric approach attempts to identify the roles played by the respective geometries of object and manipulator. Two ideas are presented: one which casts the problem in terms of a graphical relationship between a body's geometric outline and applied force vectors at a contact point and another where the object manipulator relationship is viewed as a cam follower interaction.

Paul [15] first recognized the utility of quasi-static pushing as a primitive manipulation strategy. With his hinge-plate grasping example, he showed how pushing operations could be selected to induce a desired adaptive motion of an object and could reduce the certainty assumptions on its initial position. Mason [14,15] analyzed the mechanics of planar pushing operations and developed theorems which allow qualitative geometric analysis and prediction of an object's motion. The theorems correlate the relative motion of an object to the following factors:

- An object's geometry
- Direction of motion of an applied pushing constraint
- Frictional interaction between the pusher and object
- Frictional interaction between the body and the plane

Mason showed that the sense of the total moment resulting from applied pushing forces about the COF is directly related to the sense of rotation of the body. Consider the planar slider of Fig (2). A is the total area of contact, dA is an elemental area at position vector $\boldsymbol{x}$, $p(\boldsymbol{x})$ the pressure distribution over A, and $\boldsymbol{v}$ the velocity at $\boldsymbol{x}$. Coulomb friction is assumed, with coefficient of friction μ. Coulomb's law gives the elemental tangential force at $\boldsymbol{x}$:

$$\boldsymbol{f_f} = -\mu \frac{\boldsymbol{v}}{\|\boldsymbol{v}\|} p(\boldsymbol{x}) dA \tag{1}$$

The total frictional force $\boldsymbol{F_f}$ and moment M_f is obtained by integrating over A:

$$\begin{aligned} \boldsymbol{F_f} &= \int_A -\mu \frac{\boldsymbol{v}}{\|\boldsymbol{v}\|} p(\boldsymbol{x}) dA \\ M_f &= \int_A \boldsymbol{x} \times -\mu \frac{\boldsymbol{v}}{\|\boldsymbol{v}\|} p(\boldsymbol{x}) dA \end{aligned} \tag{2}$$

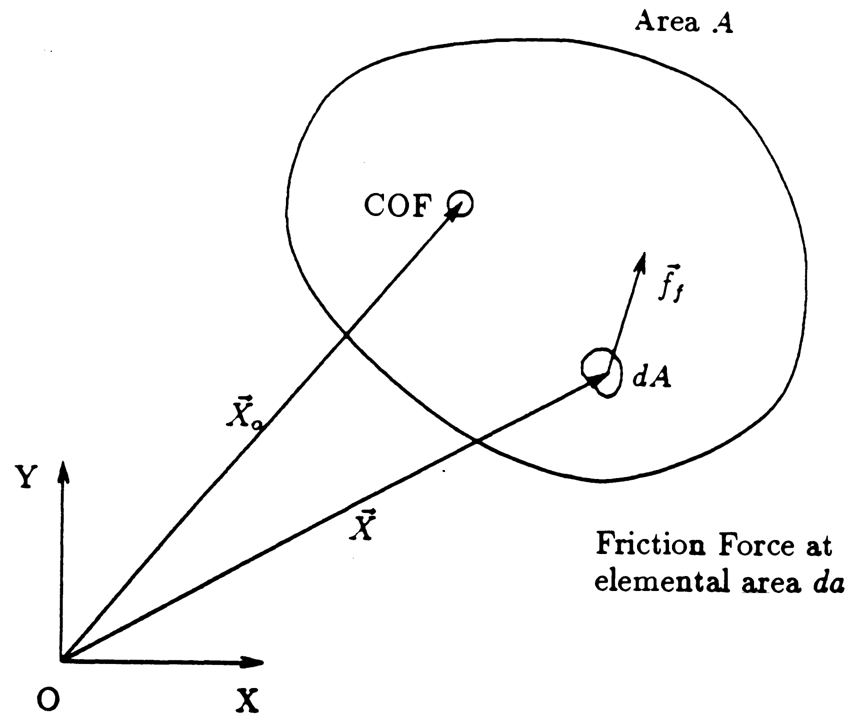

Figure 2: Planar Slider

where $\times$ denotes the vector cross product. Quasi-static equations are obtained by summation of the frictional and applied forces and moments acting on the body. The above integrals are difficult to evaluate since the pressure distribution is generally unknown. However, Mason proves for the case of pure *translation* that the total set of frictional reaction forces reduces to a single force though the center of friction (COF) which can be evaluated if the total contact force normal to the plane $F_o = \int_A p(\boldsymbol{x})dA$ is known and μ is constant over A. No moment exists about this point and is given as:

$$\boldsymbol{x}_o = \frac{\int_A \boldsymbol{x} p(\boldsymbol{x})dA}{F_o} \tag{3}$$

The COF lies directly beneath the center of mass of the object which for a uniform body corresponds to its geometric centroid. The total frictional force and moment for translation becomes:

$$\begin{aligned} \boldsymbol{F}_f &= -\mu \frac{\boldsymbol{v}_o}{\|\boldsymbol{v}_o\|} F_o \\ M_f &= \boldsymbol{x}_o \times \boldsymbol{F}_f \end{aligned} \tag{4}$$

No such simplification exists when object rotations are occurring and the COF plays no direct role in the governing equations. Mason reformulates Eqs (2) in terms of the body's *instantaneous center of rotation* and develops an analysis of rotation modes for two distinct classes of pushing contact:

- Contact with no slip between pusher and object

- Contact where slip occurs

The results are presented [23] geometrically in terms of three rays Fig (3):

- R_p - ray of pushing (i.e. line of pushing described earlier)
- R_l - left ray of the friction cone
- R_r - right ray of the friction cone

The friction cone is a geometric representation of Coulomb's law at the contacting point and portrays the range of forces which can be sustained given the surface normal and coefficient of friction between the body and the pusher. The three rays determine the direction of rotation by voting relative to the location of the COF. If two or more lie to the right of the COF the object rotates counterclockwise. If two or more lie to the left of the COF it rotates clockwise. If the ray of pushing points directly through the COF then no rotation of the object occurs. Brost [23] has developed planar grasping strategies using these *voting rules* to construct push stability diagrams for infinite planes pushing convex polygons. We note that Mason's analysis is purely quasi-static and takes no account of inertial forces. In certain cases he shows [15] that the quasi-static equations predict non-uniqueness in the motion for certain discrete support conditions. Goyal [31] predicts similar results with his limit surface analysis of frictional forces and moments. Both researchers suggest, without proof, that non-uniqueness can be removed by incorporating inertial terms in the equations of motion. Quasi-static analysis does not yield quantitative prediction of rotation rates except in simple cases where the pressure distribution is known (e.g three point support).

Mason's work serves as a basis for the development of motion strategies for planar manipulation. It provides a vocabulary which should be used to construct a robot's internal representation of a planar manipulation task. It facilitates design of termination and sub-goal recognition predicates for EDR strategies and indicates how certain preferred contact geometries may facilitate sensing interpretation and reduce knowledge requirements. For example, the use of a roller-tipped pusher can approximate frictionless contact and removes the necessity of obtaining the pusher-object friction coefficient. Mason's theorems are also useful as a set of theoretical guidelines for automatic planning. The theorems have been applied by Brost [23] to simple open loop pushing operations for fixed-base manipulators. Apriori knowledge of the task geometry, together with the relevant frictional properties associated with object-manipulator interaction can be used to plan a pushing strategy off-line. The planned strategy is executed in an open-loop manner without recourse to sensing. Currently Brost is investigating a potential role for sensing in these strategies.

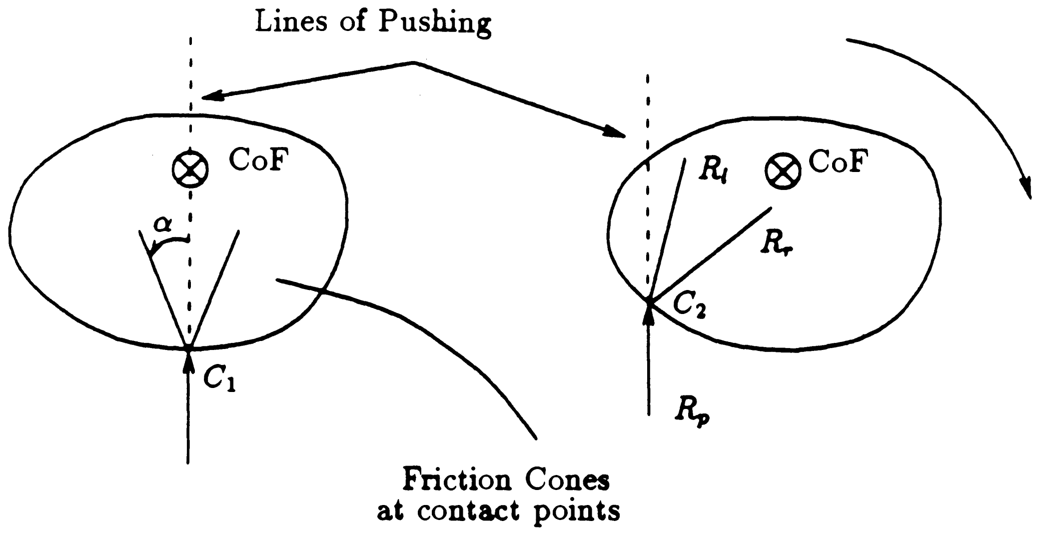

Figure 3: Pushing With Point Contact

We feel that sensing could be used by a mobile robot to allow construction of an internal geometric object model and to *monitor the objects motion.* For example, the robot could circumnavigate the object and collect a discrete array of surface normals through use of a proximity sensor. Following the EDR methodology, by assuming uniformity of the object it could approximately locate the object's COF. A successful attempt to bound the perceived COF with two pushing points would confirm the validity of the assumption. This type of experimental interaction with an object would perhaps allow the robot to construct a more detailed internal model incorporating abilities to crudely predict object rotation rates. Peshkin [36] has shown how rotation rate bounds can be obtained by considering three-point support approximations of continuous support distributions. By correlating object motions to applied forces, the robot, with a suitable algorithm, could locate three points on an internal representation which would allow it to calculate approximate rotation rates corresponding to forces applied to the object boundary. We now provide an example to illustrate how Mason's ideas may be used to construct a manipulation strategy.

Consider the two pronged manipulator of Fig (1). Suppose the object to be manipulated is a uniform disc of arbitrary radius initially at rest in the plane. Assume the robot is translating with fixed linear velocity V_y defined with respect to either of the two robot-fixed reference frames A and B shown in Fig (1). Pushers A and B are separated by a distance d which is less than the diameter of the disc. We also assume that the robot's trajectory will result in at least one of the prongs contacting the body. On sensing contact the robot is programmed to seek a *mating* configuration with the disc and eventually continue pushing it in a direction approximately parallel to its initially trajectory. We define a *mating configuration* as one where object motions are constrained so that relative rotation does not occur for a given commanded robot motion. What combination of sensing and control is required to achieve the mating configuration ? Suppose the following sensory capability exists:

- X-Y force sensing on each of the prongs A and B
- Shaft encoders which allow crude tracking of the robot displacement and velocity

The robot must recognize the mating goal (Fig (4) - Case (e)) when it is achieved. Hence, a termination condition, which uniquely identifies the goal contact configuration as a function of sensor values, is necessary and given as:

$$F_y^A < 0 \wedge F_y^B < 0 \wedge V_y > 0 \tag{5}$$

where F_y^A and F_y^B are the Y components of sensed forces along pushers A and B respectively and V_y is the translational velocity of the robot. Once this condition is achieved no rotation of the object with respect to the manipulator is possible so long as the motion direction remains constant. What series of actions should the robot undertake to eventually achieve satisfaction of the above inequality ?

Let us presume that the tips of prongs A and B are frictionless. This condition might be implemented by placing a roller at the end of each prong which ensures that forces resulting from contact are always normal to the boundary of the contacting object. For the disc, this implies that the sensed force vector must always lie along a line through the centroid of the disc. Since the disc is uniform, the COF lies directly below the centroid. No rotation of the disc will occur since it is impossible to develop moments about the COF and any gross motion will be composed of infinitesimal translations. Four additional single pusher contact scenarios (see Fig (4)) are possible. This are given with their respective recognizability conditions as:

(a) Prong B contacts to the left of the centroid - $F_x^B < 0 \wedge V_y > 0$.

(b) Prong B contacts to the right of the centroid - $F_x^B > 0 \wedge V_y > 0$

(c) Prong A contacts to the right of the centroid - $F_x^A > 0 \wedge V_y > 0$

(d) Prong A contacts to the left of the centroid - $F_x^A < 0 \wedge V_y > 0$

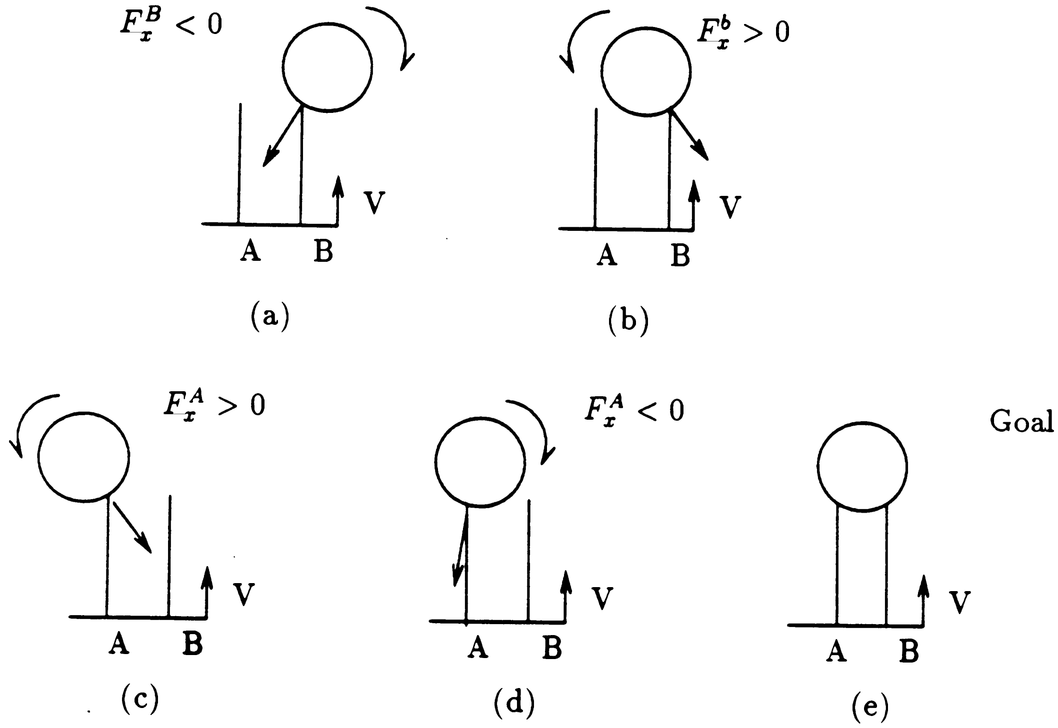

Figure 4: Possible interaction modes for Disc with COF on centroid

where F_x^B and F_x^A are sensed components of force in the X direction. If conditions (b) or (d) occur the robot's task is complete since after a finite amount of time the disc will translate to achieve the goal configuration. Conditions (a) or (c) are mirror image configurations and continued forward motion of the robot will result in failure, since contact with the disc will eventually be lost. On sensing (a) or (c) the robot must halt and initiate *recovery* actions.

Recovery actions are generally difficult to synthesize especially when the robot's knowledge of the world is incomplete. For condition (a), the robot could reverse, and attempt to make contact by following a new trajectory parallel to and to the right of the previous trajectory. An appropriate trajectory might be *randomly* selected at a distance $\leq d$. Erdmann [22] has shown that randomization proves to be a useful task achieving strategy. An example is the tapping of parts to achieve mating or shaking a part in a tray so that it achieves a desired stable orientation with some high probability. A recovery action corresponding to condition (c) would be a trajectory to the left of the initial trajectory. The robot would thus effect a series of contacts and push moves over a randomized cartesian grid. We imagine that this strategy would eventually succeed after an unknown number of iterations. We note that exact numerical values are not required for this strategy. Only force senses (i.e. directions) are required to allow the goal and individual failure modes to be recognized. This strategy could thus be implemented with single bit force sensing. Recognition of failure does not necessarily allow us to completely specify a recovery action. Often, we can only suggest a plausible action but can provide no guarantee that our goal will eventually be achieved.

This example strategy provides a demonstration of how geometric mechanics can drive sensing interpretation and object motion inference. However, it may lead to the false impression that we wish to restrict ourselves to two point pushing with force sensing. Two point pushing allows easy recognition of an achieved constraint and is sufficient for inducing controlled *linear* motion. As the robot wanders around its environment, it should be able to induce less restrictive object motions. This is necessary when steering an object around a corner for instance. Steering may be approximated by a series of translations in different directions or the geometry of the robot's front end (called the *herder*) could be suitably designed so that the object maintains contact with the robot over a range of trajectories of bounded curvature. Design aspects which we perceive as important are:

- The Specific shape of the herder
- The relationship between herder and object motion
- The nature and placement of herder mounted sensing

The front end or object herder may be viewed as a moving "potential well". Although potential field theory is not strictly applicable within our domain certain relevant concepts can be embraced. A potential well surrounds a configuration having properties such that sufficiently proximal configurations fall into it and having been attained there is an associated high probability of such configurations being maintained (i.e. stability). A complimentary notion is to think of the herder as a programmable *cam.* A cam is defined [35] as a mechanical element used to drive another element, called the *follower* through a specified motion by direct contact. In all cam systems, the follower should maintain contact with the cam at all times. Typically this is achieved by depending on gravity, by the inclusion of a suitable spring, or by mechanical constraint such as a groove or a slot. For planar manipulation, the contact constraint results from the frictional force developed due to the object's motion. The dynamics of a follower's motion may be controlled by design of the geometric profile of the cam. For a steady state motion of the cam such as constant angular velocity, the follower's motion can be made to follow a specific trajectory in phase space. Undesirable aspects of follower motion such as acceleration discontinuities can be avoided by matching derivatives at adjoining cam segments. Typically cam motion may induce a parabolic acceleration and deceleration of the follower and periods of constant position i.e. *dwell.*

Consider Fig (5) which depicts a mobile robot with a cam-like herder attached. The cam profile $y = f(x)$ is defined with respect to a robot fixed reference frame and is the locus of possible contact points with an object. Subject to a commanded forward motion of the robot the object will slide down the cam face eventually achieving a final configuration close to the cam origin. The relative motion of the object will depend on the cam profile, the commanded motion of the robot, the follower profile, and its properties. The concave shape of the cam would act as a potential well and the object would achieve a stable configuration at the bottom of the well. The exact mechanics governing relative motion are difficult to predict and would be a subject of investigation. Sensing is required to allow the robot to infer the follower relative motion. For example, individual force sensors or perhaps optical beam sensing could detect whether an object is within the convex hull of the cam outline or is making contact with the cam face. Perhaps the cam profile might include bumps where contact sensors could be positioned. Bumps could also act to restrain the object's motion over turning motions.

We could also imagine providing the cam with an adaptive capability:

$$y = f(x, \beta_1, \beta_2, ...\beta_i) \tag{6}$$

where the β_i are tunable parameters which allow the shape of the cam to be changed. This feature might be implemented by designing a flexible herder and affixing it to

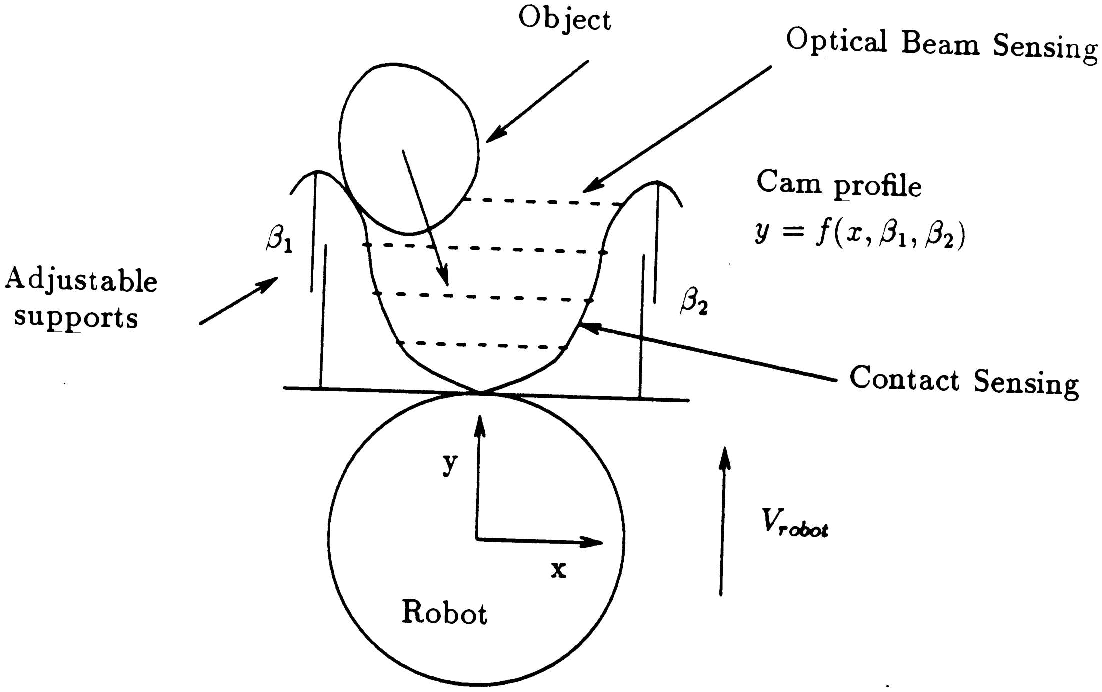

Figure 5: Cam - follower view of robot and object

the robot through a series of movable support points and programmable tension elements such as cables.

III.3 Matching Control to Mechanics

A mobile robot can be viewed as a controllable dynamical system with intrinsic stiffness, damping and inertial characteristics. As a manipulator it must interact with real world objects which are also independent dynamical systems having different intrinsic characteristics. The manipulation process seeks to join object to manipulator to achieve a coupled dynamical system. The joining process can be interpreted as the selection of a suitable interface such that the dynamical properties of the manipulator are matched to those of the object. The robot is an energy storage and transmission device while an object is a storage and dissipation device. Energy must be transferred to the object through a suitable conduit which matches the mechanical impedance [29] of the manipulator to that of the object. Mechanical impedance defines the cause-effect relationship between an applied force and a desired kinematic effect such as displacement and or velocity, and acts to modulate the observed response to a given input.

Objects with different material properties exhibit stiffness properties which give rise to different coefficients of restitution with the manipulator. Impacts which result in large inertial motions of the object are undesirable, since the object will tend to "bounce away" from the manipulator. By suitable selection of the stiffness of the contacting *interface* the object's time response can be made to appear as that of an overdamped second order system for a given range of contacting velocities. In order to select the specific impedance of the interface the robot requires a model of it's dynamical and control system and it must develop a model of the object.

It is generally difficult to construct accurate mechanics-based models of manipulation tasks. Modeling of physical constraints such as friction which give rise to non-conservative forces is generally intractable. However, certain simple dynamical models are useful in that they:

- provide a useful vehicle for abstraction
- can capture gross aspects of certain dynamical phenomena
- are a sound basis for internal qualitative representation

A simple lumped parameter model treats the mobile robot as a mass, spring, damper system. Equations which describe the dynamics and control can be written as:

$$\boldsymbol{M}_R(\ddot{\boldsymbol{x}}_R - \ddot{\boldsymbol{x}}_C) + \boldsymbol{B}_R(\dot{\boldsymbol{x}}_R - \dot{\boldsymbol{x}}_C) + \boldsymbol{K}_R(\boldsymbol{x}_R - \boldsymbol{x}_C) = \boldsymbol{F}_R \tag{7}$$

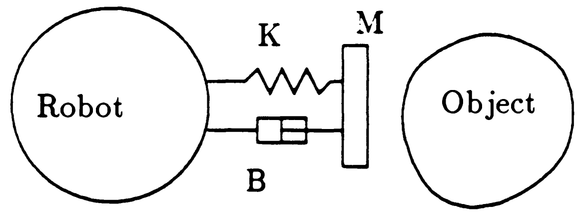

Figure 6: Construction of Robot Object Interfacial Impedence

where $\boldsymbol{M}_R$, $\boldsymbol{B}_R$, $\boldsymbol{K}_R$ are generalized mass, damping and stiffness matrices respectively. $\boldsymbol{x}_R$ is a vector of generalized coordinates which describe the robot's configuration. $\ddot{\boldsymbol{x}}$ and $\dot{\boldsymbol{x}}$ are generalized acceleration and velocity. Subscript - C refers to a commanded quantity and $\boldsymbol{F}_R$ is a generalized force/torque vector. We emphasize that these equations represent a high level control abstraction. Stiffness and Mass properties in the above may be both real or artificially induced through control software. Parameters may be set by the robot to achieve any combination of generalized behavior. For example, the robot can be made to exhibit artificial spring-like behavior by zeroing both the inertial and damping matrices in Eq (7). For stationary arm manipulation, equations of this nature have become common place [30] in implementing compliant motion strategies. Damping matrix impedance values are chosen to match the normal and tangential (frictional) stiffness of the contacting surface, and the traversal rate of the manipulator.

While artificially induced compliance provides a certain measure of generality, there is a strong argument for augmenting this approach with compliance induced through the introduction of real physical elements. Whitney [28] shows how springs of appropriate stiffness can be used to allow high speed peg insertion with his remote center of compliance device. It is conceivable that a planar manipulator, provided with adequate knowledge of the impedance characteristics of an object, could construct a suitable interface (Fig (6)) from an onboard array of real physical elements.

An object can be thought of as an adversarial dynamical system which we seek to control through the manipulator's control system. In developing a dynamical model of an object we need to account for certain phenomena which may include:

- Frictional interactions between the body and the plane.

- Frictional interactions between the body and the manipulator.

- Mass properties of the object
- Radius of gyration about a particular point
- Geometric aspects such as surface curvature
- Material properties such as stiffness

The complexity of the model reflects the level of detail devoted to each of the individual phenomena. In fact, minimal detail is deemed preferable in capturing a first order representation of the system. For example, if we require a representation of the object's stiffness, a simple spring model, as opposed to a more complete continuum mechanics based model, is probably sufficient. The functional form of our model must be chosen so that weight is assigned to each phenomenon according to the dominance of its role during the manipulation task. We suggest a form, similar to that proposed for the manipulator:

$$\boldsymbol{M}_O\ddot{\boldsymbol{x}}_O + \boldsymbol{B}_O\dot{\boldsymbol{x}}_O + \boldsymbol{K}_O\boldsymbol{x}_O = \boldsymbol{F}_O \tag{8}$$

Terms in the above are similar in meaning to those in Eq (7). Subscript - O refers to object quantities and $\boldsymbol{F}_O$ is a generalized applied force vector. Parameters in Eqs (8) will generally be unknown.

Suppose the robot can perform experiments on the object to identify the unknown system parameters in the above model. An appropriate library of experiments could be provided. Consider a one dimensional example (Fig (7)) where, the robot and object are constrained to lie on a line. The robot makes contact with the object through a nonlinear exponentially stiffening spring with characteristic

$$f = Ae^{x/c} \tag{9}$$

An exponential spring characteristic is desirable since for a constant approach velocity, the applied forces will develop gradually. Spring compression can be measured by the robot. By commanding a robot velocity, an increasing interfacial force will be transmitted to the object as the spring compresses. Eventually, a force large enough to cause motion of the object will develop after which no further spring compression will occur. The measured spring compression can be directly correlated with the object's frictional resistance to motion thus providing one model parameter. Further experiments at different commanded velocities could investigate the interelationship between velocity and steady state resistance force. Once a suitable set of parameters are selected, specific tests could be designed to collect the desired information.

Other notions from control systems theory prove useful. The relative configuration of an object constrained to motion in the plane can be described by three

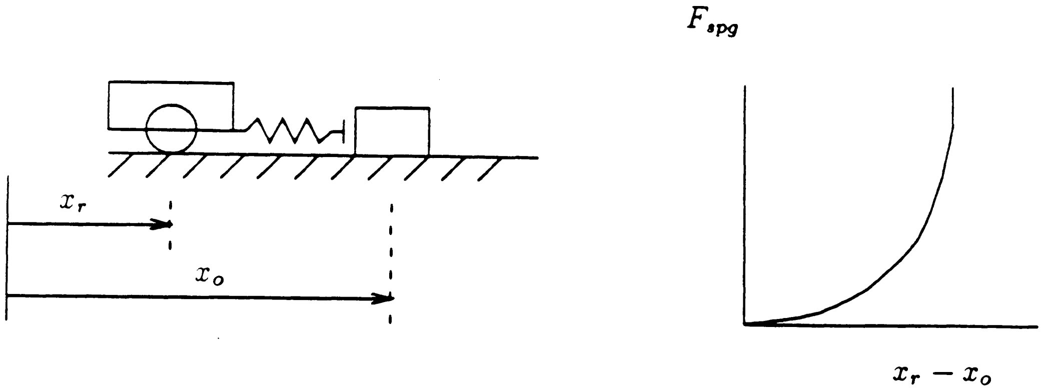

Figure 7: Contact with exponential spring

generalized coordinates. Two coordinates (x, y) describe the position of any point on the body and an angle ϕ describing the orientation of a reference frame attached to the object with respect to a robot fixed reference frame. These three coordinates together with their time derivatives $(\dot{x}, \dot{y}, \dot{\phi})$ are a total of six quantities which can completely describe the dynamical state of the object. If we view the object-robot as a plant-feedback controller (Fig (8)), then the controller must be capable of measuring the state of the plant. In general it is difficult to measure state quantities directly. However, other quantities such as contact force and rate of change of contact force can be measured. The control problem, thus becomes one of *observability.* Can the state quantities be derived from the measured quantities ? This is a difficult issue and requires the design of clever sensors which allow unambiguous interpretation. The complete determination of object state information may be extremely difficult but certain gross tendencies may be observable. For example, sensing may be able to determine that the object is rotating clockwise or counterclockwise and that left slip or right slip is occurring at a particular contact point. This information, coupled with our approximate object model, can thus allow controlled motion of the object.

We emphasize that our knowledge is currently inadequate to allow implementation of the most general ideas of matching control to mechanics. However, we have outlined some of the relevant issues which we summarize:

- Matching the mechanical impedance of the manipulator to an object
- Developing appropriate functional forms for lumped parameter models
- Automatic experimentation to infer parameter values
- Observation of relevant state quantities

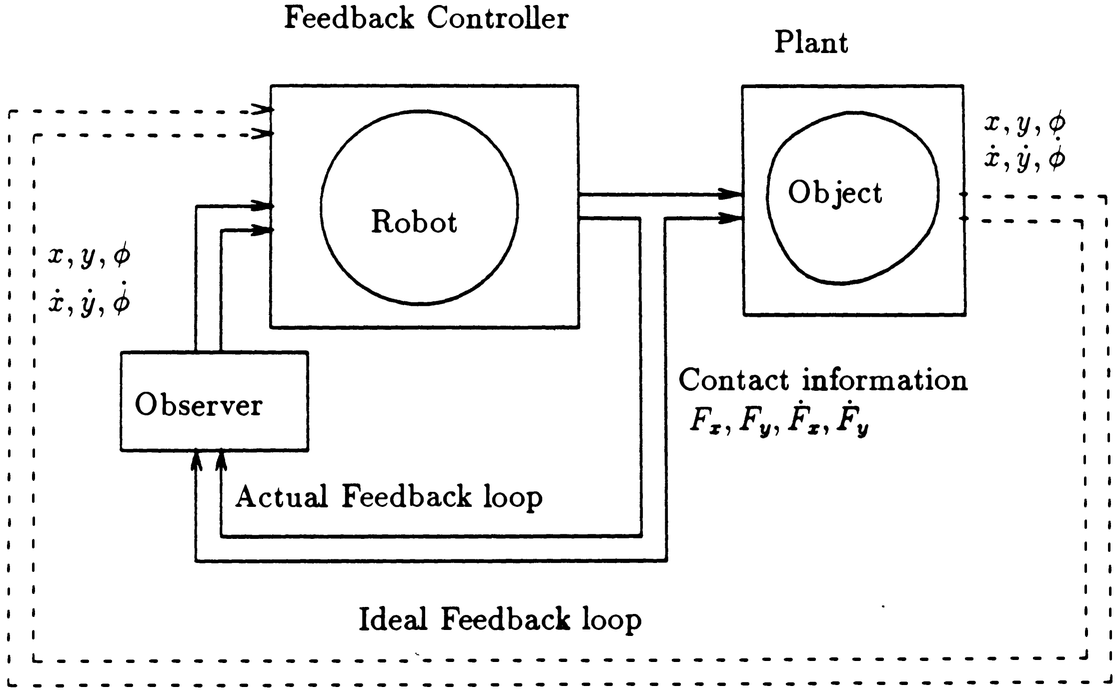

Figure 8: Control systems viewpoint

We have attempted to provide appropriate examples where possible to substantiate these ideas. Further, investigation along these lines may ultimately prove fruitful in attaining our goal of a robust planar manipulation capability.

IV An Experimental Apparatus

I will construct an experimental mobile robot on which to implement and test my ideas on planar manipulation. The mobile robot (Fig (9)), currently under construction, is a two tracked vehicle approximately 50 cm in diameter. The tracked design was selected over a wheeled design on the basis of robustness. Wheeled mobile robots have a tendency to jam on small objects such as computer cables or in elevator doorways. Each track is independently driven by a 24 Volt permanent magnet DC motor. The track drive pulleys are coupled to their respective motor output shafts through a 3:1 reduction belt drive system. Optical encoders mounted on the motor drive shafts allow position and velocity feedback. Maximum speed for the vehicle is about 1 m/sec. The vehicle is steered by differentially controlling motor speeds. Power is provided by two 12V batteries. A ring of twelve Polaroid ultrasonic transducers mounted on the robot periphery allows time of flight ranging measurements. Microprocessor based control is achieved using an Intel 80C196 real time embedded controller. Programs are developed in C on an IBM PC and can be burned on to system EPROM or down-loaded into system RAM via an RS232 serial port.

Currently I am endeavoring to define desirable attributes for planar effectors. An initial design idea involves using two passive prongs similar to those shown in Fig (10). The passive design is motivated by the inherent on board power limitations of the mobile robot. Each effector will be equipped with force sensing to allow measurement of longitudinal and lateral forces developed at its endpoint due to contact with an object. Force sensing may be implemented using strain gauges or piezoelectric load cells. Precision and range requirements of the sensors will be determined by considering the mass and frictional properties of certain candidate objects. A set of interchangeable effector tips will be designed to allow experimentation with different contact geometries. I propose a roller design which will allow an approximation to frictionless contact and a fixed cylindrical design (perhaps, rubber coated) to study contact with friction. Effector sensing will be managed by a separate microprocessor. Microprocessor responsibilities will include low level data collection from the force sensors and higher level data interpretation which will allow inference of the gross motion characteristics of the manipulated object.

Another idea is to construct a cam like herder similar Fig (5). We feel this to be an interesting approach and have outlined some important design issues.

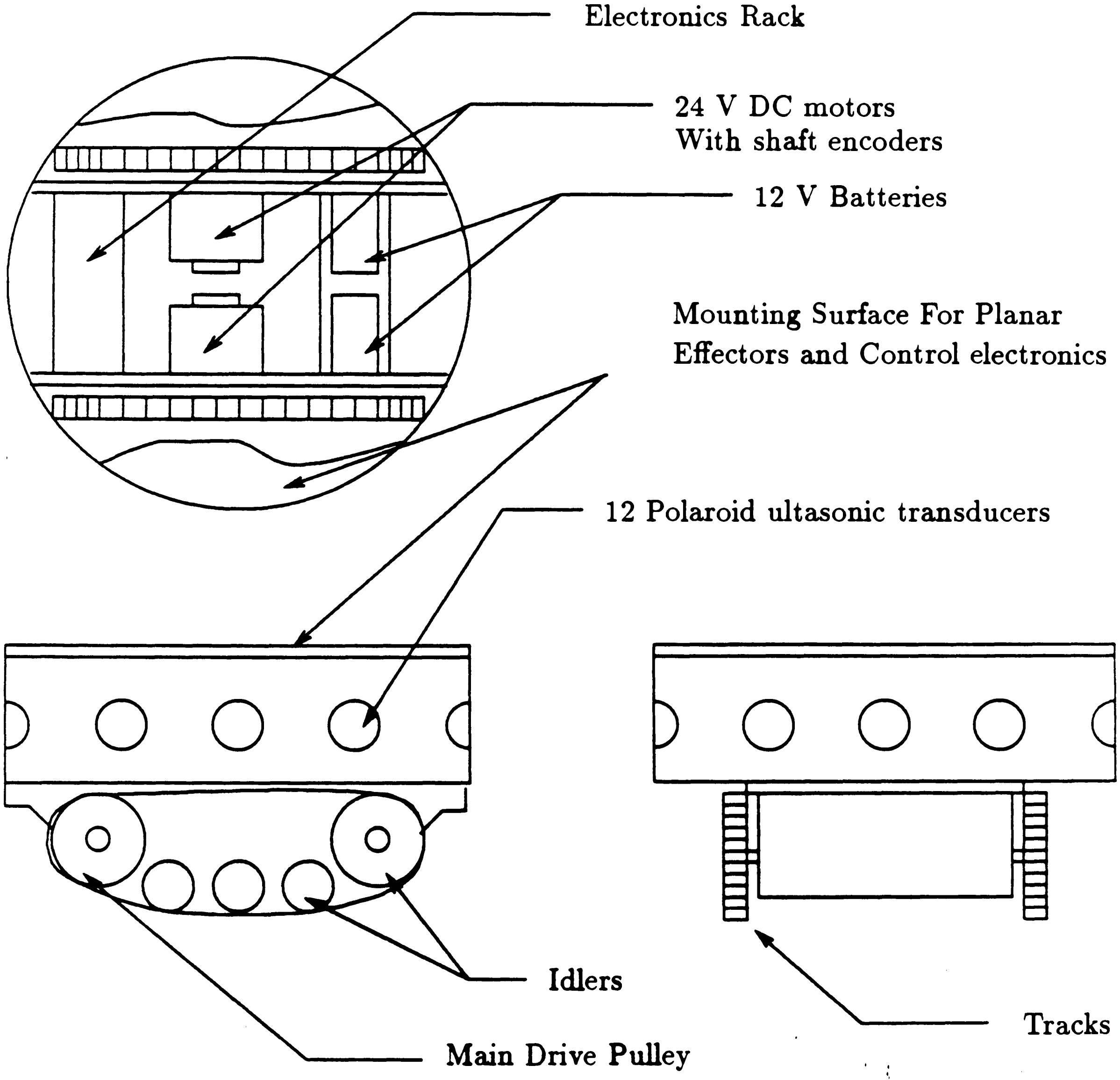

Figure 9: Schematic of Mobile Robot

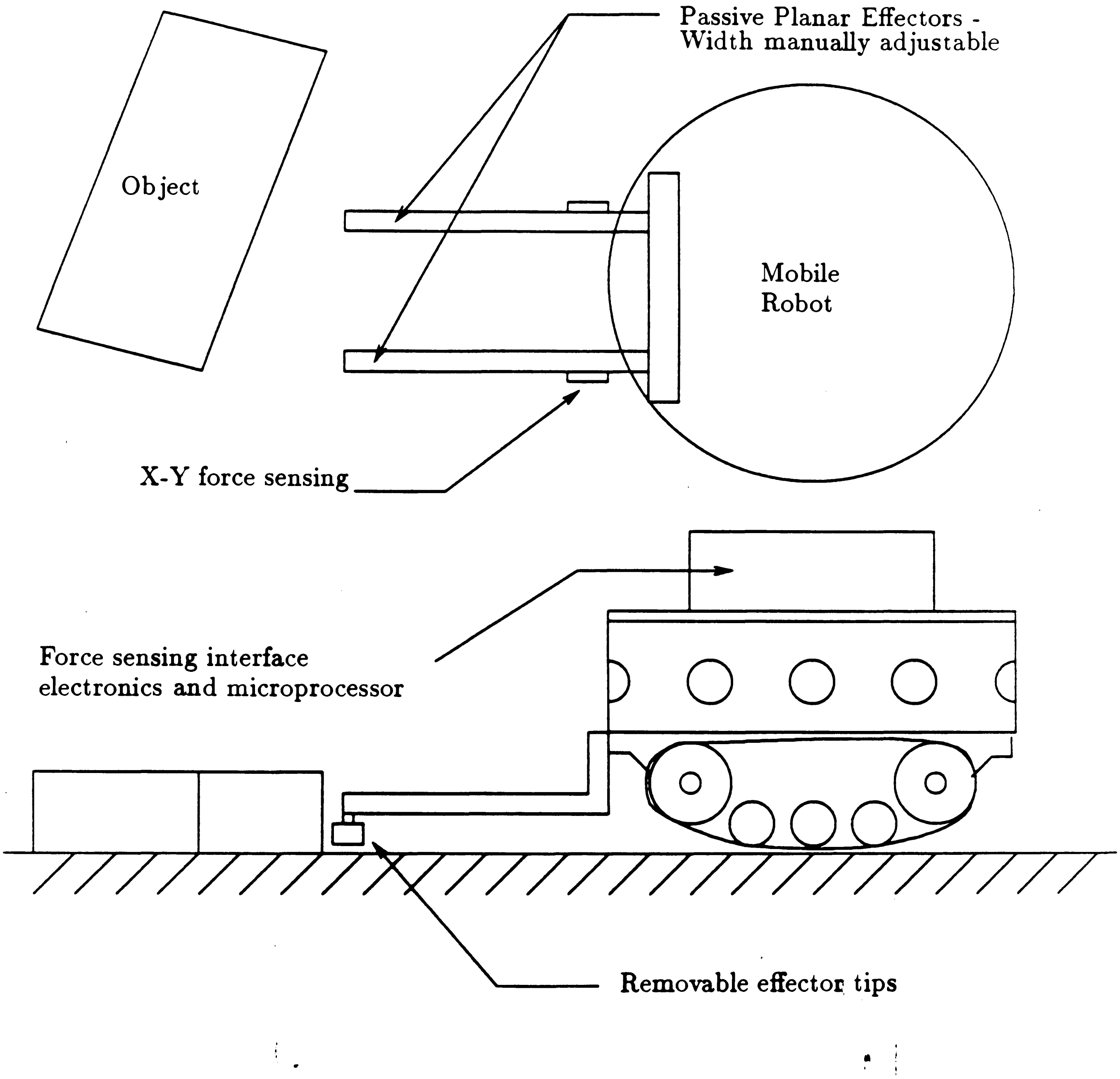

Figure 10: Planar effectors for a mobile robot

V Experiments to be performed

At this stage it is difficult to lay out a detailed experimental agenda. However, we have highlighted certain questions which will allow us to decide on the nature of appropriate experiments:

- What is the exact role played by manipulator interfacial impedance ?
- How can sensing be used to determine an objects motion ?
- What aspects of geometry are important in facilitating adaptive motions ?
- What are appropriate strategies ?

The role of manipulator interfacial impedance could be investigated by designing a series of simple experiments where robot and object motion is constrained to a straight line. Objects could be blocks of varying mass, stiffness and frictional properties. Blocks are desirable since their geometry facilitates pure translation by manipulator contact normal to a block face. The interrelationship between manipulator contact velocity, interfacial impedance characteristics, and the resultant observed motions could be systematically investigated.

In addressing the sensing question, we propose selecting a plausible array which may be composed of force, proximity and optical sensors. The role of individual sensors can be investigated by attempting to effect the manipulation of various objects. As a preliminary experiment, I propose to attempt manipulation of the planar disc described earlier, initially relying completely on force sensing. Discs of arbitrary radii and mass could be investigated. The hope is that by observation of the success or failure of disc strategies we can recognize how the force sensors' role can be complimented through use of additional sensors. Even at this level of simplicity many questions remain unanswered. In postulating strategies, we unavoidably tend to oversimplify. We idealize the performance of our sensors and tend to overlook factors such as noise and calibration errors which occur in practical implementation. We must investigate the nature of these uncertainties and endeavor to find appropriate solutions.

Additional experiments would involve relaxing the ideal characteristics of the disc and attempting to develop stable mating for discs with arbitrarily located Centers of Friction. An experimental disc similar to that of Fig (11) could be constructed. Variation in the location of the COF could be achieved by clamping different masses to the disc. Experiments could be performed for different initial relative orientations of the disc. Could the ideal disc strategy be adapted to allow the manipulator to achieve its ultimate goal ? Perhaps as an alternative to the randomized cartesian grid search, a radial search pattern would prove more effective.

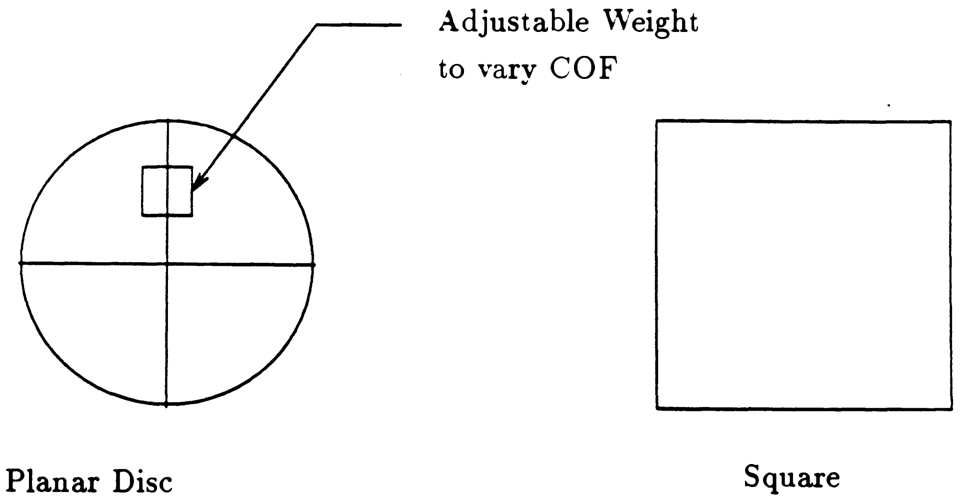

Figure 11: Experimental manipulatable objects

Ultimately we would propose experiments on geometrically more complex objects. The square of Fig (11) could be investigated. Experimentation of this nature would provide clues as to additional sensing requirements, and lead to different control algorithms.

It should be emphasized that we are seeking a general planar manipulation capability. It might appear that our proposed experiments are artificial, considering the inherent geometric symmetry and mass uniformity of the objects. We hope that by understanding strategies which exploit such features, more general strategies can be developed which will allow the robot to manipulate an arbitrary object. This is our ultimate goal.

VI Conclusions

We have presented a brief discussion of current work in mobile robotics and have summarized some approaches to behavior and navigation. We have identified a need for study on application of mobile robots to manipulation tasks. Our long term goal is to design a general purpose planar manipulator capable of herding many different objects in the plane. We feel that if such a capability can be developed, the potential for practical applications in areas such as materials handling, and manipulation in hazardous environments will be great.

Following the general trend in robotics over the last thirty years, our approach is experimental but is complimented by appropriate analytical tools and conceptual models where possible. This approach is necessary because of the fundamental lack of a unifying theory of manipulation. Newtonian mechanics provides a limited perspective in understanding the success or failure of manipulation strategies. However, our inability to model the mechanics of particular strategies does not preclude them from application. Often, failure of a manipulation experiment yields far greater insight than achieving success. One need only consider early position controlled peg insertion experiments to see the evolution in thought. Failure of position control led to an explicit recognition of uncertainty, the development of force control and eventually to compliant motion strategies as a means of reducing uncertainty. Following experimental observation, there has been an evolution in the theory associated with manipulation.

The class of tasks we propose is fundamentally interesting. However, we lack knowledge of appropriate task achieving strategies and of the hardware requirements for a planar manipulator. The scope of this research lies in addressing this fundamental lack of knowledge.

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