High-Level Planning for Dextrous Manipulation

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Abstract

The development of mechanical end effectors capable of dextrous manipulation is a rapidly growing and quite successful field of research. It has in some sense put the focus on control issues, in particular, how to control these remarkably anthropomorphic manipulators to perform the deft movement that we take for granted in the human hand. The objective of this paper is the creation of a framework within which constraints involving the manipulator, the object, and the hand/object interaction can be exploited to direct a goal oriented manipulation. The analysis here is targeted for the Utah/MIT dextrous manipulator, but will support any general purpose dextrous manipulation system[1].

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1. Introduction: High-Level Strategic Control

It is much easier to compute interaction forces and velocities given an interaction configuration which is optimally suited to the task. This intuitive idea serves to motivate the development of a planner which identifies an optimal hand/object configuration given a specification of the task. There has been a great deal of work focused on expressing the selection of grasp configurations as the lowest energy alternative in an elastic potential field [1, 3], and the dynamic control of structures so represented [2]. A characterisitic of such approaches is that while they succeed in producing configurations which are in equilibrium, they do not address the robustness of the equilibrium or the special requirements of the task in a natural way. The planner described here employs constraints derived from the object, the manipulator, and the task to select optimal positions on the object for interactions to take place. Given the location of these effective interaction sites, it is possible to use the concept of the elastic field to select, for example, the magnitude of the interaction forces.

The central issues of the proposed manipulation controller are:

1. the selection of grasp sites and manipulation strategies that are capable of regulating a robust stability of the object,
2. the selection of hand configurations that allow transmission of the required forces and velocities,
3. the direction of hand/object interaction strategies that effectively seek a goal state.

It is clear that when a manipulator and an object interact, the resulting set of possible system configurations is innumerable. The goal of this paper is to determine the character of the hand/object/task system which may be exploited to direct the manipulation strategy. The interaction of the hand and the object is viewed conceptually in terms of discrete "interaction-sites." These sites are generated by projecting the configuration of the hand on the object. The set of n interaction-sites are then used to quantize the hand/object system. This effectiveness index will then be used to direct the migration of the interaction-sites.

The traversal of the "manipulation space" enroute to an appropriate grasp will be approached by projecting a specific hand geometry on a CAD model of the object surface. The process is illustrated in Figure 1-1.

This projection yields a set of $n \leq 4$ surface positions which represents hypothetical fingertip contact positions and a starting position for the hand coordinate frame. The evolution of a manipulation strategy involves the migration of these "interaction-sites" over the object geometry. The surface traversal is directed by a gradient space in surface coordinates which effectively hill climbs manipulation space. The gradient of this scalar space will drive the traversal of the surface geometry to states that effectively address object stability and the task. The text that follows discusses the components of this manipulation space and the representations and computations which support it.

2. A Framework for Planning

The constraints proposed to direct a trajectory through "manipulation-space" are properties of the manipulator and the object seen from the perspective of the current goal-state. The expression of these constraints must be computationally efficient (off-line is preferable). The constraints used here exist across several conceptual levels in the manipulation process: the placement of individual fingers within

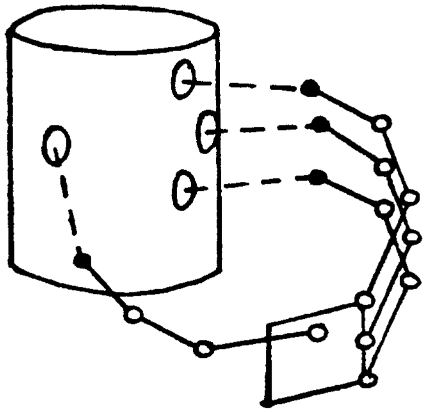


Figure 1-1: The Hand/Object Interaction Model

their workspace, the relaxation of the hand frame following a planned excursion of the interaction-sites, the ability of the set of planned interaction-sites to fully constrain an object and their ability to deliver the task defined velocities or forces effectively.

2.1. Definition of a Task

The task specification of stability is the sum of two terms as shown below.

$$\overline{T} = [\Omega_R\ \Omega_R \ldots \Omega_R] + [\Omega_{T1}\ \Omega_{T2}\ \ldots \Omega_{T6}]$$

where:

Ω_R = the task specified robustness threshold, and

Ω_{Ti} = terms used to anticipate the task force transmissions, inertial loads, or external loads.

When the task is stated as above, it may be used as the goal of a process which seeks to produce the resultant task vector. The magnitude goals have both positive and negative senses as does a contact's ability to transmit forces. A system state can be evaluated by computing a value for the error of the state with respect to the goal specified by the task.

2.2. Expressing the Object's Perogative

The object we wish to manipulate might influence the planner in a variety of ways. Most notably are those properties of the surface geometry which contribute to stable grasps. But it may be useful to have more specific information concerning object inertias, the location of the center of mass and the predominant symmetries, for instance. In this section, we will examine how a surface element implies a sub-space through which forces and velocities may be transmitted to the object and the property of a set of surface elements that addresses stability.

The discussion here asssumes that some continuous surface representation is available, such as a CAD model of the object. This allows the planner access to positions and normals at any point on the surface of an object. We add to this representation a set of object frame wrenches (generalized forces) and their derivatives in surface coordinates for points on the surface of the object. This set of wrenches describes forces and moments that may be transmitted to the object by a point contact with friction and reveals how these forces and moments change as the interaction migrates over the surface of the object. The resulting augmented object model is depicted in Figure 2-1.

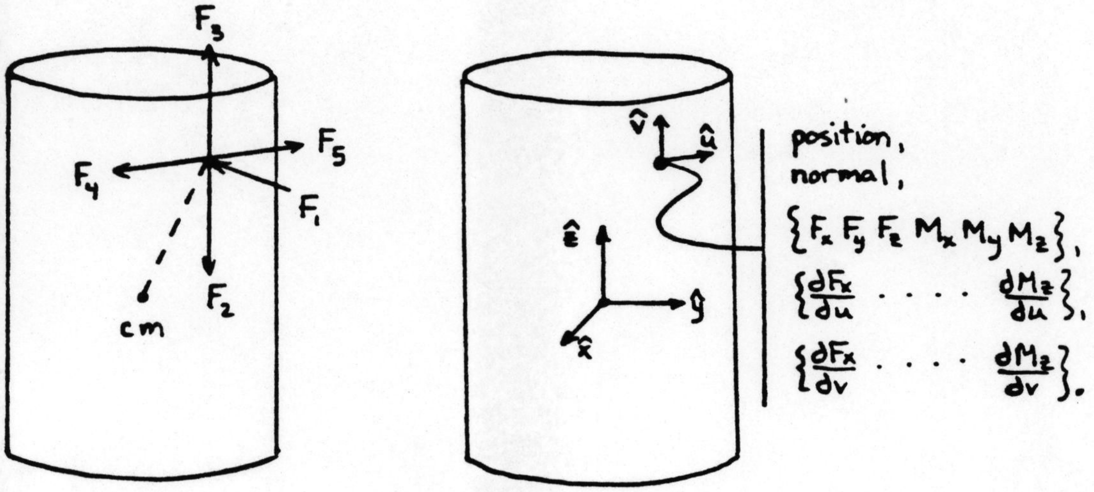


Figure 2-1: Model Description of a Point Contact with Friction

The proximity of the contact site to the object's center of mass implies a family of five wrenches which may be transmitted to the object via this surface element. Unions over sets of these contact interactions span a sub-space of the six degrees of freedom of the object.

Stability of the object requires the dimensionality of this constrained space to be six. This condition ensures that infinitesimal perturbations of the object may be controlably constrained in six degrees of freedom, however, a robust grasp should meet magnitude thresholds in each DOF. This can be anticipated by associating a unit normal force and scaled (by the coefficient of friction) tangential forces with each contact site. The planner may then produce strategies which eliminate task defined robustness deficiencies.

Control of the mechanical manipulation device is extracted from the incremental changes in the hand/object state that are directed by the planner. The procedure requires the static representation of the wrench sets mentioned above and their derivatives with respect to the local surface parameterization.

Each point contact with friction may transmit the forces depicted in Figure 2-1; it is clear that each of these forces produces a unique object frame generalized force. If we represent the six dimensional sub-space representing the forces and moments that this contact can transmit to the object by a set of n orthogonal 6-D basis vectors, then we may express the error of this system relative to the task as follows.

$$\vec{E} = \vec{T} - \Sigma_{i=1}^{n} [\text{MAG } \bar{b}_i]$$

where the coefficient MAG_i is given by:

$$\begin{array}{ll} \textit{if:} & (\vec{T} \cdot \bar{b}_i > 0) \\ & \text{MAG}_i = \min[(\vec{T} \cdot \bar{b}_i) , M_i^{+}] \\ \textit{else:} & \\ & \text{MAG}_i = \max[(\vec{T} \cdot \bar{b}_i) , M_i^{-}] \end{array}$$

and,

$\vec{E}$ = Contact system error relative to the task,

$\vec{T}$ = task vector,

$\bar{b}_i$ = an orthonormal basis vector for the contact wrench space, and

$M_i^{+/-}$ = the positive or negative sense magnitude produced by the contact system along the ith basis vector.

The procedure above removes the components of the task which project onto the contact wrench space and are within the magnitude limitations of the contact system. The residual 6-D error vector is therefore, the deficiency of the current contact system relative to the task.

In order to address this error vector, the planner interrogates the object model to determine the value of the derivative wrench systems with respect to orthogonal surface migrations. The directions used to parameterize the object might be, for example, the directions of principal curvature of the local surface. The result is a set of two (not in general orthogonal) wrench sub-spaces which represent the manner in which the composite wrench space may be changed by directing migrations over the surface for a particular contact site. Therefore, the contact position which most effectively addresses the system deficiencies can be identified and a trajectory of this site toward the stabiltity robustness goal can be computed.

The perogative of the object is expressed as the migration of the interaction sites toward positions on the object surface where stability and task goals can be realized. The requirements of the manipulator have not yet been accounted for; this will be the object of the next section.

2.3. Expressing the Manipulator's Perogative

The quantification of the manipulator in terms of its ability to control the application of forces and velocities to an object have been described in terms of the so-called manipulability ellipsoid [4, 5]. This volume of solution space can be generated for any system of linear equations of the form,

$$A \vec{x} = \vec{b},$$

where:

A = NXM transform,
$\vec{x}$ = MX1 output space vector, and
$\vec{b}$ = NX1 input space vector.

The input and output space nomenclature is used here to delineate the (input) joint angle space of the manipulator and the (output) Cartesian forces or velocities. For the case of the 4 DOF finger, the input space is the 4 DOF joint space, (N = 4), and the output space is Cartesian 3 DOF space, (M = 3). The manipulator kinematics then produce a relationship of the form above.

$$\vec{V} = J\,\vec{\omega},$$

where:

J = the manipulator jacobian ($\in R^{3X4}$),
$\vec{\omega}$ = joint angle rates ($\in R^4$), and
$\vec{V}$ = Cartesian fingertip velocity ($\in R^3$).

The "manipulability ellipsoid [4]" is defined by examining the singular value decomposition of the Jacobian.

$$\text{If} \qquad J \in R^{MXN},$$

$$\text{Then} \qquad \exists\; U \in R^{MXM} \text{ and } V \in R^{NXN},$$

$$\text{Such that,} \qquad J = U\,\Sigma\,V^T$$

$$\Sigma = \left[\begin{array}{ccccc|c} \sigma_1 & & & & & \\ & \sigma_2 & & & & \\ & & \sigma_3 & & & \\ & & & \cdot & & \mathbf{0} \\ & & & & \cdot & \\ & & & & \sigma_m & \end{array}\right] \in R^{MXN}, \text{ with}$$

$$\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_m \geq 0.$$

These σ_i represent the m singular values of J. If we constrain the joint space angular rates,

$$|\,\vec{\omega}\,| = [\omega_1^2 + \omega_2^2 + \cdots + \omega_n^2]^{1/2} \leq 1$$

then we find that the manipulability ellipse delimits the realizable Cartesian space velocities (i.e., $\vec{\omega} \in R^m$). The sub-space ellipsoid is defined by the principal axes $\{\sigma_1 u_1, \sigma_2 u_2, \ldots, \sigma_m u_m\}$ where the $u_i \in R^m$ are the m column vectors of the U matrix above.

The discussion of manipulability ellipsoids provides a powerful tool for evaluating the relative usefulness of a hand/object configuration with respect to a specific task. Consider a simplified 2 DOF system for which the singular valued decomposition of its Jacobian represents a 2-D ellipse. For the simple case at hand, we may characterize the ellipse by defining its semi-major and semi-minor axes. Recall that these properties (both directions and magnitudes) are the result of the singular valued decomposition of the manipulator Jacobian. A useful manipulation strategy will select hand/object configurations which align the principal axis (axes) of the manipulability ellipsoid for each finger with the task defined forces and velocities. The projection of a characteristic task direction on the set of pricipal axes should, therefore, be maximized in the force and velocity domains. Situations for which this condition is met will be capable of more effectively seeking the goal state of the system.

2.4. Surface Migrations

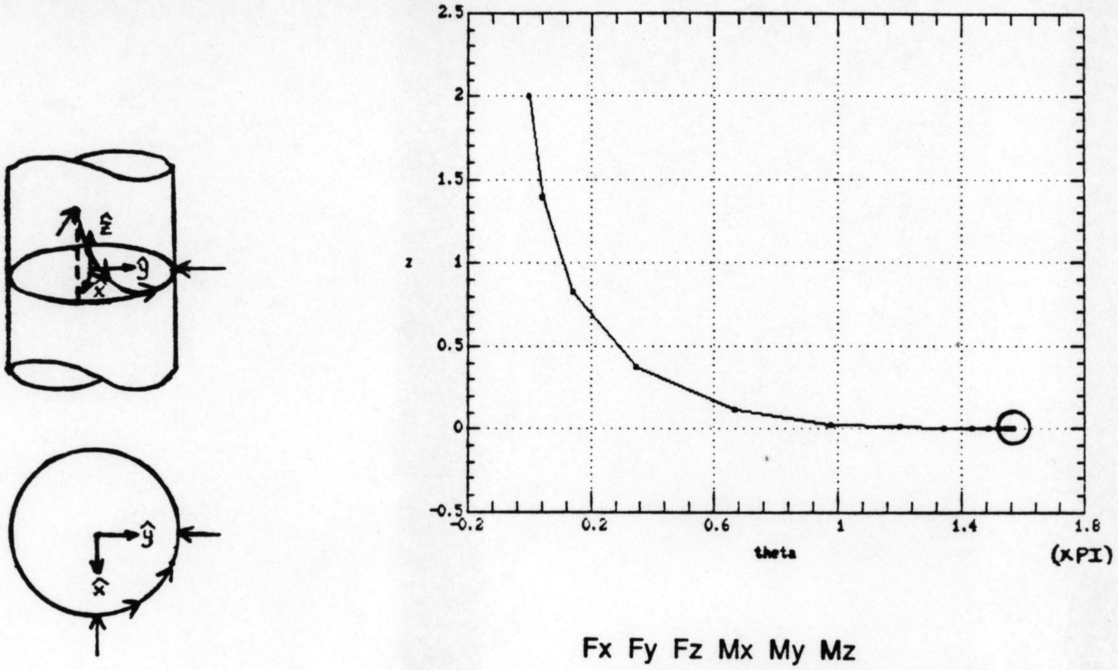
The procedure for directing the migration of a set of interaction sites from their initial position on the surface of the object to an optimal position is in many ways easier than typical feedback control systems. The interaction site is massless, and therefore the stability of the system is quite robust, even when simple proportional feedback schemes are used. The initial set of interaction sites must be used to produce the hand configuration which maximizes the registration of the principal axes of the 3-D manipulability ellipsoids at each site and the 3-D force ellipsoid that can be transmitted through that site. Likewise for the velocity ellipsoids of each finger and the velocity components of the task. If the manipulability of the initial configuration is not sufficient, the manipulator may exercise its perogative and direct the movement of the interaction sites to improve the state of the system. But before the migration can take place, the perogative of the object in the grasp must be exercised. If the wrench space spanned by the set of interaction sites is deficient, or the wrench space magnitudes are insufficient for the task, a trajectory across the object's surface which eliminates these deficiencies is likewise directed. The linear superposition of the trajectories produced by actively eliminating the 3-D error in manipulability and the 6-D error in the wrench space results in a trajectory of the massless interaction site which continues until a set is found which satisfies all components of the task or until the state of the system can no longer be improved. The next section presents some of the results of the current incarnation of the system.

3. Examples: 1 and 2 Interaction Sites and the Object Perogative

A system has been implemented which responds to the task by considering only the surface properties of the object. The planner has not yet been influenced by the character of the manipulator in the demonstrations presented below. The procedure is illustrated in Figure 3-1 for a system consisting of an infinite cylinder and a single contact point. This worst case scenario attempts to eliminate stability deficiencies by moving the contact over the surface of the cylinder. The task submitted to the system consists of two parts; first, the uniformly robust constraint of the object, and second, the application of task specific forces. Robust stability requires that the interaction is capable of transmitting generalized forces with magnitudes exceeding a robustness threshold in six object frame degrees of freedom. The task specified system goal is the application of a preferred force in the negative y direction. This is expressed by raising slightly, the threshold value in the negative y direction. Released from a non-optimal position, the system quickly approaches the intuitively obvious optimal site as shown in Figure 3-1.

A second demonstration is presented in Figure 3-2 in which a migrating interaction site is directed to improve the net wrench space defined by it and a fixed interaction site. Here, the task consists of a uniform stability robustness.

A shortcoming of the approach as stated is its dependence on the local properties of the surface to



Fx Fy Fz Mx My Mz
$\vec{T}$ask = { { 0.5 1.0 0.5 0.5 0.5 0.5 } negative sense
{ 0.5 0.5 0.5 0.5 0.5 0.5 } } positive sense

Figure 3-1: The Directed Migration of a Single Interaction Site

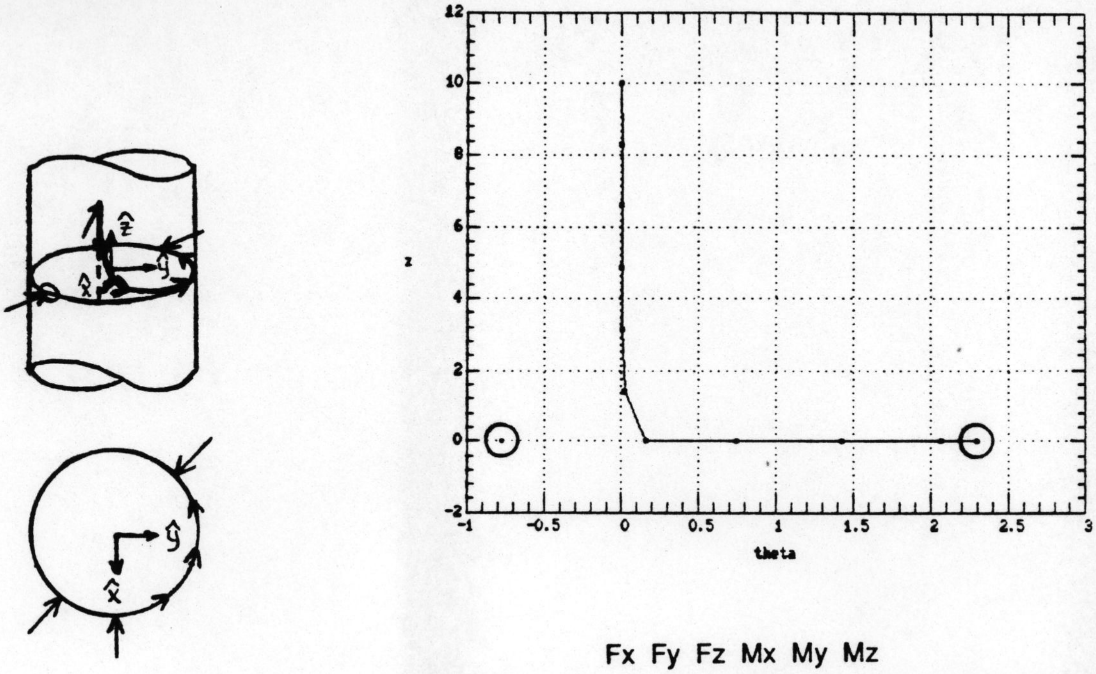
direct the migration. A system of this sort may wander aimlessly over an object's surface, never arriving at a suitable solution, when surface features capable of supporting a solution are available. The solution to this problem requires that features of this sort be given a large realm of influence when constructing the model containing the surface indexed derivative wrench spaces. In this manner, the planner can be drawn toward surface features which represent unique solutions to otherwise intractable problems.

4. Conclusion: Future Directions

A complete version of the system described here is currently being implemented. This requires that the manipulator be considered in the planning as was described in an earlier section. Following the completion of this phase, a means of computing the internal forces of the interaction must be installed so that stable grasps suited to particular tasks can be realized. The system must also be capable of commanding object velocities and forces in order to move the object closer to the task specified goal state. This may require a cycle of object velocities and robustness migrations until the goal state is reached.

The migration of a manipulation strategy through M_space can be described conceptually by rules that trigger on the conditioning of the hand/object system. A well conditioned system is stable (redundantly), is manipulable, and projects well onto the task. System velocities, however, cause the conditioning of the system to degrade as it seeks the goal. If the state of the system approaches the envelope specified in the task, then the planner must improve the state. The prioritized rules are enumerated below.

1. *If conditioning < task constraints*: The system must hill climb in the stability/manipulability sub-space until a state is found that meets the task criteria. If a contact system has not



Fx Fy Fz Mx My Mz

$\vec{T}$ask = { { 0.5 0.5 0.5 0.5 0.5 0.5 } negative sense

{ 0.5 0.5 0.5 0.5 0.5 0.5 } } positive sense

Figure 3-2: The Directed Migration of a Two Interaction Site Contact System

been established when this rule fires, the set of interaction-sites must be directed to migrate over the surface model to improve the system state. If, however, a contact system has been established, stability of the object must be maintained using a subset of the contact system while individual redundant contact elements are moved to improve the system state. This rule always results in a hand/object configuration which is well-conditioned and ready to accept object force or velocity commands.

2. *Else*: The system is prepared to undergo a task specified force or velocity command. If an object velocity results, then the system will eventually violate the task stability and manipulability envelope and return to the rule above.

If we assume that the manipulation process can be expressed in a vector space (M_space) describing the hand/object system whose axes are stability ($\overline{s}$), manipulability ($\overline{m}$) and proximity to the goal state ($\overline{g}$), and further, assume that these features of the system state are independent (orthogonal), then the task may be specified as a vector in M_space.

$$\vec{T} = A_t\overline{s} + B_t\overline{m} + C_t\overline{g}$$

The application of the above rules produces a path through M_space illustrated in Figure 4-1. The process is viewed here as the sequence of rule 1 migrations through the ($\overline{s}$,$\overline{m}$) sub-space to a well conditioned state and rule 2 migrations through ($\overline{s}$,$\overline{m}$,$\overline{g}$) space toward the goal. The final state reduces the error between the task specification and the system state to zero and optimizes locally for stability and manipulability. Rule 1 migrations may produce only local maxima, but as long as the result meets the criteria specified by the task, the solution is sufficient. If no solution is eventually produced, then the task

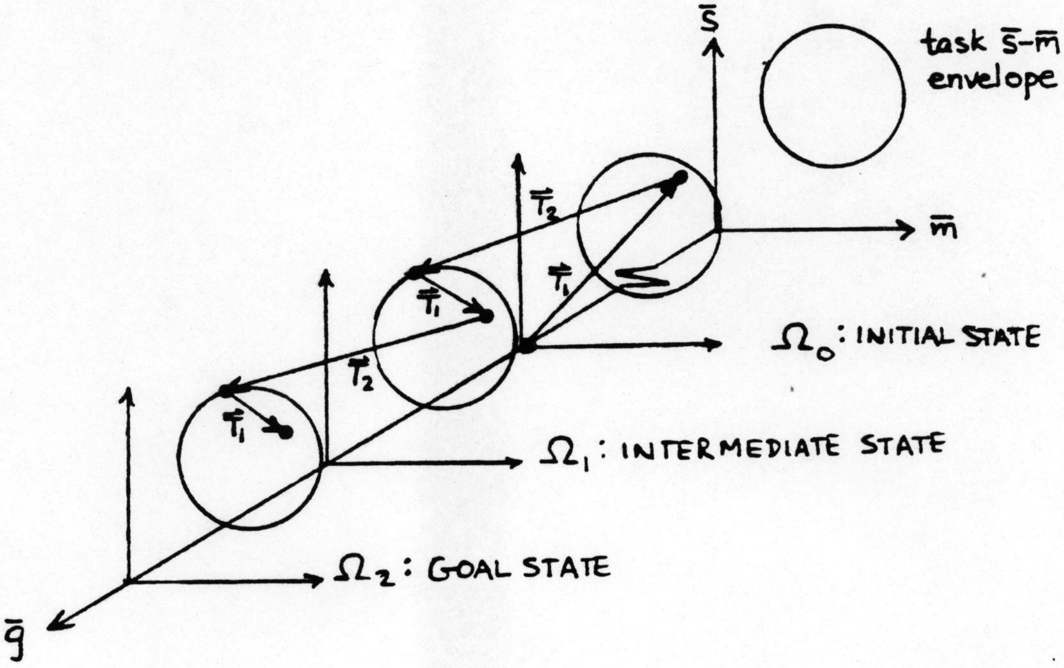


Figure 4-1: The Directed Migration of a Manipulation State Through M_space

specification of the goal is incompatible with the stability and manipulability requirements and the task must be relaxed if a solution is to be found.

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