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Manipulability-Based Spatial Isotropy: A Kinematic Reflex *

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Abstract

This paper reports results obtained from a reflexive robot controller designed to manage the posture of a 20 degree-of-freedom (DOF) hand/arm system performing grasping tasks. The goal is to provide a framework for sensor-based controllers that dynamically optimize the kinematic configuration of the robot to improve performance on the grasping task. We will present such a behavior and illustrate how it is used to suppress local errors in *a priori* models.

Introduction

A great deal of work has focused on developing cooperative and dextrous manipulation systems. This domain is composed of independently challenging issues: dimensionality, redundant degrees of freedom, uncertainty resolution in modeling, planning, and execution.

Dimensionality

The "find-path" problem for configuration spaces obstructed by polynomially described boundary (given perfect information) has already been completely solved by Schwartz and Shahir[14]. A nearly optimal solution has been suggested by Canny for this class of problems as well[3]. However, combinatoric algorithms for finding a path with algebraic constraints are exponential in the number of degrees of freedom (DOF) in the system[3]. Moreover, "complete" process models are expensive to build. Detailed plans for grasping which are beyond the limits of model certainty and reliability are of little value, consume scarce system resources, and may subsequently require significant replanning.

Complexity and dimensionality issues have led to behavior-based system architectures. In this paradigm, complex state spaces are decomposed into tractable subspaces which form a basis for all system behaviors [1, 2, 7, 12]. This *factorization* greatly enhances run-time performance. For example, the subsumption architecture[1, 2] and Raibert's hopping platforms[12] partition a complex state space into disjoint controllers that are activated by sensory events. It has been demonstrated that this approach can be used to generate controllers for rather complex processes.

The system we propose incorporates *behaviors* (controllers designed to optimize particular performance criteria) to regulate the state of the process. Elements of the suite of behavior are activated in a competitive scheme in which a task (conjunction of sub-goals), the local gradient of the performance indices, and the ability of the robot to address each gradient is considered. The objective of this work is to discover a means of modulating control such that incremental evidence and the current environmental context can continually adjust the solution strategy. Our goal is to alleviate some of the computational overhead involved in building and maintaining detailed models and to avoid replanning in situations when plans have been constructed for incorrect or incomplete models.

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Redundancy Resolution

Pseudoinverse-based techniques have been developed to exploit redundant degrees of freedom in a robot mechanism. This work establishes a prioritized set of performance criteria attempts to address low priority sub-goals of the task in the null space remaining after the solution of high priority sub-goals. Conditioning metrics for redundant manipulators have been used as a design tool for relating a manipulator to a task domain[13], as well as scalar objective fields for optimizing the inverse kinematic solution [4, 5, 8, 9, 10, 11, 15, 16].

In this literature, researchers have focused primarily on optimizing the posture of the robot during the execution of a Cartesian trajectory. The performance metrics reported include:singularity avoidance, manipulability, obstacle avoidance, postural bias, inverse kinematic accuracy and feasibility, and the compatibility of manipulator posture with task specified forces and velocities. Multiple, prioritized performance specifications can be addressed in a uniform manner. However, the relationship between the behavior produced in such a system and the behavior specified in the controller design is not clear. The behavior that emerges from the controller depends directly on the null space preserved after the indulgence of higher priority performance metrics. The performance of the system with respect to any of these criteria varies with the manipulator Jacobian.

Sensorimotor Behavior Design Specification

Reflexive, Reactive, and Deliberative Behavior

For the sake of discussion, we have adopted a nomenclature for distinguishing three forms of behavior in terms of the computational complexity and the source and scope of knowledge employed by the controller.

Reflexive behaviors are *hardwired* encapsulations of behavior. Biological organisms develop *light-weight* transformations computed on the basis of local stimulation, the local connectivity of the peripheral nervous system, and the musculoskeletal configuration. Prototypical examples include the human grasp reflex which appears for a short period in the first year of infant development, and the plantar reflex in human gait control. This form of behavior is event driven and characterized by very tight sensor-effector arcs. There is no persistence or interpretation of the sensory information.

Reactive behavior differs from reflexive behavior in its capacity to incorporate new information, perhaps extending or modifying the current context. In this sense, reactive behavior is based on more global information accumulated in persistent models rather than on local sensory information exclusively. These behaviors permit the continuous deformation of control surfaces and thus allows the data stream to modulate individual behaviors of the system and the composition of behavior.

Deliberative behavior requires relatively complete information about the world, and it uses this knowledge to predict the sequence of future states of the system. This prediction permits the system to compare the future consequences of all candidate actions and to optimize the system performance. A fundamental issue facing the designers of deliberative behavior is the non-stationary nature of the world, and that the process of observation itself is prone to error. This implies that, in general, all deliberative behavior must involve some degree of risk.

Perhaps the most compelling justification of reflexive and reactive behavior, is the property of *local, bounded error suppression* and its value to deliberative behavior. When the state of the world is not quite what it appears we may rely to some extent on reflexive and reactive behavior to suppress deviations between our models and reality. Reactive systems may be able to find solutions to simple problems in complex environments. Moreover, they may be capable of occasionally stumbling onto very good solutions. However, to increase the probability of a favorable outcome, these experiences must be fused over time and a deliberative agent must be devised to exploit this increasingly global information. In this sense, deliberative behavior can be used to position the reactive subsystems *upstream* of a particularly robust solution to a specific problem — relying on the local competence of these reactive systems to attain the goal with no further cognitive expense.

Managing Mechanical Redundancy

The Manipulability Index

The *manipulability ellipsoid* is used in this work to characterize a manipulator's ability to generate forces and velocities[16]. The Principal Kinematic Axes (PKAs) of each finger may be identified by examining the transformation from joint space to Cartesian space expressed by the Jacobian. The singular value decomposition is employed to represent the character of the transformation. For a complete and detailed description of the singular value decomposition see Golub *et al.* [6].

If we map the unit sphere in R^4

$$||\dot{\theta}|| = \dot{\theta}_1^2 + \dot{\theta}_2^2 + \dot{\theta}_3^2 + \dot{\theta}_4^2 \qquad (1)$$

into Cartesian R^3 space through the Jacobian, the result is the manipulability ellipsoid proposed by Yoshikawa[15]. The ellipsoid describes the Cartesian character of the *amplification* in the Jacobian transform from joint velocities to Cartesian velocities. If the singular value decomposition of the Jacobian is computed, the manipulability ellipsoid is described by the Principal Kinematic Axes (PKAs):

$$\{\sigma_1\vec{u_1}, \sigma_2\vec{u_2}, \sigma_3\vec{u_3}\} \qquad (2)$$

where the σ_i are the singular values and the $\vec{u_i}$ are the corresponding singular vectors.

Chiu[5] points out that the singular vectors for the force relationship $\vec{\tau} = J^T\vec{f}$ are the same as those describing the velocity domain, but that the singular values are reciprocal. This suggests that the direction for favorable velocity amplification is orthogonal to the direction for favorable force amplification. Moreover, since accuracy is inversely proportional to amplification, a reciprocal relationship also exists between accuracy and amplification in both the velocity and force domains.

The manipulability index of the finger is a scalar metric describing the conditioning of the kinematic transformation [16]. The index is proportional to the ellipsoidal volume spanned by the PKAs. This volume is approximated in practice by the product of the singular values. Since the volume of an ellipse increases as the ellipse becomes more spherical, there is a correlation between high manipulability indices and isotropic conditioning.

Manipulability-Based Spatial Isotropy

Figure 1 illustrates the manipulability index computed over the workspace of the Utah/MIT finger. This model is computed within the medial plane of the finger, ie. for $\theta_0 = 0$.

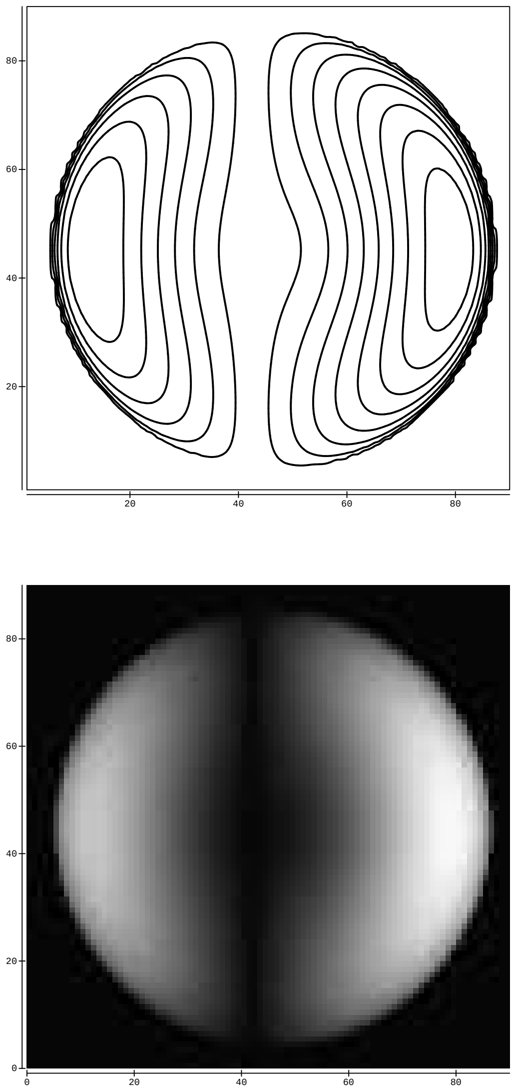

Figure 1: The Max-Manipulability Model for the Utah/MIT Finger/Thumb

The manipulability models are computed by enumerating all joint configurations for the finger and saving those configurations which produce the largest index at each Cartesian location in a regular sampling of the workspace. The sampling in this case was on a rectangular, 0.002 meter grid.

The controller that regulates the arm posture ascends the system manipulability metric. The system manipulability is a convex composition of independent, convex fields (note: only a portion of the manipulability field is convex for the Utah/MIT finger kinematics, even less for the thumb).

$$M_{sys} = \sum_i m_i$$

If the contact geometry is held fixed, then the posture of the hand/arm system can be optimized by gradient ascent with respect to posture modifications.

The gradient is computed as follows:

$$\frac{\partial M_{sys}}{\partial \vec{\theta}}^T = \left[\frac{\partial M_{sys}}{\partial \theta_0}, \ \frac{\partial M_{sys}}{\partial \theta_1}, \ \frac{\partial M_{sys}}{\partial \theta_2}, \ \frac{\partial M_{sys}}{\partial \theta_3} \right] \tag{3}$$

Notice that θ_i in the above expression refers to the arm's joint angles. The objective here is to maximize the system manipulability. in general purpose manipulation devices. This permits the system to react to unexpected interaction with the environment, and can be used to reflexively adjust the hand/arm posture in response to a task level command.

The gradient can be computed as follows:

$$\frac{dM_{sys}}{d\vec{\theta}} = \sum_i \underbrace{\frac{\partial M_{sys}}{\partial m_i} \frac{\partial m_i}{\partial \vec{x}_i}}_{convex\ scalar\ field} \ {}_{fi}R_w \ \underbrace{\frac{\partial \vec{X}_i}{\partial \theta}}_{arm\ Jacobian} \tag{4}$$

where:

M_{sys}	=	$\sum_i m_i \implies \frac{\partial M_{sys}}{\partial m_i} = 1.$
m_i	=	the scalar manipulability metric for finger i expressed in finger i coordinates
$\vec{x}_i$	=	the position of the origin of finger i's coordinate frame expressed in finger i coordinates
$\vec{X}_i$	=	the position of the origin of finger i's coordinate frame expressed in world coordinates
$\frac{\partial M_{sys}}{\partial m_i}$	=	gradient of the composition function
$\frac{\partial m_i}{\partial \vec{x}_i}$	=	gradient of the manipulability-based spatial isotropy metric
${}_{fi}R_w$	=	rotational transform from world coordinates to the finger i coordinate frame
$\frac{\partial \vec{X}_i}{\partial \theta}$	=	the arm Jacobian in the world coordinate frame

The controller utilizes this performance gradient to compute arm trajectories which optimize the M_{sys} of the task:

$$\Delta\vec{\theta} = K_m * \frac{dM_{sys}}{d\vec{\theta}} \tag{5}$$

In practice, K_m is normalized gain to improve performance in situations where the manipulability gradient gets shallow.

The summation in Equation 4 yields a convex composition since the sum of convex functions is itself a convex function[1]. Moreover, in this case, the first term in Equation 4 expresses a simple sum of convex performance indices associated with each finger, and is therefore a convex composition as well. The second term, $\frac{\partial m_i}{\partial \vec{x}_i}$, is the gradient of a convex scalar field describing "manipulability" (illustrated in Figure 1). However, Equation 4 in its entirety is not in general convex because of the manipulator Jacobian. We cannot hope to do better than this since this nonconvexity expresses the character of the particular manipulator employed to move the hand about in the world. Reflexive controllers cannot be expected to provide the deliberative behavior required to optimally posture the arm for the task, they are appropriately used to react to haptic information to generate small refinements to a predetermined nominal strategy.

Examples

Figure 2 illustrates the fingertip trajectories resulting from arm adjustments based on the manipulability gradient. The arm configuration for this example was the initial configuration illustrated in Figure 3.

Figure 3 illustrates the behavior of this reflexive configuration controller when all four fingers influence the arm posture. This example is the trace of the controller (Equation 4) executed on the hand/arm system[2]. Suppose the hand expected to encounter a plane parallel to the $y - z$ plane while moving i the x direction. Instead, suppose that it encounters a plane that is inclined 45^o. The dotted hand/arm configuration in Figure 3 represents the hand configuration resulting from this encounter with the inclined planar surface. The solid hand/arm shows the result of the reflexive, manipulability-based posture

[1] positive definite Hessians sum to positive definite Hessians

[2] The hand/arm system consists of a Utah/MIT hand and a GE P50 robot arm.

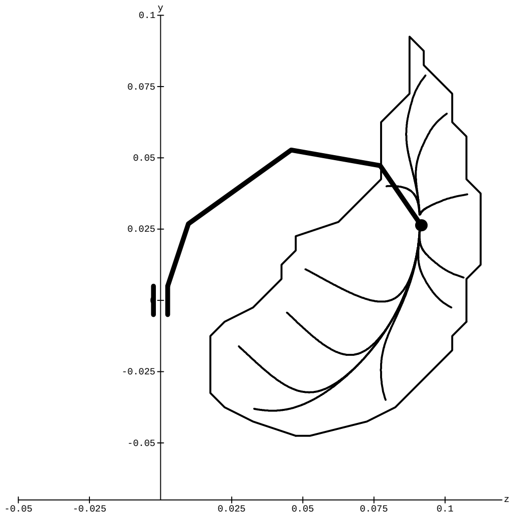

Figure 2: The Relative Fingertip Trajectories Resulting from the Manipulability Reflex

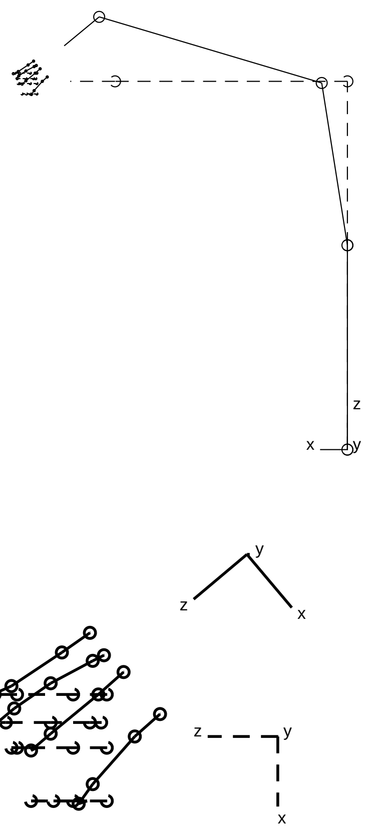

Figure 3: Reflexive Adjustment of Arm Posture to Optimize Hand Manipulability. The dotted lines define the initial hand/arm configuration, the final configuration is drawn with solid lines. Fingertip positions remain constant.

correction. All four fingers have been reconfigured simultaneously during this reposturing. The new hand posture is again compliant to unexpected interactions with the environment, or to strategic contact placement. This is a direct consequence of employing the manipulability as our performance metric — which seeks isotropic hand states.

From the perspective of the hand, Figure 3 illustrates how the adjusted posture transforms the relative orientation of the observed plane into that anticipated for the model plane. The hand-plane relationship is now approximately equivalent to that expected during the planning stages of this motion. The model of the world has been reflexively transformed into registration with observation.

Finally, Figure 4 is a trace of this behavior during a grasping task. This example is a record of the actual trajectory executed by the hand/arm system constructed in our laboratory. Several behaviors designed to position fingertip contacts on the surface of an object in order to achieve a stable grasp are used to define a grasp. The grasp geometry then provides a task level constraint to the behavior which regulates the hand/arm posture. The manipulability-based reflex tracks the grasp geometry incrementally.

Conclusions

We have demonstrated the performance of a controller which is designed to generate hand/arm postures for a multifingered robot system. The results support the value of this approach for incorporating proprioceptive information from the hand into a controller that regulates the arm posture. Moreover, we have demonstrated that such a controller can improve the system's robustness with respect to model uncertainty and incompleteness, improving the runtime performance of controllers for high dimensional systems.

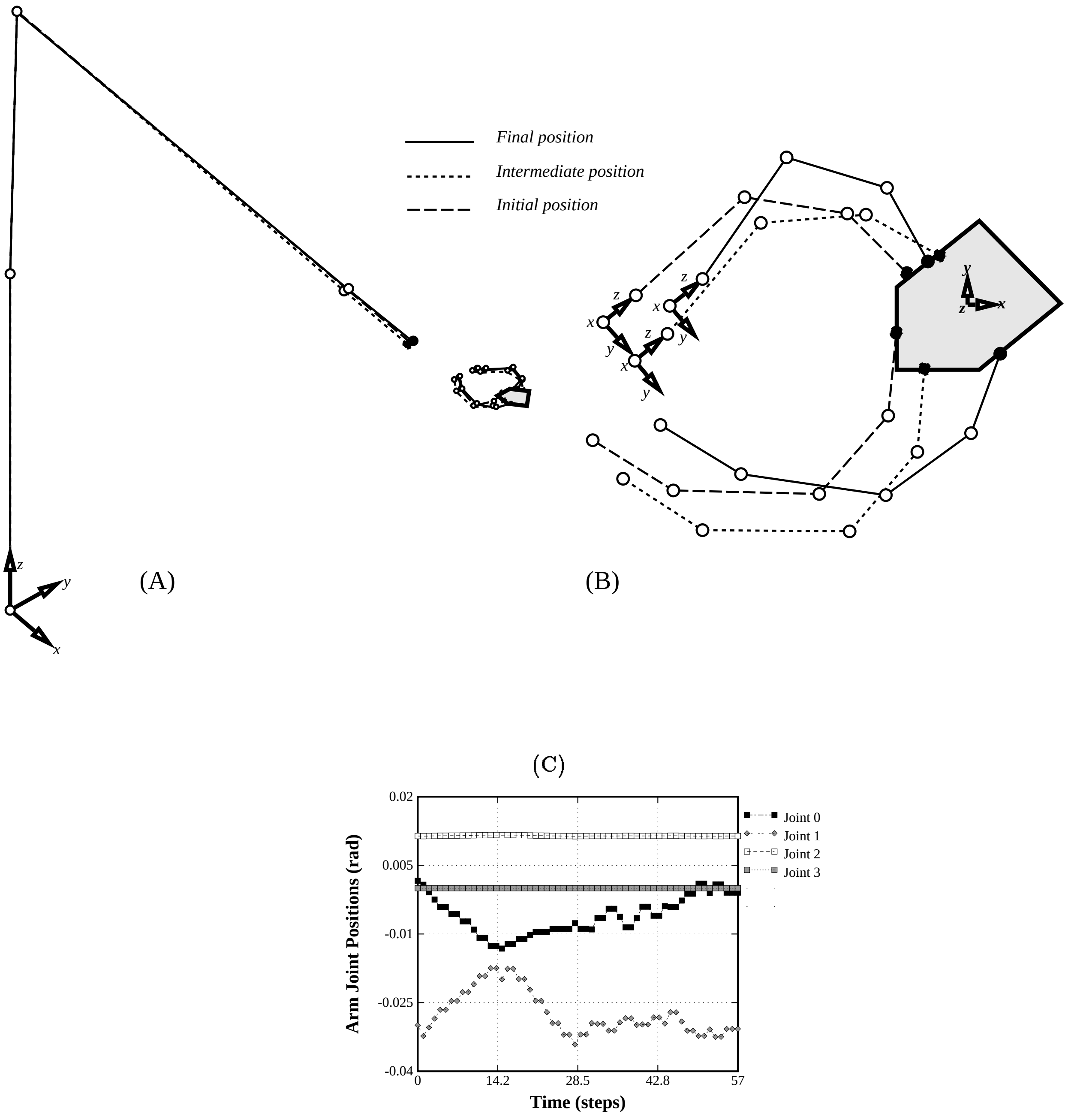

Figure 4: Behavioral Repertoire Applied to the Irregular Pentagon. (A) The hand-arm-object solution, (B) a detail of the grasp solution, and (C) the arm angles during grasp formation.

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