Parallel Algorithms for Synthesis of Whole-Hand Grasps

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Abstract

This paper describes a parallel, dynamic programming algorithm for computing the space of high quality, whole-hand grasps of a target object that match a given grasp prototype, or example grasp. The grasp prototype is used to define a quality measure that allows the contacts of a grasp to be optimized independently. Link configurations that achieve high quality contacts are identified and chained together to form good hand configurations. This algorithm results in a six-dimensional projection of the global solution space. Grasps synthesized using this technique were tested using the Salisbury hand. An example grasp is shown.

1 Introduction

Grasp synthesis is a complex problem, due to the large number of degrees of freedom of a hand and the variety of constraints that must be met: the grasp must be kinematically feasible, free of collisions, and suitable for the task to be performed. The use of a library of prototype grasps is one appealing idea for making the grasp synthesis problem simpler, but a good mechanism is needed for tailoring a grasp from the library to the specific characteristics of an object to be grasped. This paper shows how a grasp from a library can be adapted to the specific geometry of an object and the geometry of the environment while guaranteeing that the resulting grasp is suitable for the task to be performed.

This paper combines two ideas that have been presented previously — a rigorous grasp quality measure for mapping a grasp prototype to a new target object [13], and a parallel dynamic programming algorithm for computing a space of collision-free grasps [12]. In particular, Pollard [13] shows that a grasp prototype can be used to define a quality measure that allows the contacts of a grasp of a new object to be optimized independently, while maintaining a guaranteed lower bound on the quality of the grasp as a whole. This provides a flexible and rigorous way to map a prototype grasp to a new object, but it treats a grasp only as a set of contacts. Pollard [12] describes a parallel dynamic programming algorithm that focuses on the geometry and kinematics of the robot hand and the geometry of the environment in synthesizing collision-free grasps. Given constraints for each link of the hand, the algorithm computes a projection of the space of collision-free grasps that meet those constraints. Due to the lack of a rigorous, parallelizable grasp quality measure, however, this algorithm did not demonstrate flexibility to changes in the geometry of the object to be grasped.

The main contribution of this paper is to show how these two approaches can be combined to provide a more complete, flexible grasp synthesis algorithm. This algorithm satisfies a number of important grasp constraints — grasp quality, kinematic feasibility, and collision avoidance — while solving complex grasp synthesis problems for whole-hand grasps. Examples are provided that illustrate grasp synthesis of objects much more complex than the prototype object, and grasp synthesis in cluttered environments.

2 Previous Work

Lozano-Pérez et al. [7], Pertin-Troccaz [10] and others [5] [4] [9] construct grasps for varying target object geometries and in environments containing obstacles. Although they use heuristics to increase search speed, much of the search space can be analyzed in a reasonable amount of time on a parallel computer (see [6]).

Previous work on standard grasping behaviors for articulated hands allows for some variation in target object geometry, but the grasping strategies are generally designed to work for specific types of primitive objects in uncluttered environments. Bard and Troc-

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caz [2] handle varying target object geometries by decomposing each target object into ellipsoids. Nguyen and Stephanou [8] parameterize standard grasps along several dimensions. Arbib et al. [1] describe an architecture for controlling ballistic motions of a robot hand into a grasp.

If the target object is known at design time, very robust grasping strategies can be developed. Brock [3] shows that grasping strategies for articulated hands can be made very robust to uncertainty in the configuration of a known target object.

The solution presented in this paper represents a different approach to grasp synthesis for articulated hands. A prototype grasp serves as a starting point, then a global description of the set of high quality grasps is computed. The constraint that makes it possible to compute a global representation of the solution space is to require grasps to match a given grasp prototype. The quality measure that determines which grasps match the prototype is designed to allow for substantial flexibility in target object geometry, and the parallel algorithm presented allows for substantial flexibility in the environment geometry.

3 Finding Optimal Sets of Contacts

The algorithm begins by finding high quality sets of contacts, given a geometric model of a target object, a geometric model of the environment, and a grasp prototype to use as a starting point. The grasp prototype is defined as an example object and a high quality grasp of that object. Contacts are assumed to be non-singular, frictionless point contacts.

Grasp Quality

Sets of contacts are optimized based on a grasp quality measure. Computing a grasp quality measure requires comparing the task to be achieved to the capabilities of a grasp. The *task wrench space* (TS) is the space of resultant forces and torques that must be applied to the target object in order to complete the task. The *grasp wrench space* (GS) describes the capabilities of a particular grasp. In this paper, GS is expressed as follows:

$$GS = \{\underline{w} \mid \underline{w} = \sum_{i=1}^{c} \alpha_i \underline{w}_i, \;\; \alpha_i \geq 0, \;\; \sum_{i=1}^{c} \alpha_i \leq 1, \;\; |\underline{f}_i| = 1\}. \tag{1}$$

where $\underline{w}_i$ is the contact wrench at contact i, c is the number of contacts, and $\underline{f}_i$ is the applied force at contact i. Equation 1 indicates that GS is bounded by the convex hull of the contact wrenches formed from unit applied forces at the contacts of the grasp.

TS is compared to GS to form the grasp quality measure as follows:

- Grasp quality is the scale of TS required for TS to just fit within GS.

Intuitively, the grasp quality measure indicates how hard the robot hand will have to squeeze the object in order to achieve the required task wrenches.

Contact Quality

Use of a grasp prototype as a reference grasp allows the grasp synthesis process to be parallelized: information from the grasp prototype can be used to assign a quality measure to each potential contact point on the target object. This assignment can be made in such a way that a lower bound estimate of the quality of a grasp as a whole can be estimated by minimizing the contact quality measure over the contacts of a grasp.

Define the parameters of the grasp prototype as follows:

GS_p	=	grasp wrench space of prototype,
TS_p	=	task wrench space of prototype,
$\underline{w}_i$	=	contact wrench i of the grasp prototype,
g_j	=	facet j of the boundary of GS_p,
$\underline{\hat{n}}_j$	=	unit outward pointing normal of g_j,
γ_j	=	relative scale of TS_p in direction $\underline{\hat{n}}_j$.

Let G_i represent the set of facets containing $\underline{w}_i$ as follows:

$$G_i \quad = \quad \{j : g_j \text{ contains } \underline{w}_i\}.$$

A proposed contact point on the target object can be represented by a contact wrench $\underline{w}_i'$ (assuming frictionless point contact and an applied force magnitude of 1). This new contact wrench can be assigned the following contact quality measure:

$$\min_{j \in G_i} \left[\frac{(\underline{w}_i' \cdot \underline{\hat{n}}_j)}{\gamma_j} \right], \tag{2}$$

Once contact wrenches have been selected to correspond to all contacts i of the grasp prototype, a lower bound on grasp quality for this task can be stated as:

$$Q_{min} = \min_i \left(\min_{j \in G_i} \left[\frac{(\underline{w}_i' \cdot \underline{\hat{n}}_j)}{\gamma_j} \right] \right). \tag{3}$$

Because this computation requires comparing features of the grasp prototype ($\underline{\hat{n}}_j$) to features of the new target object ($\underline{w}_i'$), the transform relating the base coordinate frame of the grasp prototype to that of the target object must be specified. We assume that these coordinate frames are based at the object centers of mass, and so this leaves three orientation degrees of freedom that must be defined in order to evaluate any grasp.

More detail on the construction of these measures and implications of their use can be found in Pollard [13]. For the purpose of this paper, it is sufficient to note that the contact quality computation (Equation 2) is very simple, and that a set of contact quality measures is sufficient to obtain a lower bound estimate of the quality of the grasp as a whole (Equation 3).

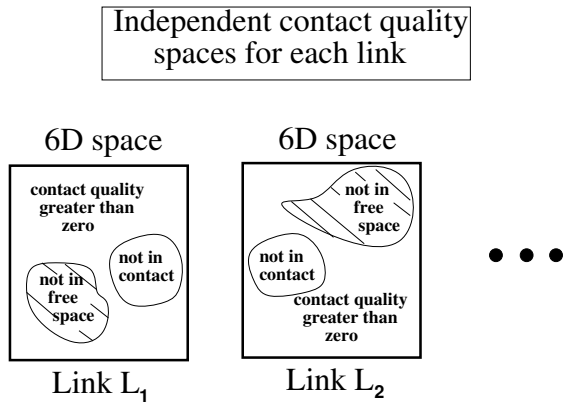

Figure 1: The contact quality computation generates a six-dimensional space of contact quality measures for each link of the robot hand.

4 Kinematics and Geometry

A complete grasp synthesis algorithm requires that a collision-free hand configuration be found to achieve a good set of contacts and therefore a high quality grasp. Because contacts of the grasp can be assigned quality measures and optimized independently, this algorithm can be easily parallelized.

Computing Contact Quality Space

The first step of the algorithm is to compute the space of contact quality measures for each link of the robot hand. This section assumes that contacts of the grasp prototype have been assigned to links of the hand, and the relative orientation of the target object and grasp prototype has been specified. This allows contact quality to be computed as in Equation 2. This equation is evaluated for every link of the hand and every configuration of that link, as illustrated in Figure 1.

For a contact quality measure to be meaningful, a given link in a given configuration must be free of collisions. If the link has not been assigned to any particular contact, this condition is sufficient for that link to be capable of forming a part of any good grasp. Otherwise, the link must be in contact with the target object. From the link-target object contact, a contact wrench can be extracted. The contact quality measure can be computed from that contact wrench.

Estimating Grasp Quality Space

Grasp quality is computed by chaining together links having optimal contact quality measures. The first step is to compose serial chains of links to form optimal quality fingers. A recursive technique is used, as shown in Figure 2. In this figure, the leftmost box represents the contact quality space for link L_1, the distal link of the finger under consideration. Point A in this space contains the contact quality measure for link L_1 at one particular position and orientation of that link.

The middle box of the figure represents the space of optimal quality measures for two-link subchains, composed by connecting link L_1 to link L_2. If the two links are connected by a single degree of freedom joint, a one-dimensional set of configurations of link L_1 can be reached from a configuration of link L_2, for example the configuration represented by point B in the figure. The one-dimensional set of L_1 configurations reachable from B is shown as the curve containing point A. The subchain quality measure at point B is obtained by maximizing the link L_1 contact quality measure over that curve, and then taking the minimum of that value and the contact quality measure of link L_2 at point B. The subchain quality measure at point C is determined in a similar fashion. The chaining process continues until the space of wrist configurations is reached: optimal finger quality measures are computed over a six degree of freedom space of wrist configurations.

Once optimal finger quality measures have been determined, the optimal grasp quality measure is computed at each wrist configuration. This measure is obtained by taking the minimum over all fingers of the optimal quality measure that can be achieved for

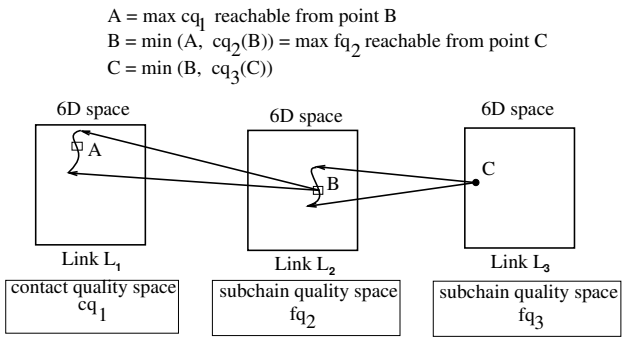

Figure 2: The link contact quality spaces can be chained together recursively to produce optimal subchain quality spaces of equal size.

that finger from that wrist configuration.

Extracting Good Grasps

Grasp quality estimates are computed over the space of wrist configurations, not over the complete space of hand configurations. While this results in a more compact solution space, it also means that some mechanism must be provided to extract optimal hand configurations. It is very easy to provide access to a single optimal hand configuration at each point in this space. The joint angles and link-target object contacts corresponding to an optimal solution can be propagated from the fingertips to the wrist along with the optimal grasp quality estimates. In Figure 2, for example, the information contained in the link L_1 and link L_2 spaces could be thrown away if optimal configurations B and A were stored as part of the three-link solution description at point C.

If intermediate subchain quality measures and intermediate optimal solution information are retained, however, it is possible to quickly and easily reconstruct the grasp quality estimate associated with any hand configuration. This means that it is easy to search through the entire space of hand configurations using the optimal grasp quality estimates to highlight regions of good solutions. This process requires only a sequence of memory references. No additional quality or collision information need be computed.

Review of Assumptions

Two key assumptions have been made in the previous sections:

- contacts of the grasp prototype have been assigned to links of the hand, and
- the relative orientation of the target object and grasp prototype has been specified.

These parameters can be selected based on the geometric description of the target object and knowledge about the grasp prototype. In the examples shown in this paper, the assignment of contacts to links is taken directly from the grasp prototype, and the portion of the relative orientation space that is examined is based around the best geometric fit of the target object to the prototype object (Section 6). The examples illustrate that even under these constraints a wide variety of grasps can be generated based on a very simple grasp prototype.

5 Implementation Issues

The parallel grasp synthesis algorithm was run on a Thinking Machines Connection Machine CM2, a Single Instruction Multiple Data (SIMD) machine. The CM2 used in these experiments has 8000 processors, each with 64K bytes of memory. Every 32 processors share a floating point accelerator. Grasps were tested using the Salisbury hand [14], a three-fingered hand with three joints per finger.

The three-dimensional space of *positions* of a link or of the robot wrist was mapped onto a three-dimensional grid of processors. Several variations of the algorithm described here were compared in order to make the best use of this particular hardware configuration, and the results are described in Pollard [11]. Computing the space of good grasps for each of the examples shown in the next section required about an hour (20 seconds for a single selection of the relative orientation of the grasp prototype and target object).

6 Examples

A Prototype Cylinder Grasp

The prototype grasp used in the examples is a grasp of a cylinder, shown in the two views of Figure 3. The hand model represents the Salisbury hand. The link geometry has been simplified, but the hand kinematics are identical to those of the Salisbury hand.

The prototype grasp consists of seven contacts: one contact on each of the two distal links of each of the three fingers and one contact on the palm. It is designed to span four dimensions of the complete six-dimensional wrench space without relying on friction.

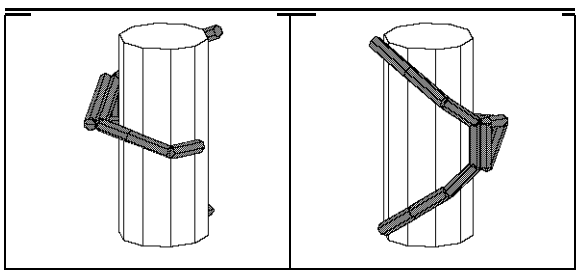

Figure 3: A prototype grasp of a cylinder.

The two dimensions that are excluded are rotation about and translation along the main cylinder axis. High quality grasps are found using only the four main dimensions, and the resulting grasps are checked to ensure that forces remain within the friction cones at the contact points. The coefficient of friction was assumed to be 0.6. The task is a wrench space ball covering the four main dimensions of the wrench space. The quality of the prototype grasp is 0.41.

In the examples below, 180 target-object / grasp prototype alignments are sampled. These represent 90 right-handed grasps and 90 left-handed grasps at evenly spaced orientations about the cylinder major axis. Every third sample is tilted $\frac{\pi}{6}$ radians away from the cylinder axis. The sample following is tilted $\frac{\pi}{6}$ radians in the opposite direction. The sample following is not tilted away from the cylinder axis.

Obstacle Avoidance

Figure 4 compares the space of good wrist positions in environments with and without obstacles for the cylindrical target object. Each box represents a horizontal slice of three-dimensional Cartesian space. The slices are read left to right, top to bottom, down the target object axis. The grey areas are the target object and the obstacles. The white areas represent good wrist positions. In this figure, we can see that the symmetrical white pattern of solutions evident in the left hand figure has been broken by the introduction of obstacles into the environment. Note that the solution space illustrated in Figure 4 is a three-dimensional projection of the complete six-dimensional solution space. White regions are wrist positions for which a good grasp can be achieved at *some* wrist orientation. To find out what orientation or orientations are represented and to extract the best solution found for a wrist position, it is necessary to query the processor representing that wrist position.

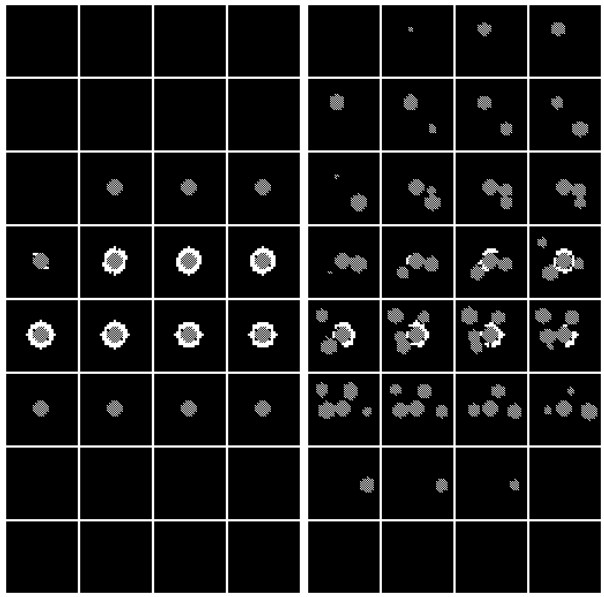

Figure 4: Wrist positions from which a good grasp of the original cylinder object can be achieved in environments without and with obstacles.

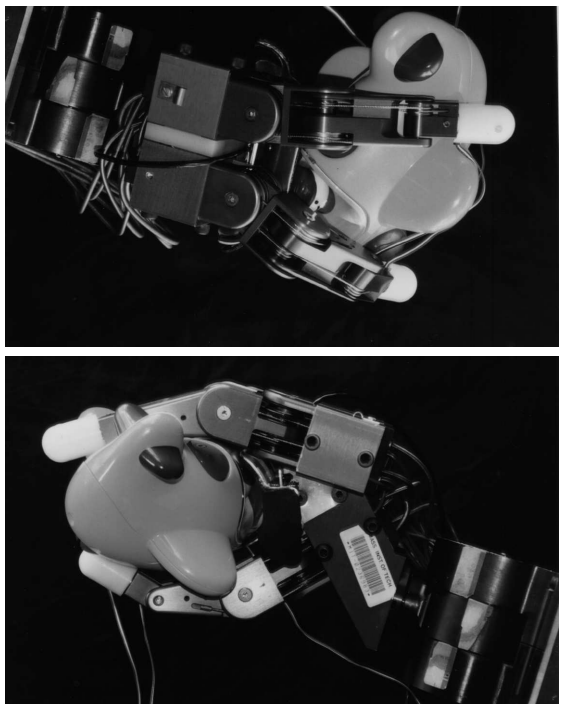

Figure 5: Two views of the Salisbury hand grasping the toy plane.

Grasp of a New Target Object

Two real objects were modelled so that the resulting grasps could be verified using the Salisbury hand. Figure 5 shows one grasp that was found for a toy plane. In the grasp of the plane, the fingers must get around the two wings. There are eight possible grasps, each with a small region of solutions. The optimal grasp found had a quality measure of 0.24, compared to 0.41 for the grasp prototype. All grasps found using the technique described in this paper and tested using the Salisbury hand were found to be easily achievable and very solid grasps.

7 Summary

This paper has described a parallel dynamic programming algorithm that uses information contained in a single example grasp, or grasp prototype, to synthesize high-quality, whole-hand grasps of target objects having geometries different from that of the prototype object. The algorithm assumes a grasp quality measure that allows contacts of a grasp to be optimized independently while retaining a lower bound estimate of the quality of the grasp as a whole. It computes a projection of the entire solution space onto the six-dimensional space of configurations of the robot wrist. This global information about the solution space allows us to find optimal grasps; evaluate how easily a grasp can be achieved; measure the effect of obstacles in the environment; measure the effect of the target object geometry; and select good values for parameters of symmetry in a grasp.

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References

[1] Michael A. Arbib, Thea Iberall, and Damian Lyons. Schemas that integrate vision and touch for hand control. In Michael A. Arbib and Allen R. Hanson, editors, *Vision, Brain, and Cooperative Computation*. MIT Press, Cambridge, 1987.

[2] C. Bard and J. Troccaz. Automatic preshaping for a dextrous hand from a simple description of objects. In *Proc. IEEE Intl. Workshop on Intelligent Robots and Systems*, Tsuchiura, Ibaraki, Japan, July 1990.

[3] D. L. Brock. *A Sensor Based Strategy for Automatic Robotic Grasping*. PhD thesis, MIT AI Lab., 1993.

[4] Joseph L. Jones and Tomás Lozano-Pérez. Planning two-fingered grasps for pick-and-place operations on polyhedra. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Cincinnati, Ohio, May 1990.

[5] C. Laugier, A. Ijel, and J. Troccaz. Combining vision based information and partial geometric models in automatic grasping. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Cincinnati, Ohio, May 1990.

[6] Tomás Lozano-Pérez, Joseph L. Jones, Emmanuel Mazer, and Patrick A. O'Donnell. *HANDEY A Robot Task Planner*. MIT Press, Cambridge, MA, 1992.

[7] Tomás Lozano-Pérez, Joseph L. Jones, Emmanuel Mazer, Patrick A. O'Donnell, W. Eric L. Grimson, Pierre Tournassoud, and Alain Lanusse. Handey: A task-level robot system. In *4th Intl. Symp. on Robotics Research*, Santa Cruz, CA, 1987.

[8] Thang N. Nguyen and Harry E. Stephanou. A computational model of prehensility and its applications to dextrous manipulation. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Sacramento, California, April 1991.

[9] I. Mazon P. Violero and M. Taix. Automatic planning of a grasp for a pick and place action. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Cincinnati, Ohio, May 1990.

[10] Jocelyne Pertin-Troccaz. On-line automatic programming: A case study in grasping. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Raleigh, North Carolina, 1987.

[11] N. S. Pollard. Parallel methods for synthesizing whole-hand grasps from generalized prototypes. Technical Report AI-TR-1464, MIT AI Lab., January 1994.

[12] Nancy S. Pollard. Planning grasps for a robot hand in the presence of obstacles. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Atlanta, Georgia, May 1993.

[13] Nancy S. Pollard. Synthesizing grasps from generalized prototypes. In *Proc. IEEE Intl. Conference on Robotics and Automation*, Minneapolis, Minnesota, April 1996.

[14] J. K. Salisbury. *Kinematic and Force Analysis of Articulated Hands*. PhD thesis, Department of Mechanical Engineering, Stanford University, 1982.