Dextrous Hand Grasping Strategies Using Preshapes and Digit Trajectories

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ABSTRACT

Inspired by human grasping behavior, use of hand preshapes has for some time been recognized as a useful way of reducing the complexity of planning grasps for a dextrous hand. We define four types of task-specific preshape and two modes of digit closure, and give criteria for the choice and positioning of the preshapes, based on intersecting digit trajectories with the graspable surfaces of the object. Grasps are planned in simulation using real range data from a laser striper and an anthropomorphic hand model. Our results show that a range of polyhedral and curved objects can be grasped using relatively simple, fast algorithms when the hand movements are constrained in this way.

INTRODUCTION

Parallel jaw grippers, with one degree of freedom, can pick up a wide range of objects. Clearly, though, dextrous hands are essential if the robot is to manipulate the object between its digits. However, dextrous hands have big advantages over parallel jaw grippers even when the aim is just to acquire the object in a stable grasp:

- Due to the increased number of hand-object contacts, dextrous hand grasps can be more stable than parallel jaw gripper grasps. Put another way, the issue of stability becomes less crucial as the number (and area, in the case of soft-fingered hands) of hand-object contacts increases.

- A dextrous hand can grasp an object from a much wider range of wrist positions and approach directions than can a parallel jaw gripper. This is useful in a cluttered environment and facilitates easier integration of arm motion planning and grasp planning.

Both these also mean that we can use grasp planners which are sub-optimal, but fast.

Napier [8] introduced the concept of *precision* and *power* grasps. In a precision grasp, the object is grasped by only the tip of each digit; a power grasp wraps around the object such that more than one segment on each digit — and possibly the palm — contact the object. The precision grasp allows maximum manipulation, as the tips of each digit can roll along the object surface in any direction; the power grasp is more stable. Lyons [7] further refined these definitions for robotics, by introducing the *lateral grasp* in which the insides of the distal (*i.e.* final) link of each digit contacts the object. This lies between the precision and power grasp in terms of manipulability and stability: the tip of each digit can roll along the object surface in one direction.

Often, *e.g.* when picking objects off the floor, a precision or lateral grasp are the only feasible grasps — in order to power grasp such an object it must be lifted by a precision/lateral grasp and then manipulated into a power grasp.

Much of the work on robot grasping has been concerned with the generation of stable grasps. *e.g.* Nguyen used static mechanics to synthesize force closure grasps [9] by maximizing the leeway in contact placement and went on to make these grasps stable [10] by modeling the contacts as virtual springs. However, as with most stability analysis, the work ignored the kinematic constraints on digit position.

The kinematics of robot grasp planning, if left unconstrained, is very complex. When mounted on a 6 degree of freedom arm/wrist combination, the two most widely used dextrous hands, the Salisbury [11] and the Utah/MIT [3] hands, have 15 and 22 degrees of freedom respectively. In recent years the preshaping paradigm has been widely recognized as a useful way to ease the complexity of the problem of finding satisfactory values for the degrees of freedom. A hand preshape is the digit posture adopted as the wrist moves towards the object. The grasp is then executed by placing the wrist into a position that encompasses the object, and then flexing (*i.e.* closing) the digits until they make contact with the object.

Stansfield [13] preshaped a Salisbury hand using a knowledge-based system, which is used to grasp polyhedral and simple curved objects, using data from two CCD cameras and haptic exploration to give 3D edges and 2D regions. Lyons [6], [7], given the desired distances between digits, used potential fields to shape the hand, but does not derive the desired distances from actual data. Bard *et al* [1] used preshaping to plan power grasps on objects. The objects are modeled using *elliptical cylinders*, which are especially suitable for planning power grasps — it is one of the few systems which provides a vision system tailored to grasp planning. The preshapes are planned using a set of heuristics based on the properties of the elliptical cylinders.

enough to simply make a decision about which preshape to use; we must also consider the trajectories taken by the digits as they are flexed from the preshape to form the grasp. We therefore define the *grasp strategy*, which associates digit trajectories with hand preshape. This is much more important for precision and lateral grasps than for power grasps, because power grasps have more possible hand-object contacts.

GRASP STRATEGIES

A *grasp strategy* consists of a *preshape* and a set of *digit trajectories*, from which a grasp can be formed without movement of the robot wrist. The preshape is a prescribed hand configuration and the digit trajectories are the motions of the tips of each digit after the preshape is formed and the wrist position has been fixed.

Grasp strategies constrain the range of possible digit movements whilst still allowing a sufficient number of degrees of freedom to be able to cope with a wide range of objects (i.e. though the digit trajectories are specified, each digit can be stopped at any point along its trajectory by contact with the object). This approach reduces the complexity of the problem whilst preserving the flexibility of a dextrous hand. Rather than viewing a dextrous hand as a completely general device, it is viewed as a set of flexible tools, where each grasping strategy is a different "tool". The decomposition also allows us to examine human grasping behavior as an successful example. Such research can lead to useful representations of hand configurations (*e.g.* [5]). The use of a limited number of prescribed trajectories means that this approach can also be utilized with dextrous robot hands that are simpler and cheaper than the Salisbury or Utah/MIT hands — exactly how much simpler remains to be seen.

It should be noted that this approach de-emphasizes stability analysis. The grasp strategies are devised to make it likely that any grasp thus formed is stable. The preshapes are symmetrical, in that all digits are flexed in parallel, and the finger abductions are coupled. In our hand model there are three digits, so the digit-object contacts lie in a plane. Assuming there is enough friction to resist gravity, we can usefully limit stability analysis to the plane. For contacts perpendicular to the plane of the digit, in the preshape formation the grasp will be in equilibrium and, in the presence of a minimal amount of friction, stable. As the contact normals deviate from this ideal or as the digits are stopped at different points along their trajectories by contact with the object, more friction is required to make the grasp stable.

It is difficult to usefully analyze the relative stabilities of different grasping strategies, since the final stability depends very much on object geometry. However, if the robot hand has soft, deformable tips at the end of each digit [12] [9] then with suitable force control a wide range of digit positions and contact orientations can be made stable.

Figure 1 shows the hand model used in our experiments. The hand is roughly anthropomorphic, in that the digit dimensions are similar to that of the human hand, and certain joints are coupled.

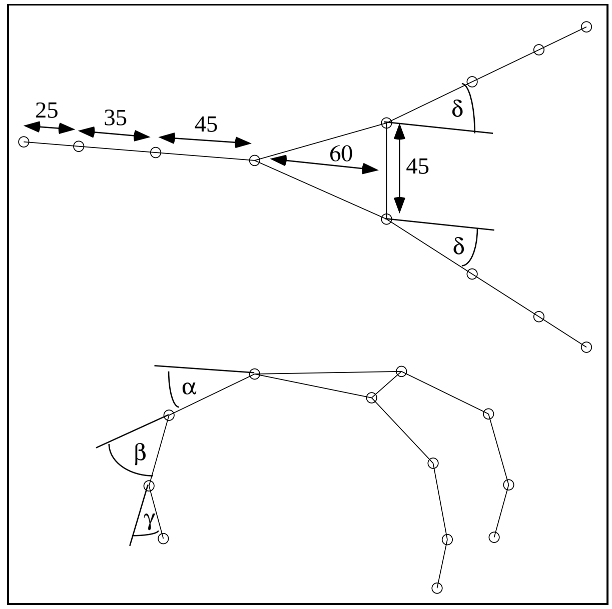

Fig. 1. Hand model showing the link distances and the location of angular degrees of freedom. All distances shown in *mm*. Refer to text for more details.

The hand has three digits — a thumb and two fingers, all with identical dimensions and, in the absence of external forces, each with equal angles of flexion (α, β, γ at the proximal, middle and distal joints respectively). The fingers can *abduct* by an angle δ (*i.e.* they can rotate about an axis perpendicular to the palm and through the proximal joint). Within each digit, the distal and middle joints are coupled (such that $\gamma = \frac{2}{3}\beta$), and the angles of abduction of each finger are coupled. This coupling of joints could be hard-wired into the hand design, in which case they would have a strong influence on how the object could be manipulated, or just used as modes of movement to facilitate the planning of the grasps with complex hands such as the Salisbury or Utah/MIT hand.

Generation of the Grasp Strategy

The grasp strategy is generated from *task-specific* sets of preshapes. A task-specific preshape is one that is ideally suited to a particular task. The task-specific preshape is fitted such that the final grasp configuration is as close to the task-specific preshape as possible. The preshape is then expanded in order to allow for errors in wrist positioning and to avoid collisions with the object.

Figure 2 shows the four categories of task-specific preshapes: PRECISION, LATERAL, MANIPULATION, HOOK. As the names suggest, these preshapes embody the task-requirements of the grasp. Given the desired angle of abduction and relative positioning of the tips of each digit, the task-specific preshapes are defined as follows:

- The PRECISION preshape keeps the angle between the wrist plane and the distal link of each digit as close as possible to $\frac{\pi}{4}$, *i.e.* it minimizes $\mid \alpha + \beta + \gamma - \frac{3\pi}{4} \mid$. This gives a contact surface at the tips of each digit.

- The LATERAL preshape keeps the distal link of each digit perpendicular to the wrist plane, or as close to perpendicular as possible, *i.e.* it minimizes $\mid \alpha + \beta + \gamma - \frac{\pi}{2} \mid$. This gives a contact surface on the insides of the distal link of each digit.

- The MANIPULATION preshape minimizes the sum of the squares of the deviations of the joints from their central values, *i.e.* it minimizes $(\alpha - \alpha_c)^2 + (\beta - \beta_c)^2 + (\gamma - \gamma_c)^2$. This gives a preshape which has maximum leeway for object manipulation between the digits. It is useful if there is no preference for a precision or lateral grasp.

- The HOOK preshape keeps the line joining the tip to the middle joint of each finger perpendicular to the wrist plane, or as close to perpendicular as possible. This gives a preshape which is suitable for grasping by hooking.

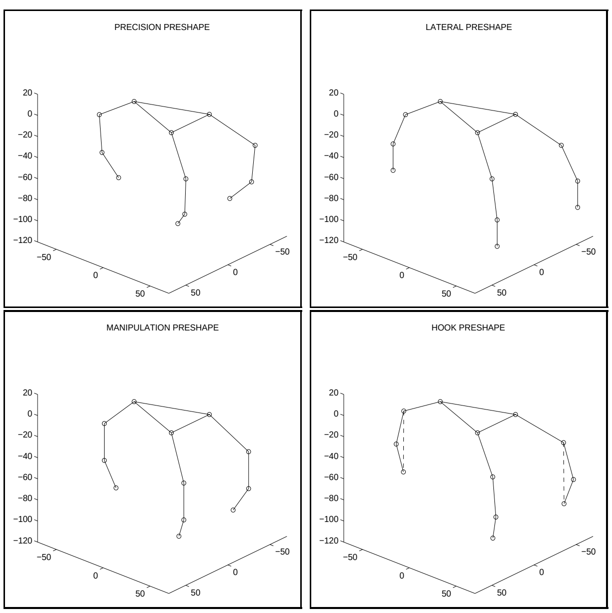

Fig. 2. PRECISION, LATERAL, MANIPULATION and HOOK preshapes

Each task-specific preshape is defined by just two variables — one controlling the flexion of the digits, another controlling the abduction of the fingers. In all of the task-specific preshapes the angle of the distal link is constrained so that it cannot point away from the "center" of the preshape, *i.e.* $\alpha + \beta + \gamma \geq \frac{\pi}{2}$. This is done to make it less likely that collisions occur between the object surface and the hand.

Strictly speaking, the HOOK grasp is not always task-depends on object geometry — *e.g.* if the contacts are concave, or on the underside of the object. However, it is a distinct enough case to be handled by some meta-reasoning about coarse object geometry. The choice between PRECISION, LATERAL and MANIPULATION depend solely on the task-requirements, and it is these classes that we use in our grasp planner. However, the preshapes may have to deform from their ideals in order to fit to the specified grasping points. Choice of preshape therefore specifies a *preference*, not a firm constraint, and ultimately the type of grasp is always strongly influenced by object size and shape; *e.g.* it is not possible to execute a lateral grasp on an object which is very small compared to the hand, nor is it possible to execute a precision grasp on an object which is large compared to the hand.

For an arbitrary object, *the closer that the final grasp configuration is to the task-specific preshape, the better the task-specificity of the grasp.*

Figure 3 shows the 2 categories of digit trajectory. Figure 3(a) shows the PROXIMAL digit trajectory, in which the digits are flexed at the proximal joints, and Figure 3(b) shows the DISTAL digit trajectory, in which the digits are flexed at the middle and distal joints. Each digit trajectory is defined by just one variable, since the middle and distal joints are coupled. The trajectories give a digit closure motion similar to that of the human hand.

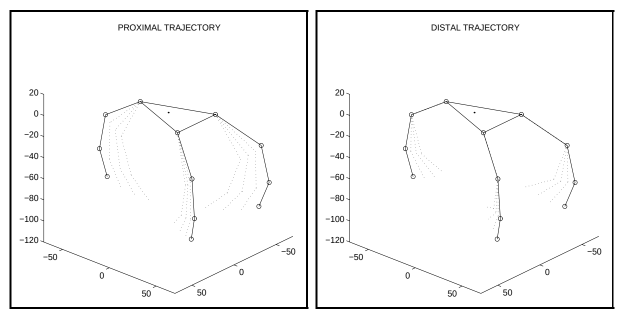

Fig. 3. PROXIMAL and DISTAL trajectories

The PRECISION, LATERAL and MANIPULATION preshapes can be combined with either the DISTAL or PROXIMAL digit trajectories to give 6 different grasping strategies. The HOOK preshape can only be used in combination with the DISTAL digit trajectory, to give a total of 7 different grasping strategies.

The grasp strategies are generated as follows:

- Task determines which preshape category is used: PRESHAPE, LATERAL, MANIPULATION or HOOK.

- Acquisition of object model.

- Determination of task-specific preshape parameters and wrist position. These are chosen such that the *estimated* distance-to-contact is as small as possible, task-specific preshape as possible.

- Choice of digit trajectory such that the *actual* distance-to-contact is as small as possible, and that the trajectories intersect the object over the error range of wrist positions.

- Adjustment of preshape, with the digits constrained to move along their trajectories, in order to allow for errors in wrist positioning and avoid collisions with the object.

This amounts to planning a whole grasp, yielding the contact points, the hand configuration and the wrist position. Details are given in the next section.

Grasp strategies are given double-barreled names. The first name refers to the task-specific preshape category used and the second to the digit trajectory used. *e.g.* Lateral-Proximal is a grasping strategy generated from a LATERAL preshape and PROXIMAL digit trajectory.

ALGORITHM

An algorithm has been implemented to plan grasps for the PRECISION, LATERAL and MANIPULATION strategies. Future work will extend this to work for the HOOK strategy.

Input

A range image of the object is taken from two known viewpoints using a laser striper. The images are taken at a resolution of 1mm in the x and y directions, with 256 different z values, the resolution of which depends on the height of the object. A typical image has dimensions of 100×100.

The range data is then segmented by fitting planes and quadric surfaces, grown from seeds acquired by an (H, K) curvature classification procedure (following [2]). Surfaces which are too small or too fragmented to provide good contact for a circular fingertip are discarded (by erosion/dilation), to leave a set of graspable features [15]. A *graspable feature* is a sufficiently large surface feature with curvature characteristics that provide good digit-object contact for soft (*e.g.* rubber-coated) digits. The graspable features are then rotated into the global coordinate frame to provide the visual input to the grasp planner.

The graspable features are grouped into candidate grasping sets. These sets comprise of 2 or 3 features, according to whether the two fingers are placed on the same or a separate feature respectively. We find all sets where opposition between candidate thumb and finger patches exists. Some of these sets will not be reachable by the hand; however, the subsequent algorithm is fast enough not to make this a problem.

Task-Specific Preshape Fitting

For each candidate grasping set, we calculate the task-specific preshape and the wrist position. Because the tips of the three digits form a plane, this can be treated as a

- The *aperture plane* is the plane in which the tips of the digits lie.

- The *preshape aperture* is the positions of the tips of the digits in the preshape — it is a function of the hand's flexion and abduction parameters. The *size* of the preshape aperture is the distance from the thumb-tip to the point midway between the two finger-tips.

- The *projected closure* is the orthogonal projection of the digit trajectories into the aperture plane.

- The *projected closure distance* is the sum of the squares of the distances, in the projected closure, from the tip of each digit to contact.

In choosing the preshape we use three observations based on human grasping behavior. Firstly, the minimum size of the preshape aperture is proportional to the expected distance between the graspable features (see [4]). Secondly, the preshape aperture is kept as small as possible, taking into account the uncertainty in wrist and object position (see [14]). Thirdly, the orientation of the aperture plane is determined more by environmental constraints and the relative positions of the object and robot arm than by the object geometry. For many objects and tasks the aperture plane is extremely simple to determine, *e.g.* for objects lying on the ground a good aperture plane will almost always be one which is parallel to the ground, in order to give maximum leeway with respect to hand-ground collisions. In the experiments described here, therefore, the aperture plane is always parallel to the ground plane.

We combine these with two stability criteria. Firstly, we try to keep the contact normals co-planar, to minimize the amount of friction required for the contact forces to be in equilibrium. Secondly, we keep the thumb in a plane perpendicular to the contact surface. This recognizes the fact that the thumb is the single most important digit in terms of grasp stability and, as such, should be kept normal to the contact surface in order to avoid slippage.

Combined, these give the following algorithm for grasp planning. For each candidate grasping set:

1. Task-specific preshape set chosen: PRECISION, LATERAL or MANIPULATION.

2. The aperture plane is oriented parallel to the ground plane.

3. The range of possible positions for the aperture plane is determined such that within this range the aperture plane intersects all the grasping features in the candidate grasping set.

4. The position of the aperture plane is chosen from within this range with the aim of keeping the contact forces co-planar. The angle between the plane and potential contact normals is minimized: *i.e.* the

the plane and the object normals over the aperture plane/grasping feature intersection curves is minimized. The sum is normalized, such that the thumb and finger grasping features have equal weight. If the graspable features are all planes (to within some given threshold) the position of the aperture plane defaults to the center of its range.

5. The thumb-tip trajectory in the projected closure is kept normal to the intersection of the thumb contact surface with the aperture plane.

6. The preshape aperture is chosen such that the projected closure distance is minimized. If a given projected closure distance can be achieved with a range of abductions, then the abduction chosen minimizes the sum of the squares of the angles between the projected closure and the contact normals.

7. The wrist position and task-specific preshape parameters are then uniquely determined by the preshape aperture.

Choice of Digit Trajectory

The digit trajectory — PROXIMAL or DISTAL — is chosen in order to minimize the *actual* closure distance, whilst providing enough leeway for expected wrist positioning errors.

Expansion of Preshape

The task-specific preshape is expanded, by extending (*i.e.* opening) the digits along the chosen digit trajectory until there is sufficient leeway of preshape placement over the expected wrist positioning error.

RESULTS

Experiments were conducted in simulation using object data acquired from real objects, and the hand model shown in Figure 1.

Figure 4 shows grasps planned on a simple cuboid using the PRECISION, LATERAL and MANIPULATION preshapes. The expected positioning error is 10 mm in the x,y and z directions. The object patch boundaries are displayed. The joints and digit-tips of the hand are drawn as circles, the hand segments as straight lines. Curves joining digit-tips to surface patches show the digit trajectories from the preshape position to the final contact point. Figure 4(a) shows a Precision-Proximal grasp strategy. Figures 4(b-d) show side-views of Precision-Proximal, Lateral-Distal and Manipulation-Proximal grasps. For the LATERAL grasp, the PROXIMAL trajectory provides the smaller closure distance but because the proximal joint is close to its limit, in the event of a positioning error the trajectory would not reach the object. The DISTAL trajectory is therefore chosen instead.

Figure 5 shows a Manipulation-Proximal grasp on a smaller object, which approximates a cuboid. The fingers abduct so that they can both fit on the same feature (step # 6 of algorithm); without finger abduction, they

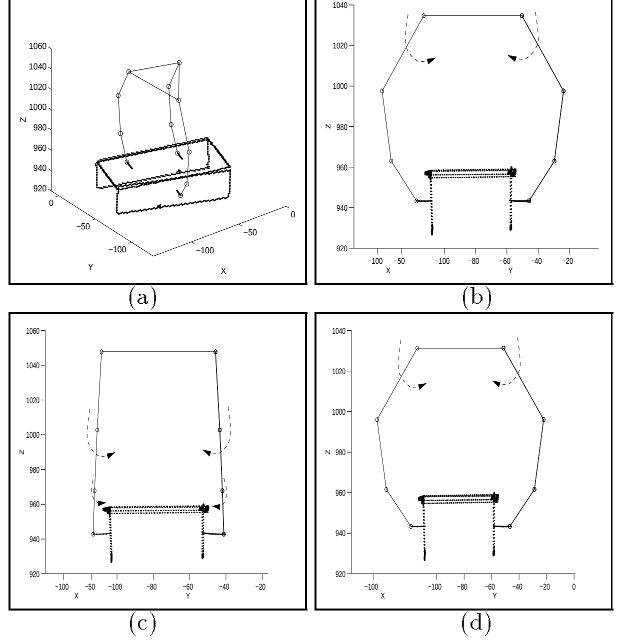

Fig. 4. (a) Precision-Proximal strategy, (b) Precision-Proximal strategy viewed side-on, (c) Lateral-Distal strategy viewed side-on, (d) Manipulation-Proximal strategy viewed side-on. Curves joining digit-tips to surface patches show the digit trajectories from the preshape position to the final contact point.

would be too far apart to grasp the object. This demonstrates that abduction is necessary in order to make some grasps kinematically feasible.

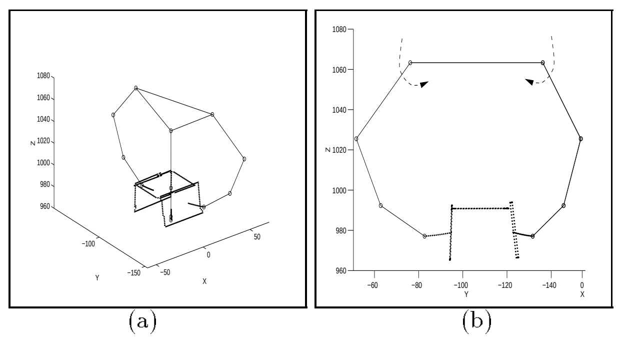

Fig. 5. (a) Manipulation-Proximal strategy, (b) viewed side-on.

Figure 6(a) shows the range data from two views of a sphere, (b) shows the planned grasp (Lateral-Proximal), with the sphere drawn as a mesh surface. Figure 6(c) shows the side view of the grasp — note how the sphere is grasped around it's center, in order to keep the contact forces co-planar (Step # 4 of algorithm). Figure 6(d) shows the top view of the grasp — note how the fingers abduct to give normal contacts (Step # 6 of algorithm).

Finally, Figure 7 shows the results on a more complex object, with the two fingers having different grasping fea-

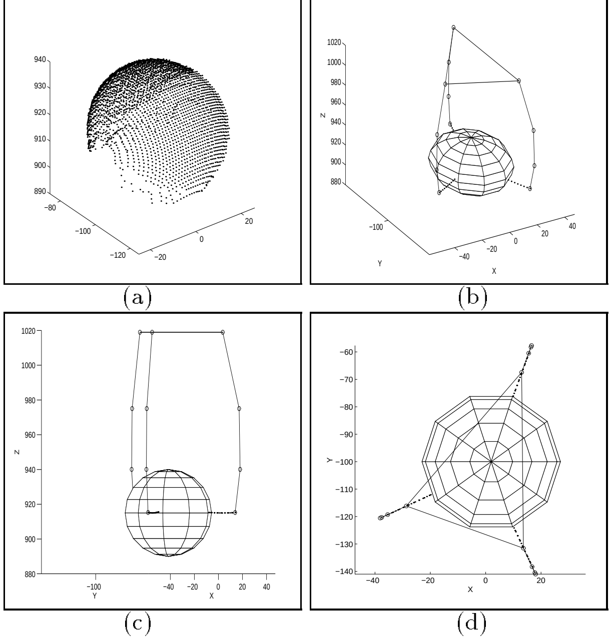

Fig. 6. (a) range data, (b) Lateral-Distal grasp strategy, (c) viewed from side, (d) viewed from top

tures. Figure 7(a) shows the range data from two different views combined, (b) shows the planned Manipulation-Proximal grasp, (c) the same grasp viewed from above. For this grasp it is crucial to consider the digit trajectories, because the DISTAL trajectory fails to intersect with the object (see Figure 7(d)). The quality of this grasp, in terms of both stability and task-specificity, is lowered by the large deviation of the final grasp configuration from the task-specific preshape. Analysis of the static mechanics of the grasp shows that it requires a minimum coefficient of friction $\mu = 0.32$.

The algorithms are run on a Sun SparcStation 10. Acquisition of one range image typically takes 1-2 minutes. The segmentation and quadric-fitting typically takes 20 seconds. The planning of a grasp for a set of grasping features takes a few seconds, the length of time depending on feature size and shape.

CONCLUSIONS

We have introduced the notion of associating digit closure modes with preshapes. Firm criteria, based on human grasping, have been given for deciding on preshape parameters tailored to the task-requirements. Preshapes are then fitted with the aim of minimizing the distance from preshape to contact. This helps give stable grasps, and helps avoid collisions.

The only drawback with the algorithm as it stands is that it can fail to plan grasps, because of the lack of any feedback mechanism. Feedback reasoning will be applied to alter the choice of wrist position in the case that neither digit trajectory intersects with the grasping features. Further work will also examine the initial choice of aperture

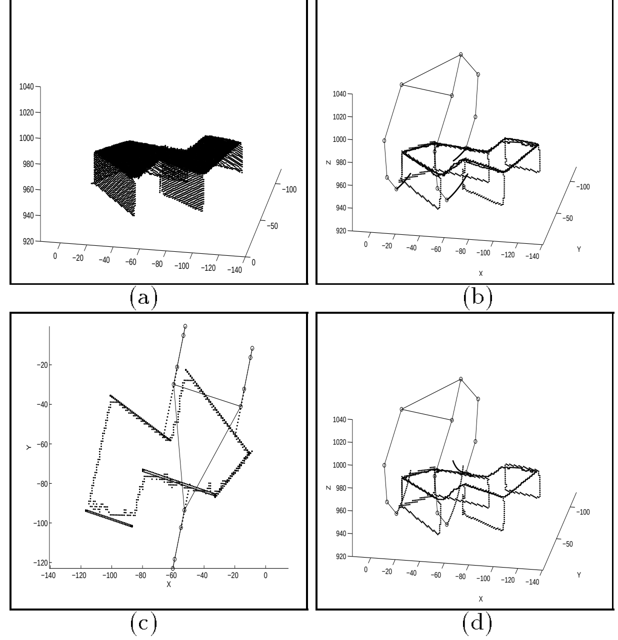

Fig. 7. (a) range data, (b) Manipulation-Proximal grasp strategy, (c) viewed from top, (d) distal trajectories do not intersect with the grasping features.

plane orientation. In the work here the plane is fixed to be parallel to the ground. For some objects, *e.g.* cylinders with their axes vertical (such as mugs), there are other good aperture planes to be used — in the case of the vertically aligned cylinder, any plane which goes through the axis of the cylinder is a good aperture plane. Finally, we intend to analyze the grasping strategies for stability, on a large set of randomly generated polyhedral objects. This should help us design grasping strategies which maximize the chances of producing stable grasps.

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