GRASP PLANNING FOR HUMAN PREHENSION

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ABSTRACT. The study of the human hand in prehensile movements can offer insights into the design of robot grasp planners. A design for a two-level hierarchical grasp planner is presented. The first phase maps an object and task representation into a grasp-oriented description of the task The second phase maps this description into an opposition space, which captures the available forces and degrees of freedom of the hand As these mappings are not unique, constraints acting on the hand/object /task interaction are discussed.

I. Introduction

Current research into the nature of robot task specifications has demonstrated the need for hierarchical systems [Lozano-Perez and Brooks 1985, Vijaykumar and Arbib 1986]. In Vijaykumar and Arbib [1986], four different types of planners were identified. A strategic planner deals with high-level, more global, decisions, breaking down high-level task specifications into more primitive commands. A tactical planner then deals with lower-level, more local, decisions, performing a subset of primitive commands. Other primitive commands go to the path planner, necessary for moving the manipulator through a cluttered space. Finally, a grasp planner determines a proper grasp, based on the primitive 'grasp' command coming from the strategic planner. A task plan is produced by first searching for relationships that constrain the solution. In a similar planning system, Lozano-Perez and Brooks [1985] produce a skeletal plan, and then look towards refining it through application of constraint knowledge.

By studying the interaction between the central nervous system (CNS) and the human hand within the context of prehension (i.e., grasping), we hope to isolate issues for grasp planners for dextrous robot hands. The shape that the hand takes on during prehension depends on a variety of complex issues, involving object and task properties, hand and arm capabilities, and even CNS features. When observing human reaching and grasping behaviors, one notices both variability and invariances. Examples of invariances include the typical S-shaped trajectory of the arm [e.g., Jeannerod 1981], the two-phase velocity profiles noted by [Jeannerod 1981] and modelled by [Arbib *et al* 1985], and the opening of the hand larger than the object to be grasped [Jeannerod 1981]. However, human arm and hand movements also contain a great deal of variability [e.g., MacKenzie and Marteniuk 1985]. Variability is also observed at a higher level, in the multiple strategies people use to grasp objects. Yet, even at this high level, stereotypical hand postures have been noted in the literature [Schlesinger 1919, Napier 1956].

Our approach, therefore, to designing a grasp planner for human prehension is to account for invariances and variability, identifying and resolving the constraints acting on these behaviors. Both the path planner and the grasp planner are limited both by internal constraints as well as constraints that arise from their interaction. The arm, while following some internal kinematic and dynamic constraints [Hollerbach and Flash 1982, MacKenzie and Marteniuk 1985, Marteniuk *et al* 1987], cannot be directed anywhere; instead, it must be directed towards a location that makes sense for the prehensile posture. Such hand constraints, as finger pad locations, lengths of fingers, flexibility of ligamentous and tendonous structures, etc., all contribute to determine what that planned location should be.

In the next section, a human hand-oriented grasp planner is discussed, in isolation for now from path planning issues involving arm and body effects. In the third section, some of the constraints acting at the hand vs object level are analyzed.

II. Grasp Planner

In order to develop a grasp planner, both an object representation and a task representation are needed. Furthermore, hand variables that will be modified during a particular motion must be described. Between the input and the output, the mapping from the object/task representation to the hand also must be described. In Figure 1, a block diagram of a grasp planner is shown.

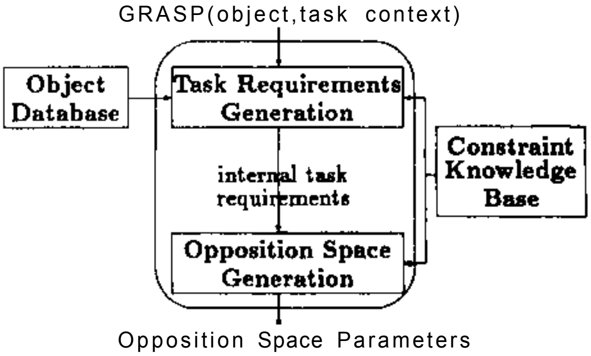
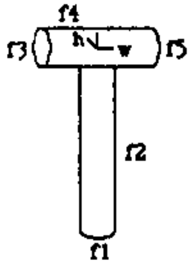


Figure 1: A Two-Level Grasp Planner

The grasp command is sent from the strategic planner, along with a pointer to the object to be grasped and the context within which it will be grasped. Information about the object is available in an object database. For example, if the object to be grasped is a hammer, then the command GRASP(HAMMER, SWING_UP_DOWN) would tell the grasp planner that the object is the one in the database identified as HAMMER. The task for which it will be used involves the SWING_UP_DOWN degree of freedom. (See

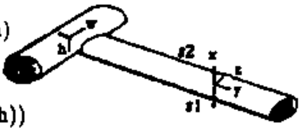
Lyons [1985] and Vijaykumar and Arbib [1986] for other context information). For the object representation, systems that select the correct object features that can then be mapped into a robot hand posture have previously been discussed Lozano-Perez and Winston 1977, Lyons 1985]. While Lozano-Perez and Winston [1977] define objects in terms of solid geometries (e.g., cylinders, holes, etc), Vijaykumar and Arbib [1986] define objject features in terms of surfaces (e.g., cylindrical surfaces, rectangular faces, etc). We find this latter approach to be more useful for a grasp planner, because the hand must grasp surfaces. An object representation for a large steel hammer, based on the specifications of Vijaykumar and Arbib [1986], would be:



```
(hammer-1
 (length       276mm)
 (width        83mm)
 (height       29mm)
 (weight       .45kg)
 (material     'steel)
 (features     (f1 f2 f3 f4 f5))
(f1
    (circular-face
     (adj-features        (f2))
     (diameter            31mm)
     (normal-axis         '-l axis)
     (center              (-261.5mm 0 0))))
(f2
    (cylindrical-surface
     (adj-features        (f1 f4))
     (height              247mm)
     (diameter            31mm)
     (surf-normal-axis    '-w axis)
     (center              (-138mm 0 0))))
(f3
    (circular-face
     (adj-features        (f4))
     (diameter            29mm)
     (normal-axis         '-w axis)
     (center              (0 -41.5mm 0))))
(f4
    (cylindrical-surface
     (adj-features        (f2 f3 f5))
     (height              83mm)
     (diameter            29mm)
     (surf-normal-axis    'l axis)
     (center              (14.5mm 0 0))))
(f5
    (circular-face
     (adj-features        (f4))
     (diameter            29mm)
     (normal-axis         'w axis)))
     (center              (0 41.5mm 0))
     (antic-force-axis    'w axis))))
```

Once a command is sent, the grasp planner maps the grasp command into hand variables. A two-step process is visualized to accomplish this task (see Figure 1), In the first phase, the grasp command parameters are mapped into a more useful, grasp-oriented, set of task requirements. Task requirements consist of both functional constraints and physical constraints [Iberall *et al* 1986, Iberall 1986]. Functional constraints are less a property of the object to be grasped, and more a property of the manner in which the object will be used within the task. A fundamental functional constraint on most prehensile tasks is that the object not be dropped. The posture used by the hand during the task must be able to overcome the anticipated forces acting on the object. Initially, during the lifting phase of a task, the initial force is likely to be just the weight of the object. Later, during the actual task, other forces such as additional inertial forces come into play. Underlying these functional constraints are physical constraints, that are based both on properties of the object as well as on properties of the hand. In Iberall [1986], we showed how task requirements could be described in terms of one or more *opposition vectors.* Opposition vectors exist between opposable surfaces, and task-related DOFs, forces, and torques all are described relative to an opposition vector. For example, the center of mass of a hammer is somewhere in or very near the head of the hammer. When one picks up a hammer by its handle, a torque therefore arises and it can be measured relative to the opposition vector. The opposition vector extends through the handle between hand surfaces. The swinging of the hammer through the air will cause the opposition vector to both rotate and translate. This swinging will also, of course, generate other torques acting upon the opposition vector. The internal task requirements for lifting the hammer, lying on a support that allows access to the handle, would be as follows:

```
(opposition vector-1
     (magnitude         31mm)
     (relat-to-wrist    (-65mm 395mm 140mm))
     (loc-on-obj        (-210mm 0 0 90° 0 90°))
     (opp-surface       (s1 s2))
     (dofs              (0 380mm 310mm 140° 0 0))
     (resolution        'little)
     (forces            (4.38nt (-1 0 0) 48.7nt (0 0 1)))
(s1
     (length            247mm)
     (rad-curvature     0.5)
     (compliance        'none)
     (texture           'smooth))
(s2
     (length            247mm)
     (rad-curvature     0.5)
     (compliance        'none)
     (texture           'smooth)))
```



In the second phase of the grasp planner (Figure 1), these internal task requirements are mapped into specific hand variables. In Iberall [1987a, 1987b], it was shown that hand postures could be described as combinations of three basic *oppositions* (pad, palm, and side), with an opposition being defined by the axis along which the force was being applied relative to the palm. The opposition occurs between the surfaces of *virtual fingers* [Arbib *et al* 1985], which are groups of real fingers acting together in applying a force against other fingers or against task torques. The particular shape chosen by the hand is called an *opposition space* [Iberall *et al* 1986], which defines the functional capabilitites of that hand posture for executing a stable grasp and manipulating the object.

As seen in Figure 2, a hand is shown grasping two different size hammers, with a simple vector notation showing the virtual fingers being used in the oppositions. In Figure 2a, two opposition vectors are shown for a medium-sized hammer. The vectors go through the same opposable surfaces but are positioned differently along the handle. As

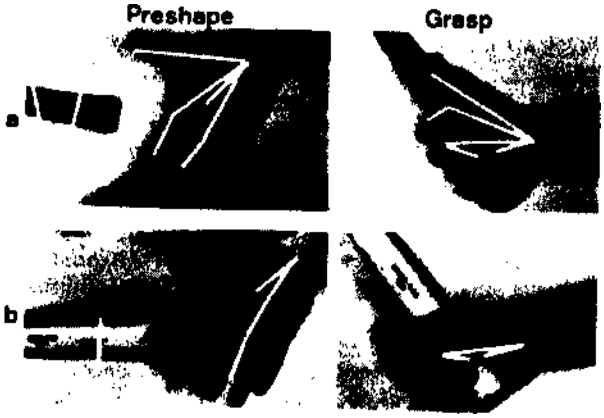


Figure 2: Preshaping and Grasping Two Different Sized Hammers.

the hand preshapes (seen in the left side of Figure 2a), the opposition space thus formed is the one where side opposition (between the thumb as VF1 and index finger as VF2) occurs with palm opposition (between the palm as VF1 and all four fingers as VF2). In Figure 2b, we see the mapping for a larger and heavier hammer. One opposition vector is used, with palm opposition occurring between the palm (VF1) and the four fingers (VF2). In this latter case, the thumb is pressing against VF1, helping VF2 to create more force to counteract the anticipated large task-related torques.

Objects of course have an infinite number of opposition vectors. However, only some of these locations are useful for the task for which the object will be used. The point of the internal task requirements is to discover those useful locations in a way that will capture the person's intent for the object as it relates to the object's task-significant properties. However, neither the object-to-task-requirement mapping nor the task-requirement-to-opposition-space mapping (which is basically an inverse kinematic mapping) are one-to-one mappings. In order to approach a functional specification of these mappings, we look towards capturing the constraints acting on both phases. In the next section, the sources for some of these constraints are analyzed.

III. Constraints on Grasping

Constraints on prehensile behaviors arise from a variety of sources. The hand and wrist bones have been shaped through millions of years of evolution, leaving modern man with a skeletal support and articulation system useful for enhanced object manipulation. Extrinsic muscles in the forearm send tendons into the hand, thus allowing the hand to be relatively small [Tubiana 1981]. Many of these extrinsic muscles have common origins in the forearm, thus causing constraints on fractionated finger movements. Ligaments as well cause constraints on finger movements. For example, abduction of the fingers at the metacarpophalangeal joint is only possible when those ligaments are relaxed.

Thus, *anatomical constraints* arise from the size and shape (length, width, etc) of the bones, the shape of the articular surfaces between bones, the location of tendon insertions and origins, the location of passive ligaments, the location and nature of skin specialized for prehension (with glands and epidermal ridges), and the size of the hand's surface areas (of the palm, of the finger pads, etc). *Biomechanical constraints* arise from the stresses placed on these same bones, tendons, muscles, and ligaments. These include relative mechanical advantages of the various tendons, directions of movement of the fingers, the amount of force that can be applied by different hand configurations, and the way that these forces can be brought to bear.

Other constraints arise from the object *(object property constraints),* and its anticipated interaction with the hand *(interaction constraints).* Object property constraints arise because objects have dimensions, such as length, width, and height. The size along these dimensions produces constraints on the location where an object can be grasped. If an object is larger than the hand along one of these dimensions, then any opposition vector along that dimension is not useful. If the object is very much smaller than the hand surfaces (as is a thread, for example), then the hand is limited by *perceptual constraints* that require additional information for discriminating the tactile sensations. Objects also have shape. A complex object can be divided into object features, each of which then have dimensions (as was done in [Vijaykumar and Arbib 1986]). Small features on large objects do not generally make useful locations for grasping [Popielarczyk 1987]. If an opposition vector is chosen through a small feature on a heavy object (for example, through the knob on a radio), the arising torque produced by lifting will most likely exceed the available force at the fingers. Of course, with large objects that specifically have small features carefully placed for grasping (e.g., handles placed above the center of mass on heavy boxes), this is not the case. In addition to the weight consideration, the size and placement of features puts limits on the type of opposition possible (e.g., palm opposition could not be used in grasping the knob).

During the task (object lifting and manipulation), forces and torques act on the object. The weight and distribution of mass create constraints on the prehensile activity. A torque will arise if the opposition vector chosen fails to pass through a vertical line through or above the center of mass of the object. Moments that tend to twist the opposition vector can be cancelled by increasing the friction between the fingers and object, either by applying more active force or else increasing the amount of skin surface against the object. If the weight of the object is not offset by (at least) an equal and opposite force, the object will not be lifted. This force can be supplied in a direction normal to the weight vector, with its magnitude affected partially by the coefficient of static friction. This latter value depends on the material and texture of the object surfaces, as well as on the hand surface's frictional responses [Johanssen and Westling 1982]. Frictional characteristics can enhance interactions, thus reducing the amount of active force necessary in the prehensile configuration (e.g., fewer real fingers in a virtual finger). If the surface texture is smooth, then any opposition vector between the surfaces will have a reduced frictional component. If the pads (with their epidermal ridges and greasy lubricant) are not used (with an appropriately larger applied force), the object will likely slip out of the grasp. A surface also has a measure of compliance, affecting the amount of force that can be applied against the surface. Another surface feature is the temperature of the object, which provides constraints in terms of the acceptable range for contact with human skin.

Objects and their features have *accessibility constraints.*

Some object features are unavailable for grasping because of other objects. An example is the bottom of an object not being accessible because of the table or the surface supporting it.

In this short analysis, major constraints arising from the hand (anatomical, biomechanical, and perceptual), the object (dimensions, shape, feature accessibility), and their interaction in the task (forces and torques, skin and object surface characteristics, object and hand size relationships) have been delineated. Further analysis is needed, and empirical results for quantifing these variables. Some of the more general issues have been ignored, such as constraints related to the arm and body, constraints imposed by the laws of physics, and constraints related to the CNS in general.

IV. Conclusion

The study of the human hand in prehensile movements can offer insights into the design of robot grasp planners. A design for a hierarchical grasp planner is presented. The first phase takes an object and task description and breaks them down into internal task requirements. These task requirements include functional and physical constraints, and are designed to capture the intended use of the object in prehensile-specific terms. The task requirements are then mapped into an opposition space, which captures the available forces and DOFs of the hand, using vectors to represent virtual finger configurations. As the mappings in these phases are not unique, knowledge about constraints acting on the hand/object/task interaction first must be identified and then applied. Empirical verification and quantification of the effects of these constraints and other constraints remain as future tasks.

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