A Three-Finger Gripper for Manipulation in Unstructured Environments

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Abstract

This paper describes a gripper for manipulation in natural, unstructured environments. The specific manipulation task is to pick up surface material such as pebbles, or small rocks, in a natural terrain. The application is to give autonomous sampling capabilities to an autonomous vehicle for planetary exploration. We describe the task analysis process that led to the selection of a configuration with three "soft" fingers. We carry out a complete analysis of the stability of a grasp for this gripper including an analysis of the deformation of the fingers at the points of contact. Finally, we describe the implementation of a grasp selection algorithm and present results on three-dimensional representations of objects computed from range data.

1 Introduction

The challenge in autonomous manipulation in unstructured environments is to be able to deal with many different situations (terrain configuration, object shape, etc.) that are encountered in the course of a single mission.

This paper addresses one aspect of the problem, that is the design and use of a gripper for manipulation of natural objects. Specifically, the task that we face is to pick up small rocks and pebbles of arbitrary shape and size in a natural environment. The only assumptions are that the shapes are reasonably smooth and that the sizes are bounded by known min and max values.

The motivation for this task is autonomous planetary exploration in which an autonomous mobile robot has to navigate and collect surface samples (e.g., small rocks or pebbles) for scientific analysis. This work is part of the CMU Ambler project [1].

We could use a general purpose gripper to perform the task. Such a gripper, however, may lead to less reliable grasping strategies and may require a complex analysis. Our approach is instead to analyze the task to design a special-purpose gripper that gives us the best compromise between appropriateness to the task, reliability, and simplicity.

The emphasis of the paper is on the use of complete three-dimensional representations of object to carry out a complete analysis of the grasp selection problem. The paper is organized as follows: In Section 2 we analyze the task to select a gripper configuration. We also introduce the object representation used to compute the grasp position. The design of the selected gripper is presented in Section 3. We conduct the theoretical analysis of the stability of a grasp in Sections 4 and 5. Section 4 studies the properties of the contact between one finger and the object, Section 5 studies the stability of a grasp given the contact with all the fingers. Finally, we describe the implementation of the grasp selection algorithm in Section 6.

2 Task analysis

To design a system that performs autonomously, we need to design perception, representation, and manipulation modules. Two requirements are usually in conflict during the design phase: the need for a system that is general enough to perform the task in all cases and the need for a robust system. In this Section, we describe how task analysis leads to the design of a gripper and a grasping strategy.

The task analysis problem can be stated as: Given a task and some knowledge of the environment, and given a set of perception capabilities (sensors, segmentation algorithms, representations, etc.), select a grasping strategy, a manipulator configuration to implement the strategy, an appropriate representation of the environment, and a sequence of algorithms that construct the representation for sensor data. We have applied this paradigm to the problem of grasping isolated objects resting on soft ground and to the problem of bin-picking of man-made parts [8]. In this Section, we briefly describe the task analysis process that lead to the design of the gripper for the problem of manipulating smooth natural objects, typically rocks, in a cluttered environment.

Grasping In order to study the grasping system design, we have to determine how many grasping strategies are available. Taylor and Schwarz [14] classified the grasping strategies into six categories (Figure 1).

Among the six grasping strategies, workspace and grasping stability decrease in the listed order [13]. Thus, we prefer to use the grasping strategies in the listed order, if possible.
In the case of cluttered environments, the workspace is reduced because of the objects surrounding the target object. Therefore, we need to step down the list of grasping configurations to find a configuration that requires a smaller workspace while keeping the highest possible level of reliability. The first configuration that satisfies those criteria is a three-finger gripper (Figure 2) that can realize palmar grasping. To achieve greater stability of the grasps, the gripper has soft fingers in that the surface of the fingers is deformed as it enters in contact with the object [6].

Perception and representation To be able to manipulate objects in the scene, the manipulation system needs geometric descriptions of the objects built from sensor observations. Since geometric information is needed, using a range sensor is the natural choice. The selection of the geometric representation that must be computed from range data is more difficult because we need a representation that fits the data closely and that can handle arbitrary shapes. As shown in [2], this can be achieved by the use of deformable surfaces that are the 3-D equivalent of the 2-D “snakes” widely used in Computer Vision [9]. Deformable surfaces are essentially rubber sheets that are stretched to fit the data closely, to be at the same time consistent with the salient surface features, and to be reasonably smooth. The algorithms used for extracting such representations from range data are described in [2].

For each object, the final representation is a discrete surface that approximates the shape of the object. Typically, discrete surfaces with 500 points are sufficient. The model of the object of Figure 3 is shown in Figure 4 as wireframe and shaded displays.

3 Gripper design
The gripper uses air pressure technology like its manipulator. The three fingers slide on two pairs of rods in order to remain parallel. Figure 2 shows the idea of the mechanism that uses only rods and aluts. Plastic washers were inserted between all the metal pieces that slide on each other. Each finger is made of a metal rod that is screwed into the fingerholder which is enclosed by a rubber pipe that was chosen for its good friction properties. The rubber is compliant so that the surface of the finger is deformed as it enters into contact with the object. This is an implementation of the idea of “soft” fingers. There are three shreds in each fingerholder in order to have different selectable initial positions of the fingers. It also allows the gripper to deal with objects of different sizes. The fingerholders were made out of plastic to improve their grasp of the metal rods.

Palmar grasping is achieved by selecting one of the two positions of IO and F1, and by opening and closing F2. Tip grasping can also be achieved by using only fingers IO and F1 and keeping F2 open.

4 Analysis: properties of the contact finger/object
The first step in the analysis of the gripper is to determine the properties of the contact between each individual finger and the surface. The goal of the analysis is threefold. First, it provides a model of the deformation of a finger as it enters into contact with the object. Second, it yields an expression of the friction forces as a function of the local shape of the surface and the force applied on the finger. Third, it leads to a criterion to evaluate the local stability of a contact finger/surface.

We derive these results in three stages from a simple case, single contact point with normal force, to the more complex case of a single contact point with arbitrary force direction, to the general case of multiple contact points with arbitrary force. The analysis is similar to the ones in [6] and [12].

4.1 One point of contact/normal force
Assumptions We first need to study the local deformation of the finger as it enters into contact with the surface. To do that, we make the following assumptions:

- Elasticity of the finger: the finger is considered as a cylinder of elastic material described by its Poisson ratio, \( \sigma \), and its Young modulus \( E \).
- Rigidity of the object: The object is perfectly rigid.
- Quadratic approximation: The surface of the object around the point of contact can be described by a quadric surface. More precisely, the surface normal, \( \hat{N} \), the two principal curvatures, \( \hat{K} \) and \( \hat{\kappa} \) along with the corresponding principal directions, \( \hat{V}_1 \) and \( \hat{V}_2 \) define a quadric surface that locally approximates the object surface around the point of contact (Figure 5). By convention, \( \hat{K} \) is always the smallest curvature. By convention, \( \hat{N} \) points outward, and a curvature is positive if the corresponding center of curvature lies within the object.
- Small deformations: The deformations of the finger are small compared to its size. This assumption ensures that local approximations by quadratic surfaces of both the surface of the finger and the surface of the object can be used.

Analysis of the deformations Under those assumptions, as the finger enters in contact with the surface at a single point with a force \( \vec{F} \) along \( \hat{N} \), the finger is deformed according to the local shape of the surface. Since the force is exerted along the normal to the surface, a symmetry argument shows that the local shape of the finger is a quadric surface whose principal directions are parallel to \( \hat{V}_1 \) and \( \hat{V}_2 \). The area of contact is therefore an ellipse of elongations \( a \) and \( b \) along \( \hat{V}_1 \) and \( \hat{V}_2 \). To conduct the analysis of the contact we need to compute the normal force \( \vec{F}_n \) and the friction force \( \vec{F}_f \) for the stability analysis and the pressure \( P \) at each point of the area of contact for the friction analysis. To compute these quantities, all we need to know are \( a \) and \( b \), and the depth of penetration of the object into the finger, \( h \). The quantities \( a \), \( b \), and \( h \) can be estimated using a standard elasticity model. Since no analytical expression can be derived in general, we use a discrete approximation leading to a deviation of less than 1% between theoretical and computed values. Due to space constraints, we cannot include those calculations in this paper. The reader in referred to [4] for a detailed derivation.

Given \( a \), \( b \), and \( h \), the magnitude of the normal force \( F_n \) is given by [11]:

\[
F_n = L h^{3/2}
\]

where \( L \) depends on the shape of the object, the orientation of the finger, and the elongation of the contact region, \( a/b \). The computation of \( L \) is described in [4].
The pressure at a point \((x,y)\) in a coordinate system centered at the point of contact with axes parallel to \(V_1\) and \(V_2\) is given by [11]:

\[
P(x,y) = \frac{3F}{2 \pi h(b^2 - x^2)^{1/2}} = \frac{y^2}{b^2}
\]  

(2)

**Friction forces** The magnitude of the friction force is the integral of a function \(f\) of the pressure over the area of contact [10]. Different models of friction have been proposed leading to different expressions for \(f\). The special case \(f = \text{constant}\) is the classical Coulomb friction. Although we have run simulations for various models of friction, we consider only the Coulomb friction in the implementation.

### 1.2 One point of contact/arbirtary force

In the case of an arbitrary force, a phenomenon of rolling can occur, that is the center of the finger may be subject to a small displacement \(\mathbf{e}\) in the direction perpendicular to the direction of contact. We assume that it is negligible compared to the penetration of the object into the finger, therefore \(\mathbf{e} \ll h\). We define \(\mathbf{f}_n\), the normal force at the surface of the object as the projection of \(\mathbf{F}\) on the normal \(\mathbf{N}\). We also define \(\mathbf{f}_t\), the tangential force, as \(\mathbf{F} - \mathbf{f}_n\). Therefore, the previous assumption yield to the case of the normal force only.

The quantities \(\mathbf{f}_n\), \(\mathbf{P}\), and \(\mathbf{f}_t\) all depend on the physical characteristics of the finger described by the two numbers \(\sigma\) and \(E\). In practice, it is not possible to determine these numbers exactly. It is important to note, however, that we are interested in the behavior of \(\mathbf{f}_n\) as a function of \(\mathbf{F}\), of the direction of the finger, and of the local geometry of the surface. We are interested in the relative values of \(\mathbf{f}_n\) for different configurations since they are used to select the best configuration. Therefore, we need only an estimate of \(\sigma\) and \(E\) for our purpose.

In the rest of the paper, we will assume that the friction force follows Coulomb's rule: \(T < \mu N\). When the area of contact is large enough, there may be, in general, a moment about the center of contact in addition to tangential and normal forces [5, 7]. We will neglect this effect here. A brief discussion of the rolling effect is presented in Section 4.2.

### 4.3 Several points of contact/arbirtary force

In the case of several points of contact between finger and object, we have a normal force vector \(\mathbf{f}_n\) for each contact point \(P_i\). Given the input force \(\mathbf{F}\), each normal force vector is computed as described in 4.1. The tangential force is given by the system of equations:

\[
\mathbf{T} + \sum \mathbf{f}_n = \mathbf{F} \quad \mathbf{T} \cdot \sum \mathbf{f}_n = 0
\]  

(3)

Equation 3 completely defines all the forces at the points of contact assuming that the number of contact points and their locations \(P_i\) are known.

Once the contact points, normal forces, and tangential forces are computed, the case of multiple contact points can be reduced to the previous case by calculating the characteristics of a single virtual contact point:

\[
P = \frac{1}{N} \sum P_i f_n = \sum f_n \quad \mathbf{T} = \mathbf{F} - \sum f_n \quad \mathbf{M} = \sum P_i \times f_n
\]  

(4)

where \(N\) is the number of contact points. \(P\) is the equivalent contact point, \(f_n\) and \(\mathbf{T}\) are the equivalent normal and tangential forces, and \(\mathbf{M}\) is the torque generated by the set of contacts. Equations 4 correspond to the reduction of a set of torques to a single equivalent torque. We will also combine the friction law that applies to each contact point to the friction law for the virtual contact point \(T < \mu f_n\).

### 5 Analysis: equilibrium of a grasp

In this Section, we study the equilibrium of an object in contact with the three fingers. The resulting equilibrium criterion is used in Section 6 to compute the best grasp position.

The object is in static equilibrium if there exist a point \(Q\) such that

\[
\sum \mathbf{F}_i + m\mathbf{g} = 0 \quad \sum QP_i \times \mathbf{F}_i + \sum M_i + \mathbf{G} \times m\mathbf{g} = 0
\]  

(5)

where \(\mathbf{F}_i\), \(P_i\), and \(M_i\) are the parameters of the contacts between each finger and the object, and \(G\) is the center of gravity of the object. Assuming that we can neglect \(m\mathbf{g}\) compared to \(\mathbf{F}\), and that we can neglect the torques \(M_i\), we obtain:

\[
\sum \mathbf{F}_i = 0 \quad \sum QP_i \times \mathbf{F}_i = 0
\]  

(6)

The first assumption is justified because the object's weight is always considerably smaller than the forces applied in practice. The second assumption is justified by the fact that the distances between the contact points of a single finger are small compared to the object size.

Equation 6 implies that the forces must be coplanar and must intersect at \(Q\). Given Equation 6 the equilibrium problem consists in finding such a point \(Q\). \(Q\) is always inside the polygon defined by the intersection of the plane formed by the three contact points and of the three friction cones of vertices \(P_i\) and half angle \(\alpha\) such that \(\mu = \tan \alpha\).

The construction of the polygon is illustrated in Figure 6. A given triplet of contact points is an equilibrium position if and only if the polygon is not empty. This yields only an existence condition for the equilibrium. If the polygon is not empty, \(Q\) is the point that minimizes the energy among all the possible points inside the polygon [3].

### 6 Implementation

In this section, we address the problem of finding the best grasp position given a description of the object surface in terms of a triangulated surface as described in Section 2. We describe the implementation in four steps. First, we solve the problem of determining the contact points between one finger and the surface given an approach direction for the finger. Then, we described the algorithms used to compute the parameters of the object surface around a point of contact: curvatures and principal directions. After defining a reference frame for the three finger system, we describe the algorithm for selecting the best grasp position.

#### 6.1 Determination of contact points and contact geometry

The approach direction of a finger toward the object is defined by a line \(\Delta\). The points of contact are the points of the surface that
are tangent to a circle of radius $R$, the radius of the finger, centered on the line $A$. To find the contact points using a discrete surface, we first compute the point $P$ of the surface that is closer to $A$ and we search for the contact points in a neighborhood around $P$.

The next implementation problem is to determine the local geometry of the object's surface in the vicinity of each contact point. The quantities that describe the geometry of the surface are $\vec{k}$ and the principal directions $\vec{V}_i$. The curvatures are calculated as the two solutions of the quadratic equation, the coefficients of which depend only on the first and second derivatives of the surface. We use a discrete approximation of the derivatives since our model is discrete. Viewing the set of points in the neighborhood of the contact as a sampled version of a continuous surface $z = f(x,y)$, the second derivatives of the surface are approximated by finding a quadratic function $f'$ to the points. The size of the neighborhood is empirically chosen from the expected level of noise, the maximum surface curvature, and the radius of the fingers.

### 6.2 Definition of a frame of reference

In order to define the position of the gripper, we need a frame of reference that is attached to the three-finger system. The frame of reference is shown in Figure 7. The midpoint between fingers 0 and 1 is independent of the opening between the two fingers. Further, the direction of the vector between fingers 1 and the midpoint of 0 and 1 depends only on the orientation of the gripper and does not depend on the opening of the fingers. The orientation of the gripper is therefore entirely defined by the direction of this vector. This defines a gripper-centered frame of reference.

Since the grasp positions are computed relative to the object, we need to relate gripper frame and object frame. This done by observing that the orientation of the gripper as defined above is entirely defined by the three points of contact which in turn are completely determined by the direction of approach of one finger, for example 0. Knowing $\theta$, we can compute the contact points and the corresponding gripper orientation. The set of all possible grasp positions is therefore parameterized by $\theta$, the angle between the line $C_{0}C_{1}$ and a reference axis, where $C_{0}$ is the center of gravity of the object.

### 6.3 Determination of the best grasp position

The best grasp position is defined theoretically as the point $Q$ within the polygon defined in Section 5 that realizes the minimum of the energy of the system [3]. Finding the minimum involves a model of the entire mechanism and can be expensive. Instead, we take advantage of the fact that we use soft fingers so that the stability of a grasp position is directly related to the surface of contact between fingers and object.

Given a grasp position, we define the area of contact $S$ as the average of the areas of contact between fingers and object over all the possible configurations of forces for this grasp position. or, equivalently, the average over all the points $Q$ inside the acceptable polygon of Section 5. Taking the average over the acceptable polygon is a conservative approach that allows us to compensate for the approximations that we made. Strictly speaking, $S$ is a function of the local shape of the surface, of the physical characteristics of the finger, $D$, and of the forces applied to the fingers. In the case of a smooth surface, however, $S$ is of the form: $S \approx kS'$, where the component $S'$ is independent of the mechanical properties of the gripper and depends only on the local geometry of the surface, and $k$ depends only on $D$ and $S$. Consequently, nominal values for $D$ and $S$ can be used since only the relative values of $S$ are relevant.

Since in practice we cannot compute the average directly, we use an algorithm that decomposes the acceptable polygon into a set of small triangles. computes the area of contact $Q$ at the center of each unit, and averages the result:

1. Construct the acceptable polygon.
2. Decompose the polygon into small triangular units.
3. For each triangle:
   a. Set the intersection of the force vectors $Q$ at the center of the triangle.
   b. Compute $f_1$ and $T_i$ for each finger given $Q$.
   c. Compute the area of contact $S_i$ from $f_1$ for each finger.
   d. Add the $S_i$s to the current total $S$.
4. Compute the average by normalizing the total $S$.

If we assume that the gripper has one degree of freedom along $z$ and an additional degree of freedom about $S_b$, becomes a function $S(\theta)$ where $\theta$ is defined as in Section 6.2. In that case the best position is found by extracting the local maxima of $S(\theta)$ and by choosing the smoothest one (smallest second derivative of $S(\theta)$).

In practice, $S$ is computed for discrete values of $\theta$ ranging from $0^\circ$ and $90^\circ$ with a $1^\circ$ increment. The local maxima are found by comparing each value with its neighbors.

Figures 8 and 9 show the simulation results on an ellipsoid. The function $S(\theta)$ is shown in polar coordinates: the distance between each point of the curve and the center of gravity of the object is proportional to $S$. The impossible positions in which the object would immediately slip out of the fingers are displayed as $S = 0$. Figure 8 shows a possible but unstable grasp position. The position is unstable because the $S$ is non zero only in a very narrow interval around the position. Figure 9 shows an unacceptable grasp position: the search polygon is empty and the object will slip through the fingers. Figure 10 shows a stable grasp: $S$ is a local maximum and is stable.

Figures 11 to 12 show the result of the grasp selection algorithm on the object of Figure 4. The left part of Figure 11 shows the evaluation of the possible grasp position on the model. The right part shows the best grasp position. Figure 12 shows the actual grasping operation.

### 7 Conclusion

We have described the design of a simple three-finger gripper with "soft" fingers for manipulation in natural environments. The gripper is designed to realize a good compromise between limited workspace and robust grasping. The design is based on a systematic analysis of the task including the type of object representation that must be used for the evaluation of grasp positions. We purposefully avoided a general-purpose gripper design. Instead, we choseadesignatthissufficientforthe task and for which a detailed stability analysis can be carried out. The gripper was demonstrated on real scenes using threedimensional representations of objects that are essentially triangulated surfaces. The automatic grasp selection demonstrated in Section 6 is essentially 2-D, that is there.
is only one degree of freedom in rotation. The algorithms are extended to three dimensions by adding another angle of rotation of the gripper. This involves modifying the surface representation to mark points that are not visible in the original sensor data to avoid computing grasp positions that are not accessible. We are now working in incorporating the gripper in a complete manipulation and perception system.

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References

Figure 4: Wireframe (left) and shaded (right) displays of surface model.

Figure 5: Local geometry of a contact.

Figure 6: Acceptable polygon.

Figure 7: Frame of reference.

Figure 8: Unstable position.

Figure 9: Impossible grasp: slipping will occur.

Figure 10: Stable grasp.

Figure 11: Evaluation of the grasp positions: total area of contact as a function of gripper orientation (left); best grasp position (right).

Figure 12: Grasping operation.