Sequential Improvement of Grasp based on Sensitivity Analysis

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Outline

- Introduction
- Problem Formulation
- The Sequential Grasp Improvement (SGI) Algorithm
- Simulation Results
- Discussion
Motivation

- Complex human-like multifingered robot hands.
- Demanding applications (e.g. household/medical/space robotics) → Demanding Grasp Specifications (e.g. task specificity, precision, safety, power saving)
- Constraints (hand’s structure, object geometry, surrounding Environment etc.)

Grasping can become a multiparametric problem.

*Sensitivity Analysis*: “how sensitive is the state of a system to perturbations of its parameters”.

Algorithm that determines the parameters’ perturbations that improve the grasp.

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Our Approach: Post-Optimal Grasp Improvement

Given:
- an initial *random force closure grasp* with a *locally optimal* force distribution
- *local* knowledge of the grasped object’s surface geometry around the contacts

we address the problem of *on-line improving the grasp*.

This is achieved by *sequentially perturbing*:
- the contact points
- the wrist’s position/orientation towards the directions of the desired Grasp Improvement.

*Sequential optimal states $s^*$ wrt the function $z(f,p)$*
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Modeling

- **Multifingered Robot Hand**
  - $n_c$ fingers
  - $n_q$ joints
  - Contact Force distribution $f$
  - Joint displacements $q$

- **Object**
  - Object center of mass
  - Weight
  - (Local) Surface Geometry information around the contacts

- **Contacts**
  - Friction coefficient $\mu$
  - Hard Finger Model

*Infinite ways to grasp it*

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Aspects of Grasp Quality

- **Force Closure**: Fundamental Grasp Property (object equilibrium & friction cone inequalities) → “Stable Grasp”

- **Contact Force Minimization**: e.g. Norm of the Normal Contact Force Components:
  \[ F(f) = \sqrt{\sum_{i=1}^{n_c} f_{ni}^2} \]

- **Singularity Avoidance**: e.g. Volume of the Manipulability Measure
  \[ M(q) = \sqrt{\text{det}(J(q)J(q)^T)} \]

- **Mechanical Joint Constraints**: e.g. Distance from Mechanical Joint Limits
  \[ Q(q) = \sum_{i=1}^{n_q} \left( \frac{q_i - q_{0i}}{q_{\text{max}_i} - q_{\text{min}_i}} \right)^2 \]

- **Adopted Combined Quality Function**:
  \[ z = w_1 \cdot F(f) + w_2 \cdot \frac{1}{M(q)} + w_3 \cdot Q(q) \]
Grasping Force Optimization as a general NLP

NLP for deriving a minimal force distribution that guarantees the **Force Closure** sufficient conditions:

\[
f^* = \arg\min_f F(f) := \sqrt{\sum_{i=1}^{n_c} f_n^2}
\]

s.t.

\[
h(f^*, p) = 0
\]
\[
g(f^*) \leq 0
\]

Where:

- **h** ➔ Balance Equations
- **g** ➔ Friction Cone inequalities
- **f** ➔ Contact Force Distribution (decision variables)
- **p** ➔ System Parameters (**contact points, wrist position/orientation**) considered **constant**
KKT First Order Necessary Conditions

In a local minimum of $F$, the Karush-Kuhn-Tucker (KKT) conditions hold:

$$
\nabla_f F(f^*) + \lambda^*^T \nabla_f h(f^*, p) + \mu^*^T \nabla_f g(f^*) = 0
$$

$$
h(f^*, p) = 0
$$

$$
g(f^*) \leq 0
$$

$$
\mu^*^T g(f^*) = 0
$$

$$
\mu^* \geq 0
$$

Where:

$\lambda^* \rightarrow$ Lagrange Multipliers for the equality constraints

$\mu^* \rightarrow$ Lagrange Multipliers for the inequality constraints

System parameters considered constant $\rightarrow$ also a local minimum for the combined quality metric

$$
z(f, p) = w_1 \cdot F(f) + w_2 \cdot \frac{1}{M(p)} + w_3 \cdot Q(p)
$$

wrt $f \rightarrow$ KKT hold for $z$ as well.
Deriving the Directions of Grasp Improvement I

Through total differentiation of the KKT conditions for the objective function $z$, we can demand that the KKT conditions continue to hold after small perturbations $dp$ of the parameters:

\[
(\nabla_f z(f^*, p))^T \, df + (\nabla_p z(f^*, p))^T \, dp - dz = 0
\]

\[
\left( \nabla_{ff} z(f^*, p) + \sum_{j=1}^{n_c} \mu^*_j \nabla_{fj} g_j(f^*, p) \right) \, df
\]

\[
+ \sum_{k=1}^{6} \lambda^*_k \nabla_{fp} h_k(f^*, p) \, dp + \nabla_f h(f^*, p) \, d\lambda
\]

\[
+ \nabla_f g(f^*, p) \, d\mu = 0_{3n_c}
\]

\[
(\nabla_f h(f^*, p))^T \, df + \nabla_p h(f^*, p)^T \, dp = 0_6
\]

\[
(\nabla_f g(f^*)^T \, df = 0_{nc}
\]
Deriving the Directions of Grasp Improvement II

We rewrite the equations in matrix form as:

\[
\begin{bmatrix}
    \frac{df}{dp} & \frac{df}{d\lambda} & \frac{df}{d\mu} & \frac{df}{dz} \\
    \frac{d\lambda}{dp} & \frac{d\lambda}{d\lambda} & \frac{d\lambda}{d\mu} & \frac{d\lambda}{dz} \\
    \frac{d\mu}{dp} & \frac{d\mu}{d\lambda} & \frac{d\mu}{d\mu} & \frac{d\mu}{dz} \\
    \frac{dz}{dp} & \frac{dz}{d\lambda} & \frac{dz}{d\mu} & \frac{dz}{dz}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    z_f \\
    z_{ff} + \sum_{j=1}^{n_c} \mu_j^* g_{ff} \\
    \beta^T_f h_f \\
    \gamma_f g_f
\end{bmatrix}
\begin{bmatrix}
    \frac{dp}{dp} & 0 & 0 & 0 \\
    \frac{d\lambda}{dp} & 0 & 0 & 0 \\
    \frac{d\mu}{dp} & 0 & 0 & 0 \\
    \frac{dz}{dp} & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\end{bmatrix}
\]

and separate the components associated with the system parameters \( p \) from the other components \((f, \lambda, \mu, z)\) as:

\[
U^{-1} S = 0
\]

Partial Differentiation of both sides wrt \( p \)

Inversion of \( U \)

\[
D = \begin{bmatrix}
\end{bmatrix} = \begin{bmatrix}
\end{bmatrix}
\]

Step that minimizes \( z \)

\[
1^{st} \text{ order approximation of the new values}
\]

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Introduction

Problem Formulation

The Sequential Grasp Improvement (SGI) Algorithm

Simulation Results

Discussion
Sequential Grasp Improvement (SGI) Algorithm

Start

Initialization: Grasping Force Optimization

Calculation of Sensitivities ($f$, $\lambda$, $\mu$, $z$)

Step Determination ($dp$)

First Order Approximation of the new values of $f^*$,$\lambda^*$,$\mu^*$,$z^*$

Hand Movement

- Feasible Configuration
- No Fingers Collision
- Grasp Improvement “Significant”

End

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The DLR/HIT II five-fingered robot hand: 5 identical fingers, 15 DOFs in total.
Simulation Results: Cylindrical Object

Cylinder (diameter 6 cm, height 15 cm, weight 200 gr) | Friction Coefficient at the contacts: \( \mu = 0.8 \)

The initial and the final hand configuration as well as the contact points and wrist transitions.

Grasp Quality: Comparative illustration of the cost function components.

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Simulation Results: Spherical Object

The initial and the final hand configuration as well as the contact points and wrist transitions.

Comparative illustration of the cost function components.

Sphere (diameter 4 cm, weight 200 gr) | Friction Coefficient at the contacts: $\mu=0.8$

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Simulation Results: Video Example
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Contributions

- General Framework for on-line improving the Grasp Quality.
- Only requires local information of the object surface (around the contacts)→ can be acquired by a tactile/force/vision sensor suite → Generalization for objects of unknown geometry.
- Simulation verification for a real multifingered robot hand (DLR/HIT II).
- Confrontation of mechanical and geometrical constraints, imposed by the hand and the object.
- Low Complexity (1 matrix inversion per loop).

Future Work

- Experimental Verification of the Algorithm with the DLR/HIT II.
Acknowledgements

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Thank You !
Related Work

Grasp Quality Optimization:
Many different approaches, criteria and algorithms.


Sensitivity Analysis:

• Adelman et al. – “Selecting step sizes in sensitivity analysis by finite differences”, National Aeronautics and Space Administration, Scientific and Technical Information Branch, 1985