Selecting a Suitable Grasp Motion for Humanoid Robots with a Multi-Fingered Hand

Tokuo Tsuji, Kensuke Harada, Kenji Kaneko, Fumio Kanehiro, and Yoshihiro Kawai

Intelligent Systems Research Institute,
National Institute of Advanced Industrial Science and Technology (AIST), Japan

Abstract—This paper discusses grasp planning of a multi-fingered hand attached at the tip of a humanoid robot’s arm. Our planner can select a different grasping style even for the same object if a position/orientation of the object is changed. Also, if the planner cannot find a feasible grasping posture with arm/hand kinematics, a humanoid robot tries to use the whole body motion. These functions are necessary for realizing the robust grasp planning. Our planner defines convex models on both the object and each grasping style. By considering geometrical relationship among these convex models, we determine several parameters needed to define the final grasping configuration. The effectiveness of the proposed method is confirmed by several numerical examples and experimental results.

I. INTRODUCTION

We focus on grasp planning of a multi-fingered hand attached at the tip of the humanoid robot’s arm. A multi-fingered hand has potential possibility to grasp several objects under several situations. However, this grasp planning often becomes difficult due to its complexity. To plan a grasping motion, we have to first select a feasible grasping style[19] according to the required task. Then, we have to determine contact positions on both the fingers and the grasped object surface. The contact positions have to be determined so that the fingers can grasp the object without dropping it and has to keep the limit of the actuator power. Finally, we have to plan the motion of the humanoid robot achieving the required grasping task.

Fig. 1 shows the humanoid robot HRP-3P [22] where a four-fingered hand[21] is attached at the tip of the right-arm and where a stereo camera system is attached at the head. Let us consider actually performing some task by using this humanoid robot. So as to grasp an object, the humanoid robot will first measure position/orientation of the object by using the visual sensor. Then, based on the information taken by the visual sensor, the grasp planner plans the whole body motion of the humanoid robot finally realizing the grasping task. Although the grasp planning is complex, the robot should complete the grasping task as fast as possible even if the position of the object is not known in advance. Hence, for the grasp planning, a heuristic but fast algorithm is preferred rather than precise but time-consuming algorithms[3].

This paper is an extended version of our previous work[1] where the grasp planning was calculated within the reasonable time taking into account several constraints imposed on the grasp system such as the feasible grasping style, the friction cone constraint at each contact point, the maximum contact force applied by the fingers, the inverse kinematics of the arm and the fingers etc. This paper aims to improve the reliability of the proposed planner and confirms the effectiveness. The originality of this paper is the following three points; Firstly, a human changes the grasping style depending on the position/orientation of the grasped object. As shown in Fig.2, while a human grasps the side of the can with all the fingers, he/she grasps the top of it with just some of the fingers. Especially for the case of the robotic hands, it is often difficult to put all the fingers on the top of such a can. Secondly, for the purpose of grasping a heavy object firmly, the human sometimes try to grasp the object by using the whole body motion. With our planner, if the planner failed in finding the feasible grasping posture only by using the arm/hand kinematics, the planner tries to use the whole body kinematics. Thirdly, we confirmed the effectiveness of our proposed approach by experiment. We used the robot system shown in Fig. 1 and planned the grasping
motion by using the information obtained from the stereo vision system attached at the head. This paper is organized as follows: After showing the related works in Section 2, we explain our proposed algorithm in Section 3. In section 4, we show several numerical examples and experimental results.

II. RELATED WORKS

As for the works on grasp planning, there are a number of works on contact-level grasp synthesis such as [11], [12], [10]. As for the grasp planning considering the hand/arm model, Cutkosky[2] first proposed an expert system to select one of the grasp styles based on the grasp quality measures. Pollard[9] proposed a precise grasp planning algorithm by utilizing heavy computation. Morales et al.[8] proposed a planning method applicable to the Barret hand. Morales et al.[17] also proposed a method of planning a grasp by preparing the candidate grasping style corresponding to the grasped object. Prats et al.[18] proposed a method of for planning the hooking task of a door.

Recently, some researchers researched the fast grasp planning problem. Borst et al.[14] proposed a planning method to determine contact positions of a four-fingered hand assuming a fingertip grasp. Miller et al.[5] uses a grasping simulator[6] and proposed a method for determining candidates of a contact point set for grasp planning. Their method calculates $1 \sim 44$ candidates of grasp configuration between $11.4$[s] and $478$[s] depending on the complexity of the object’s shape. Their approach was extended to the learning approach [7] and imperfect visual information [4].

As for the grasp planning based on a random sampling approach, Niparnan[10] and Borst et al.[13] proposed a method to realize the force closure using the random sampling. Yashima et al.[16] proposed a manipulation planning based on the random sampling.

III. GRASP PLANNING

A. Reference Posture and Rectangular Convex

When a human grasps an object, a human selects one of the grasp styles according to the shape and the estimated mass of the object. Fig.3 shows some of the grasp styles shown in the book [19].

We assume that the shape of the object is given by a polygon model such as VRML. For given shape of the object, the grasp planner has to automatically select one feasible grasp style. For realizing this function, we assume the reference posture as shown in Fig.4. For each reference posture, we assigned the finger links contacting with the object. In this research, we constructed the reference grasping posture for three-fingered fingertip grasp, four-fingered fingertip grasp, and four-fingered enveloping grasp. We also constructed the reference posture for small, mid and large sized objects. We manually constructed these reference postures.

For each reference posture, we assumed the grasping rectangular convex (GRC). The GRC is used to select the feasible grasping style for given grasped object. As shown in Fig. 5, we assumed three GRC. The GRCmax is the maximum size of the recutangular-shaped grasped object without interfering the finger links. The GRCmin and the GRCdes are the assumed minimum and desired sized grasped object.

By modifying the reference posture, the actual grasping posture is planned by using the method explained in the next section. For the $i$-th grasping style with the GRCmax which position/orientation is $\vec{p}_{\text{max}}$, $\vec{R}_{\text{max},i}$ $(i = 1, \cdots, n)$, we assume the vector of the edge length $\vec{e}_{\text{max},i}$ of the GRC. This vector is used to select the grasping style. Also, we assume the approach vector $\vec{d}_{\text{max},i}$. This vector defines the approach direction to the object and is one of the outer unit normal vector of the GRC’s surface. Furthermore, we assume the maximum and the minimum mass, $m_{\text{max},i}$ and $m_{\text{min},i}$ of the object grasped by using the $i$-th grasping style.

Next, we focus on the object to be grasped. Given the shape of the object, we calculate the object convex polygon (OCP).
The OCP is the minimum sized convex polygons including the grasped object. In this paper, we consider the case where the rectangular convex is used as the OCP. For complex shaped objects, we consider splitting the object into some regions and calculate the OCP. Fig.6 shows the OCP of the vase placed on the table. We split the object into three regions.

Once the polygon model of the grasped object is given, we have the set of points included in the surface of the object. By using the eigen vectors of the co-variance matrix of the point set, we can calculate the OCP. For the i-th OCP which position/orientation is \( p_{oi}/R_{oi} \) \( (i = 1, \ldots , m) \), we assume the vector of edge length \( e_{ei} \).

Miller et al.[5], [7] also used the convex model for the grasped object. In this research, in addition to the OCP, we use the GRC and determine the grasping style and the nominal grasping posture.

### B. Nominal Position/orientation of Palm

Let us consider selecting one of the grasping styles and determining the nominal position/orientation of the palm. For such purpose, we introduce some heuristic rules in this subsection. We first focus on the geometrical relationship between the GRC and the OCP. Let \( \text{sort}(a) \) be the function replacing the elements of the vector \( a \) in a decreasing order. We impose the following conditions:

\[
\begin{align*}
\mathbf{b}_{\max,ij} &= \text{sort}(\mathbf{e}_{\max,i}) - \text{sort}(\mathbf{e}_{\min,j}) > 0 \\
\mathbf{b}_{\min,ij} &= \text{sort}(\mathbf{e}_{\min,j}) - \text{sort}(\mathbf{e}_{\max,i}) > 0 \\
&\quad i = 1, \ldots , n, \quad j = 1, \ldots , m
\end{align*}
\]

If \( \mathbf{b}_{\max,ij} > 0 \) and \( \mathbf{b}_{\min,ij} > 0 \) are satisfied, the OCP can be included inside the GRCmax. In this case, the hand may be able to grasp the object by using the i-th grasping style. Also, we use the following function to select the grasping style:

\[
I_{ij} = \frac{||\text{sort}(\mathbf{e}_{\min,j}) - \text{sort}(\mathbf{e}_{\max,i})||}{ \sum_{i=1}^{n} \sum_{j=1}^{m} ||\text{sort}(\mathbf{e}_{\min,j}) - \text{sort}(\mathbf{e}_{\max,i})||}
\]

Let \( m \) be the mass of the object. We also impose the following conditions:

\[
\begin{align*}
\delta m_{\max} &= m_{\max,i} - m > 0 \\
\delta m_{\min} &= m - m_{\min,i} > 0
\end{align*}
\]

If there are multiple candidates of grasping styles, we preserve this multiple candidates and proceed to the next stage of finding the nominal palm position/orientation. Due to this function, the robot can select the different grasping style for a same object if the position of the object is changed.

Once the grasping style is determined, we next determine the nominal position/orientation of the palm. Fig.7 shows the overview of the method. Let us focus on the surface of the GRCmax having the approach vector \( d_{ri} \) as its normal. Assuming that this surface is parallel to one of the surface of OCP and that the center of GRC coincides with the center of the OCP, there are four possibilities for the orientation of the GRC as shown in (b),(c),(d) and (e). For this example, the posture of the GRC shown in (b) and (d) is not feasible since the GRCmax does not include the OCP even if the GRC moves to the direction of the approach vector. On the other hand, for the position/orientation of the palm shown in (a) and (c), we try to solve the inverse kinematics of the arm. If the inverse kinematics problem has a solution, we have a candidate of the nominal position/orientation of the palm. We iterate this calculation for all the surface of the OCP without contacting another OCP.

In case where we have multiple candidates of the nominal position/orientation of the palm, we have to choose one. In this research, we applied the nominal position/orientation of the palm where the norm of joint angles of the wrist is minimum.

### C. Force Closure Condition

By using the nominal position/orientation of the palm, now we determine the final grasping posture. The grasping posture is determined so as to satisfy several constraints imposed on the grasp system.

The grasped object has to resist the external wrench without breaking the contact. For this purpose, we formulate the wrench set generated at a point in the object. In our method, we consider approximating the friction cone constraint by using multiple ellipsoids.
Let us consider the contact force $f_i (i = 1, \cdots, n)$ applied at the $i$-th contact point position $p_i$. One of the ellipsoids approximating the friction cone can be expressed as

$$(f_i - f_{\text{max}} n_i)^T U_i U_i^T (f_i - f_{\text{max}} n_i) \leq 1$$

where $S = \text{diag}[\mu_{\text{max}}, \mu_{\text{max}}, \alpha_{\text{max}}]$ and $U_i$ is a $3 \times 3$ matrix composed of the unit normal and tangent vectors. By using this equation for $n$ contact points, the set of the wrench $w$ generated by the object can be given by

$$f(p_1, \cdots, p_n) =$$

$$(w - f_{\text{max}} G N)^T (G U^{-1} G^{-1}) (w - f_{\text{max}} G N) \leq n$$

where

$$G = \begin{bmatrix} I & \cdots & I \\ \gamma p_1 \times & \cdots & \gamma p_n \times \end{bmatrix},$$

$$N = [n_1 \cdots n_n]^T,$$

$$U = \text{block diag}[U_1 U_1^T \cdots U_n U_n^T].$$

This method is useful since we can check the force closure condition very quickly just by calculating the left-hand side of eq.(7). However, if we use one ellipsoid for each friction cone, it would be a rough approximation. Hence, we approximated each friction cone by using multiple ellipsoids.

### D. Random Sampling

To obtain the final grasping posture, we use the random sampling technique. Let $n$ be the number of fingers. We use $2 + n$ variables to search for the final grasping posture; $\Delta p_p \in \mathbb{R}^3$, $\Delta p_i \in \mathbb{R}^3$ and $\Delta \alpha_i \in \mathbb{R}^3 (i = 1, \cdots, n)$.

As shown in Fig.8, the three dimensional vector $\Delta p_p$ expresses the position of the OCP w.r.t. its nominal position and is used to determine the position of the palm. On the other hand, $\Delta p_i$ and $\Delta \alpha_i (i = 1, \cdots, n)$ express the position of the shoulder and the $i$-th fingertip, respectively, w.r.t. its nominal position. Here, as for $\Delta p_s$ of this paper, we only use the vertical component of this vector if it is difficult to find the grasping posture assuming $\Delta p_s = 0$.

### E. Planning Algorithm

We assume that we have the polygon model of both the finger and the grasped object. To check the collision between the finger and the object, we used the software PQP (Proximity Query Package). By using PQP, even if two polygon models do not contact each other, we can calculate the distance between two models, the points on both models where the distance becomes minimum, and the unit normal vector on the points of the model’s surface.

We first explain the method to find the posture of a finger contacting the object. First, for each grasping style, we defined the links of the fingers contacting the object. Then, for each defined link, we assign a joint of a finger compensating its position. We changed the angle of the assigned joint by a small amount and checked the collision between the link and the object. We iterate this calculation until the distance between the link and the object is smaller than a predefined value.

By using the pseudocode shown in Algorithm 1, we summarize the algorithm explained in this section. In this algorithm, after confirming that $n - f(p_1, \cdots, p_n) \geq \delta f$ is satisfied, we terminate the algorithm.

### Algorithm 1 Determination of Grasping Posture for $n$ finger grasp

```
loop
  Sample $\Delta p_i$ and $\Delta \alpha_i$.
  if Arm IK is solvable then break
end loop
for $i = 1$ to $n$
  for $j = 1$ to $m$
    Sample $\Delta p_i$.
    if Finger i IK is solvable then
      if Found finger i posture contacting object then break
    end if
  end for
  if Not found finger i posture then break
end for
if $n - f(p_1, \cdots, p_n) \geq \delta f$ then break
end loop
```

### IV. Results

To confirm the effectiveness of the proposed method, we show some numerical examples. As a model of the hand/arm system, we use the 7dof arm of the HRP-3P[22] and a developed 4 fingered hand [21]. This 4 fingered hand has the thumb with 5 joints and the index, middle and third fingers.
with 4 joints. The distal joint of each finger is not directly actuated and moves along with the next joint.

We prepared 9 reference motion as shown in Fig.4. The overview of numerical example is shown in Fig.9. We used a can with 0.15[kg] placed on the table as a grasped object. For this weight of the object, the grasp planner selects 3-fingered fingertip grasp or 4-fingered fingertip grasp. For each grasping style, we make only the distal link of finger contacting the object.

As shown in Fig.10, when grasping the can at a high position, the humanoid robot grasps the can by using the four-fingered fingertip grasp. On the other hand, as shown in Fig.11, when grasping the can at a low position, the finger grasps the top of the can by using the three-fingered fingertip grasp. When grasping the top of the can, it is often difficult to grasp it by using the four-fingered fingertip grasp due to the size of the fingers.

On the other hand, we set the weight of the object as 0.35[kg] for the case of Fig.12. In this case, the humanoid robot grasps the object by using the enveloping grasp with squatting down since it is difficult to grasp the object by simply standing on the ground.

Then we performed experiment. As an grasped object, we used a 200[ml] can. We set $m_{\text{max},i}$ and $m_{\text{min},i}$ so that the hand grasps this can by using the enveloping grasp. In case of the enveloping grasp, we determined the finger posture (the 10th line of Algorithm 1) as follows: We first set that the distal (5th) link of the thumb and the 2nd and the 4th link of other fingers contact the object. Then, for the finger links contacting the object, we assigned a joint to each link supposed to make contact and adjusted the angles of this joint. If all the contacts are realized at the same time, 10th line of Algorithm 1 returns $\text{true}$. This grasp planning takes between 5[s] and 15[s] by using Pentium M 2.0[GHz] PC. If we use faster PC, then we can shorten the calculation time. However, the improvement of the proposed algorithm so as to save the calculation time is also our future research topic.

Fig. 13(a) shows the image taken by the camera attached at the head of HRP-3P humanoid robot. Three cameras are attached at the head. We used image processing software developed in VVV, AIST. Given the geometrical model of the can, the position/orientation of it was calculated by using the segmentation based stereo method. Fig. 13(b) shows the result of extracting the segment. Although it takes less than one second to obtain the position/orientation of the can, we took the image for a few times to cope with the fault of the image processing.

The image processing was performed on the same PC with the motion planner. This PC was connected to the cameras by using IEEE 1394 cable. The image taken by the camera was processed by using this PC and the position/orientation data was transferred to the motion planner. After the motion planner plans the grasping motion, the joint angle data were transferred to the CPU boards controlling the motion of the robot. Here, we have two CPU boards installed in the chest of the robot where one is used to control the multi-fingered hand and the other is used to control the rest part of the robot. The wireless LAN is equipped with the robot. A directory of the motion planner PC was mount on the CPU boards and the robot is controlled by using the joint angle data stored to this directory. As shown in Fig.14, HRP-3P successfully grasps the can by using the enveloping grasp.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we proposed an algorithm of grasp planning for hand/arm systems. By using the convex model for both hand and the object, we showed that the nominal palm position/orientation can be calculated easily. Also by using the ellipsoidal approximation of the friction cone, we showed
that the final grasping posture can be calculated within a short period of time.

We improved the performance of the planner by considering the following things; First, depending on which part of the object to be grasped by the hand, our planner changes the grasping style. We numerically confirmed that, when grasping the side of the can, the robot grasps it by using the four-fingered fingertip grasp. On the other hand, when grasping the top of the can, the robot grasps it by using the three-fingered fingertip grasp. Also, if it is difficult to find the grasping posture only by using the arm/hand kinematics, the planner tries to use the whole body motion. Finally, we confirmed the effectiveness of our planner by using experimental results.

Finally, this research was supported by the NEDO project of R&D of Intelligence for Robots Working at Institution. Also, the authors would like to express their sincere gratitude for Dr. Shuuji Kajita and Mr. Hajime Saito for their helpful discussions.

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