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Grasp Strategy Simplified by Detaching Assist Motion (DAM)

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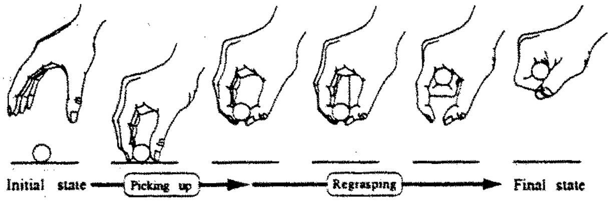
Abstract:

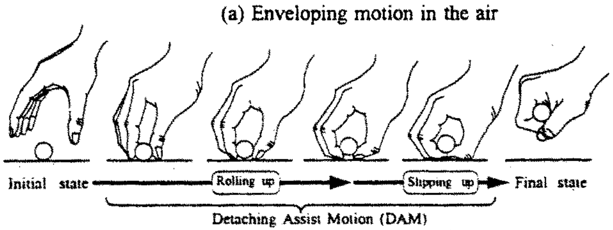
For a small object placed on a table, human easily captures it within the hand by changing the finger posture from upright to curved ones after each finger makes contact with the object. A series of this motion is called as Detaching Assist Motion (DAM). This paper discusses a generalized grasp strategy where a multi–fingered robot hand can approach an object and finally envelop it, irrespective of the size of object.

1. Introduction

For considering the grasp strategy of robot hand, human motion often provides us with good hints. Due to this reason, many researchers have discussed the classification of either final grasp patterns or grasp postures[1]–[3] learnt by human motion. On the other hand, we are particularly interesting to consider the whole grasping procedure where the hand first approaches an object placed on a table and finally achieves an enveloping grasp. Through the observation of human grasping, we learnt that human changes his (her) grasping strategy according to the size of objects, even though they have similar geometry. We called the grasp planning *Scale-Dependent Grasp*[4],[5]. Through these works, we found that human roughly switches the grasp pattern three times depending upon the size of objects. The most complicated pattern is observed for an object whose representative size is smaller than that of our fingertip, while a simple grasp pattern can work for a relatively large object. For such small objects, two characteristic patterns are observed. One is that human first picks up the object from the table, and then finally achieves the target grasp through a grasp transition from the fingertip to the enveloping grasps, as shown in Fig.1(a). The other one which is observed just by chance is that human first approaches the object until fingertips make contact with the object, and then the finger posture is changed from upright to curved ones gradually, as shown in Fig.1(b). This is what we call *Detaching Assist Motion (DAM)*. From the viewpoint of robot application, the most attractive feature of *DAM* is its extremely simple finger motion, while the grasp pattern in Fig.1(a) is so complicated that the robot hand may often fail especially in changing the phase from fingertip to enveloping grasps. The second advantage is that the *DAM* is achieved on the table in most



(a) Enveloping motion in the air



(b) Enveloping motion on the table

Figure 1. Two grasp strategies for enveloping a cylindrical object placed on a table

phases and, therefore, it is not necessary to worry about dropping the object. Due to its simple motion planning, we can easily apply it to a multi–fingered robot hand[6]. In this paper, we further intend to implement the *DAM* not only to small objects but also to other size of objects, so that we can obtain a generalized grasp strategy which is applicable for various size of object, apart from the *Scale–Dependent Grasp*.

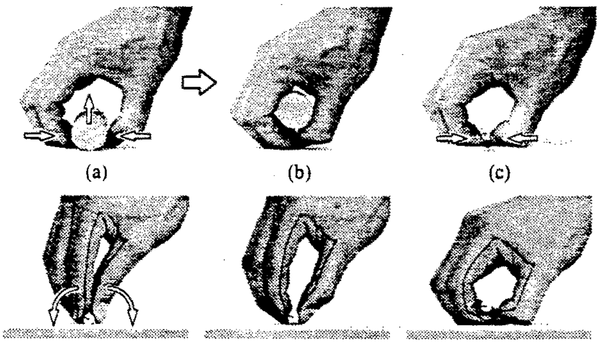
2. Related Works

Salisbury[7] has proposed the *Whole–Arm Manipulation (WAM)* capable of treating a big and heavy object by using one arm allowing multiple contacts with an object. Mirza and Orin[8] have applied a linear programming approach to solve the force distribution problem in power grasps. Bicchi[9] has showed that internal forces in power grasps can be decomposed into active and passive. Omata and Nagata[10] have considered the indeterminate contact force which does not influence on neither joint torque nor external wrench. Trinkle, Abel and Paul[11] have analyzed planning techniques for enveloping without friction. Trinkle et al.[12] have discussed the quasistatic, "whole-arm," dexterous manipulation of enveloped slippery workpieces. Kleinmann et al.[13] have showed a couple of approaches for finally achieving the power grasp from the fingertip grasp. There have been various papers discussing manipulation of object under enveloping style[14]–[16] or within the hand [17], [18].

3. Detaching Assist Motion (DAM)

3.1. What is DAM?

An enveloping grasp can be achieved by the following three fundamental phases: detaching an object from a table, lifting it up toward the palm, and firmly grasping. For detaching the object whose size is larger than fingertip, a human often utilizes the *wedge–effect* where a simple pushing motion of the bottom



(a) (b) (c)

(d-1) (d-2) (d-3)

(d) DAM for a small object

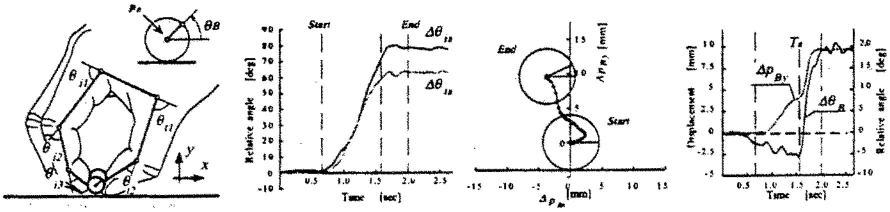
Figure 2. Grasping motion by human

part of object makes the object detach from the table as shown in Fig.2(a) and (b)[4]. Due to its simple motion planning, we can easily implement it into the grasping procedure of a multi–fingered robot hand. Either under significant friction or for an object with small diameter, we can not detach the object by using the *wedge–effect*, since the finger forces balance within the object and do not produce a lifting force any more as shown in Fig.2(c). Under such a situation, human can detach a small object without the *wedge–effect*. By changing finger posture from upright to crooked ones as shown in Fig.2(d), the object is automatically lifted up from the table. We call this grasping motion *DAM*. We would note that either a rolling or a sliding motion or perhaps both occur at the point of contact between the object and the fingertips.

3.2. Analysis of the Change of Finger Posture

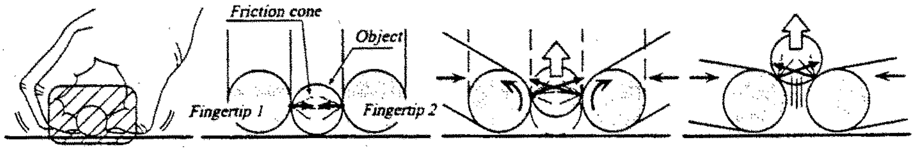
Why does the *DAM* work effectively for detaching the object from a table? What kind of principle exists behind it? In this subsection, to clarify the basic working mechanism of *DAM*, we examine both finger posture and object position while human purposely applies the *DAM* as shown in Fig.2(d). The seven markers are attached at the side of object and each joint of index finger and thumb as shown in Fig.3(a). We measure the coordinates of markers from the video image sequences recorded by video camera system, where the sampling time is 1/30[*sec*]. The absolute angle of tip of index finger θ_{ia} and thumb θ_{ta}, and the center of gravity of object $\boldsymbol{p}_B = [p_{Bx}, p_{By}, 0]^t$ can be obtained from the image sequences.

Figs.3(b) through (d) show experimental results for a cylindrical object with the diameter of 8[mm], while human utilizes the *DAM* from the initial posture (Fig.2(d-1)) to the final posture (Fig.2(d-4)), where Figs.3(b),(c) and (d) show the changes of $\Delta\theta_{ia}$ and $\Delta\theta_{ta}$, the trajectory of $\boldsymbol{p}_B$, and the change of Δp_{By} and angular displacement of object $\Delta\theta_B$, respectively, where $\Delta\theta_{ia} = \theta_{ia} - \theta_{ia0}$, $\Delta\theta_{ta} = \theta_{ta} - \theta_{ta0}$. $\Delta p_{By} = p_{By} - p_{By0}$ and $\Delta\theta_B = \theta_B - \theta_{B0}$, respectively, and subscript 0 denotes the value at initial posture (0[*sec*]). From Fig.3(b), it can be seen that both fingertips rotate uniformly with respect to time and finally keep constant in posture. An interesting behavior appears for



(a) (b) (c) (d)

Figure 3. Visual observation during *DAM*



(a) (b) Initial posture (c) Rolling-up phase (d) Wedge-effect phase

Figure 4. The basic mechanism of *DAM*

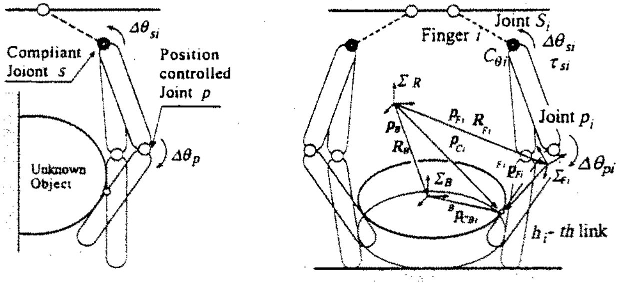
the object motion when $t = 1.57[sec](= T_a)$. At the moment of T_a, the object suddenly start to move up with rotating motion as shown in Fig.3(d), while it slowly moves before T_a.

3.3. Basic Working Mechanism of DAM

Let us consider what happen during the *DAM* by using the fingertip model as shown in Fig.4. We assume that the object is small enough to ensure that a simple pushing motion in the horizontal direction can not lift up the object as shown in Fig.4(a). Further, we simplify the fingertip model as shown in Fig.4(b). If each fingertip does not slip on the surface of object, the object will be lifted up according to the geometrical constraint between the fingers and the object as shown in Fig.4(b) and (c), while both fingertips rotate from the initial to the final postures. We call this phase *Rolling–up phase*. As the object is lifted up, the normal direction of friction cone gradually changes upwards while the contact point moves towards the bottom of object. Finally, the moment the contact force is away from the friction cone, the object slips on the surface of fingertips. Once the contact force is away from the boundary, the *wedge–effect* effectively helps to move up the object as shown in Fig.4(d). We call the final phase *Wedge–effect phase*. These are the outline of the working mechanism of *DAM*. The phase from *Rolling–up* to *Wedge–effect* is automatically switched depending upon the contact friction as well as the finger rotating motion.

4. SPCM can Simulate DAM

While several strategies for robot hands which are equivalent to the human *DAM* can be considered, we utilize compliant motion of link system having one compliant joint (*s-th*) and one position–controlled joint (*p-th*) as shown in Fig.5(a). Now, suppose that we impart an arbitrary angular displacement $\Delta\theta_p$ at the position–controlled joint for such a link system contacting with an environment. Under the condition, the link system will automatically change



(a) Object is fixed (b) Object's motion is allowed

Figure 5. Self-Posture Changing Motion

its posture while keeping contact between the environment and the link system, if $\Delta\theta_p$ is given appropriately. This series of motion is termed as *Self–Posture Changing Motion (SPCM)*[19]. *SPCM* has been conveniently utilized for detecting an approximate contact point between a link system and an unknown object under the assumption that the object does not move during sensing. For example, let us consider two different link postures during *SPCM*. Between two link postures, we can always find an intersection, which provides us with an approximate contact point. This approach allows us to detect an approximate contact point without implementing any tactile sensor, which is a great advantage. In this work, however, we allow the object to move according to the contact force imparted by the link as shown in Fig.5(b).

For an n-fingered robot hand with m-joints per finger, suppose that h_i-th ($h_i \geq 2$) link of each finger makes contact with an object, and the angular displacement, $|\Delta\theta_{pi}| \neq 0$ is applied at the position-controlled joint p_i ($h_i \geq p_i$) as shown in Fig.5(b). If we can find the vector $p_{ci} \in R^{3\times1}$ satisfying the following equations during a change of link posture, it is said that there exists *Self-Posture Changeability* (*SPC*)[19].

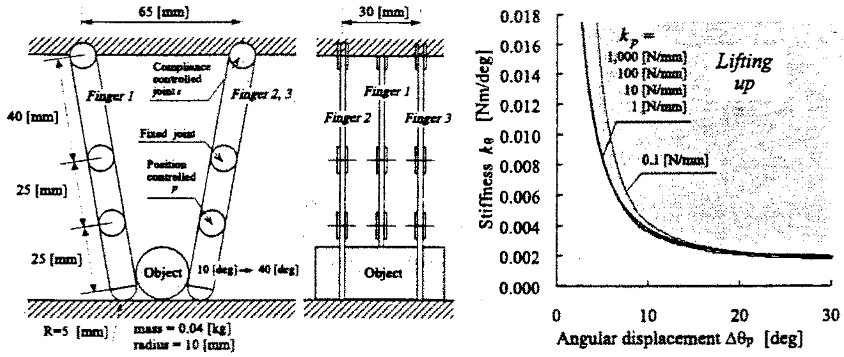
$$S_B({}^{B}\boldsymbol{p}_{CBi}) = 0, \quad S_{Fi}({}^{Fi}\boldsymbol{p}_{CFi}) = 0 \tag{1}$$

$$\boldsymbol{p}_B + \boldsymbol{R}_B{}^{B}\boldsymbol{p}_{CBi} = \boldsymbol{p}_{Fi} + \boldsymbol{R}_{Fi}{}^{Fi}\boldsymbol{p}_{CFi} = \boldsymbol{p}_{Ci} \tag{2}$$

$$\boldsymbol{n}_{CBi} = -\boldsymbol{n}_{CFi} \tag{3}$$

where $S_B({}^{B}\boldsymbol{p})$ ($S_{Fi}({}^{Fi}\boldsymbol{p})$) and $\boldsymbol{n}_{CBi}$ ($\boldsymbol{n}_{CFi}$) are function representing the surface shape of object (*i-th* finger link) and unit normal vector directing outside at *i-th* contact point on the surface of object (*i-th* finger), respectively.

The series of motions bringing about a *SPC* is defined as the *Self-Posture Changing Motion* (*SPCM*) and we express it as $SPCM\{\boldsymbol{K}_\theta, \Delta\boldsymbol{\theta}_p\}$ where $\boldsymbol{K}_\theta$ and $\Delta\boldsymbol{\theta}_p$ are the stiffness matrix of compliant controlled joints and the angular displacement matrix of position controlled joints, respectively. Since the basic behavior of *DAM* is similar to that of *SPCM*, we can discuss the condition where the robot hand can lift up the object by utilizing the $SPCM\{\boldsymbol{K}_\theta, \Delta\boldsymbol{\theta}_p\}$. Now, let $\boldsymbol{f}_c = [\boldsymbol{f}_{c1}^t, \cdots, \boldsymbol{f}_{cn}^t]^t \in R^{3n\times1}$ and $\boldsymbol{W}_{ext} \in R^{6\times1}$ be the contact force vector at each contact point and the load wrench, respectively. The equation of the force and the moment balancing on the object can be expressed as



(a) Simulation model (b) Simulation result

Figure 6. Analytical model and simulation result

$$\boldsymbol{W}_{ext} = -\boldsymbol{G}^t \boldsymbol{f}_c, \tag{4}$$

where $G^t \in R^{6\times 3n}$ is the grasp matrix and given by

$$G^t = \begin{bmatrix} I_3 & \cdots & I_3 \\ (\boldsymbol{R}_B{}^B\boldsymbol{P}_{CB1}\times) & \cdots & (\boldsymbol{R}_B{}^B\boldsymbol{P}_{CBn}\times) \end{bmatrix}. \tag{5}$$

Suppose that the load wrench is $\boldsymbol{W}_{ext} = [0, 0, -(m_B g + f_{ez}), 0, 0, 0]^t$ where m_B, g, and f_{ez} are the mass of object, the gravitational acceleration, and the virtual force in the gravitational direction, respectively. The combination of $\boldsymbol{K}_\theta$ and $\Delta\boldsymbol{\theta}_p$ leading to *DAM* can be obtained by solving the following problem.

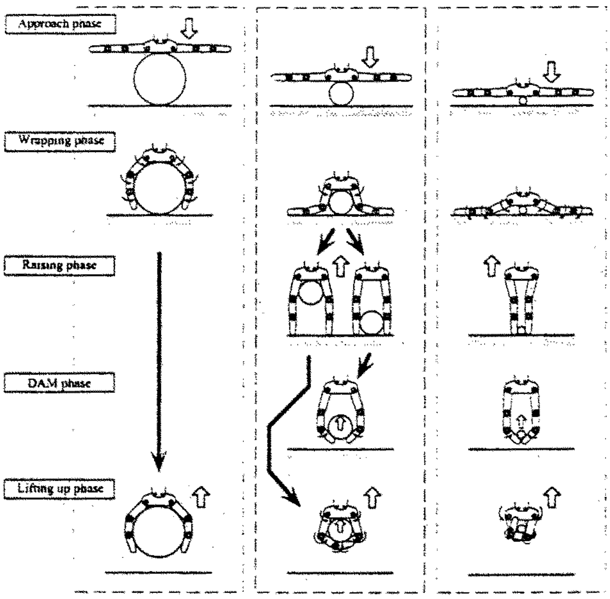
Search $SPCM\{\boldsymbol{K}_\theta, \Delta\boldsymbol{\theta}_p\}$ where $\boldsymbol{f}_c$ balances with $\boldsymbol{W}_{ext}$ and $f_{ez} \geq 0$.

The mathematical formulation for computing $\boldsymbol{K}_\theta$ and $\Delta\boldsymbol{\theta}_p$ has been discussed in [6]. Fig.6(a) shows the simulation model where parameters are chosen so that they are same as the robot hand we used for our experiment. Fig.6(b) shows the simulation result where we assume that the contact stiffness $k_p = 1,000[N/mm]$ through $0.1[N/mm]$, and the object is guaranteed for lifting up when we choose parameters with the hatched region. We would note that the lower boundary of the hatched region does not change largely as far as $0.1 \leq k_p \leq 1,000[N/mm]$, which means that the determination for both k_θ and $\Delta\theta_p$ can be easily achieved from Fig.6(b), if contact point is stiff enough.

5. Toward a Generalized Grasp Strategy

5.1. Outline

Since the motion planning of *DAM* (or *SPCM*) is simple enough, we now challenge to construct a generalized grasp strategy (*GGS*) which is applicable not only for small sized objects but also for other sized objects. Fig.7 shows an example of a *GGS* where it includes the *DAM* (or *SPCM*) phase in the central part. The *GGS* consists of the following five motions.



(a) Large object (b) Middle-sized object (c) Small object

Figure 7. General Grasp Strategy.

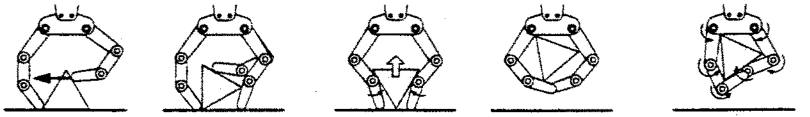
Approach phase : The robot hand approaches the target object until it makes contact with the object. By this contact, the robot can detect the height of the object H_{object}.

Wrapping phase : Each finger is closed in sequence from the 1*st* to the *n-th* joint under constant torque control, until the finger posture does not change any more. If an enveloping grasp is completed at the end of this phase as shown in Fig.7(a), the robot hand skips both *raising* and *DAM phases*, and switches to the *lifting up phase* directly.

Raising phase : The palm position is lifted under an appropriate compliance control where joint position is commanded so that the finger posture may be ready for starting the *DAM*. During this phase, there are two possible cases, the one is that the object is grasped by both palm and a couple of links, and the other one is that the object is stationary on the table. In case that the object is lifted, the target grasp can be achieved by simply closing each joint. In this case, we can skip the *DAM phase*.

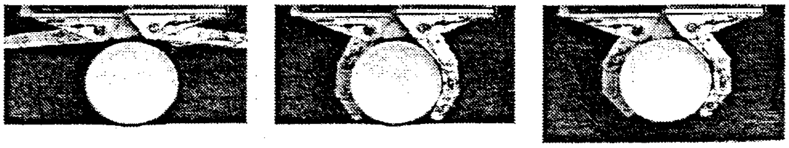
DAM phase : The robot hand executes the *DAM* (or *SPCM*), so that the object can be captured within the hand. In case that the object needs the *initial adjustment motion*, the robot applies it before the *DAM*, as shown in Fig.8.

Lifting up phase : Each joint control is switched into constant torque control.



(a) Initial adjustment motion (b) DAM (c) Enveloping grasp

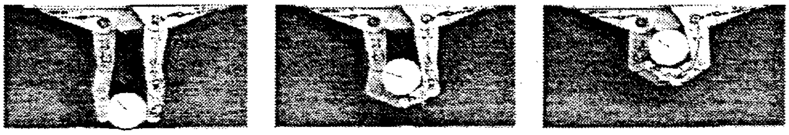
Figure 8. DAM with initial adjustment motion.



(a-1) Approach phase (a-2) Wrapping phase (a-3) Lifting up phase

(a) Large object

(b-1) Approach phase (b-2) Wrapping phase (b-3) Raising phase



(b-4) Raising phase (b-5) DAM phase (b-6) Lifting up phase

(b) Middle sized object

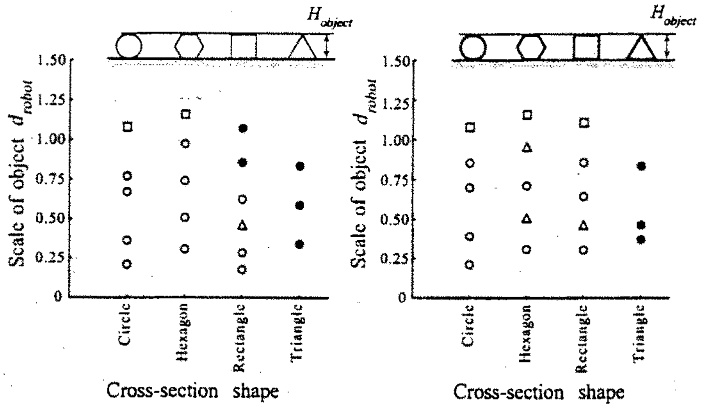
Figure 9. GGS by three–fingered robot hand.

The torque commands are chosen so that the grasped object may receive the upward resultant force under the given frictional coefficient[14].

In case that a vision system can observe the object continuously, we can immediately start either *wrapping phase* for a large object or *DAM phase* for other objects. Depending upon the contact friction, the object may stop during the *lifting up phase* due to so called jamming. When such a failure is detected, one feasible approach to recover is to apply small vibration signal (dither signal) to each joint, so that we can reduce the equivalent contact friction. We would note that according to the size, shape, and contact friction, there is a chance for detaching the object from a table in one of the three phases (*wrapping, raising and DAM phases*) during the whole grasp process.

5.2. Experiments

Fig.9 shows series of finger postures during the *GGS* by the robot hand. The robot hand consists of three same finger units and each finger has three links. The lengths of each link are $l_1 = 40[mm]$, $l_2 = 25[mm]$, and $l_3 = 25[mm]$, respectively. Each finger link is driven by wire and a torque sensor is included in each joint. Rotary encoder is used as an angular sensor. The palm is



(a) Drawing paper (b) Rubber sheet

Figure 10. Experimental results for general column objects.

equipped with ON/OFF type tactile sensor.

Figs.10(a) and (b) show the experimental results where objects used in Figs.10(a) and (b) are covered by drawing paper and by rubber, respectively. The horizontal and the vertical axes denote the shape of object and the normalized value $d_{robot} = L_o/L_r(L_r = 224[mm])$, respectively, where L_o and L_r denote the circumference of the object and the distance between fingertips, respectively. As the height of object increases, d_{robot} also increases. We prepare four types of object where cross–section of object are circle, hexagon, rectangle and triangle, respectively. "○", "□", "△" and "•" denote that the object can be detached from the table in *DAM phase*, *wrapping phase*, *raising phase* and by utilizing *initial adjustment motion*, respectively. The experimental results show that the robot hand can grasp various kinds of objects by utilizing the *GGS* proposed here.

6. Conclusion

We discussed the basic working mechanism of the *DAM* and examined the condition leading to the *DAM* by using *SPCM* which is easily implemented for robot hand. We have proposed a generalized grasping strategy (*GGS*) which is applicable for various sized (shaped) objects. We have experimentally shown that the robot hand can achieve the enveloping grasp for most kinds of objects which have various sizes, cross–section shapes, and contact friction by utilizing the *GGS*.

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