A NEW APPROACH TO THE PROBLEM OF ACQUIRING RANDOMLY ORIENTED WORKPIECES OUT OF A BIN.

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ABSTRACT

A complete solution to the problem cf picking randomly oriented workpieces out of a bin is presented. The geometry of the workpieces is arbitrary, the only parameters to be known are those of the grasper. The paper includes a description of the 3-D sensor and of the algorithm involved.

KEYWORDS

Robotics, 3-D sensing,silhouette, stable prehension

INTRODUCTION

The aim of this paper is a complete description of a system able to acquire workpieces which are arranged in an arbitrary way in a bin. This problem is of most importance in production automation for it allows workpieces to be fed from bins into machines in an automatic way [9]. Kelley and all. [10] solved the problem by using simple machine vision techniques and a surface adapting vacuum gripper. But, in many cases, the light intensity information is impraticable (see Figure 6) and the information contained in the range data must be preferred. From this information the proposed method isolate a workpiece, or more generally, a part of a workpiece to be handled by a robot grasper, without recognizing the workpiece. The proposition, the orientation and the aperture of the grasper are then calculated in such a way as to optimize the success of the prehension. The workpiece is then posed on a table where it lays isolated and in a stable position. In such a case, the recognition, precise orientation and transport toward machines are well understood problems [1].

The paper consists of three sections, rather autonomous, each with independent applications, but used together here to solve the grasping problem. In section II the 3-D sensor is described. This sensor provides the three coordinates of a point of the surface of an object, i.e., provides the z coordinate as a fuction of the x and y coordinates. The 3-D information is derived by means of stereo vision and of a laser beam to avoid the matching problem between the views. The originality with respect to the use of light striping [2] or structured light [3] for range data acquisition is in the random acces owing to a great simplicity of software. Section III presents a particular contour detector algorithm using the range data. It provides the silhouette of a visible part of a workpiece. This silhouette is used in section IV to choose the grasp and the parameters of the robot hand. This method, based on an appropriate segmentalion and parametrisation of the silhouette, seems to be a general solution for the matching problem between a hand structure and an object silhouette. No a priori information about the workpieces is needed ; the only entries of the program are the parameters of the grasper. Finally, the last section is devoted to the performances of the system and to the simulation results.

I. A <u>3D sensor</u>

The sensor used is a sensor which gives the z coordinate of a point on the surface of an object as a function of the x and y coordinates.

It is based on the "Active Stereoscopy" principle : stereoscopy because it uses at least two cameras to give images from different points of view ; active because the difficult problem in stereo vision of matching the two views is avoided by a strong lighting of one point of the surface to be observed.

1. <u>General</u> principle

The strong lighting is provided by a laser beam which can he swerved in two directions x and y. The deflection system is controllable and so the sensor is a random access one. The laser beam creates a little spot on the surface which is, by diffusion, a secondary source of light and so creates two images on both cameras. It is then possible to calculate from the position of these images on both retinas and from the geometrical parameters of the cameras, the three coordinates x y z of the brightly lit point. This is done by means of the same simple geometrical formulas as in classical stereoscopy.

2. <u>The system under development</u>

The principle of the sensor is very simple ; the realisation is more tedious and needs the determination and coordination of four distinct systems : the retinas, the optics of the cameras, the laser, the logical unit.

Because of their poor resolution and geometrical distortion, the vidicon type cameras or the image-dissectors cannot be used easily and do not give good results. Solid phase receptors have been prefered. But in this category, the 2-D receptors are expensive and of poor resolution (at least as this paper is written). This is why the cameras have photodiode array. Note that each camera indicates one plane containing the overlighted point. At least three cameras are needed.

b) The optics od the cameras

In addition to requiring the enough light on the retinas, we also need an anamorphoseur system to observe on a rectangular photodiode array, a scene which looks generally like a square. That is the reason why cylindrical lenses are used.

c) The optics of the laser

This system has two functions. Firstly, the laser beam must be swerved in both the x and y directions. This can be done by means of an opto electronic device, but a system composed of mirrors steered by galvanometers is preferred. These are the only moving parts of the whole apparatus. Secondly, the beam must be focussed. The optics are arranged so as to maintain the diameter of the laser beam constant and minimal in the whole problem domain ; this arrangement also depends on the parameters of the laser.

d) The_logical__uni_t

Each camera is associated with a microprocessor which essentially determines the significantly lighted diodes and performs an interpolation to obtain a position which is accurate to $1/8^{tn}$ of a diode width. A second microprocessor controls the whole system, in particular the galvanometers, and performs the triangulation from the data provided by each camera.

So this sensor is relatively autonomous. The connection with another logical unit, whose size depends on the application, is assumed by the second microprocessor. The exchanges between both are very few : the logical unit sends to the sensor the two parameters of the direction of the beam and receive as feedback the three coordinates x y z of the measured point. With the specifications, the time of a measure is approximately 1 ms.

II. <u>How to use the sensor to pick up workpieces from a bin</u>

As we briefly mentionned, we do not want to recognize the workpieces in the bin and to calculate their orientation. This would involve great difficulties, and, in particular, would require the construction of a 3-D model of the workpieces, which is itself an open problem.

Moreover, the workpiece probably slides a little relative to the gripper during the prehension, and so it does not seem reasonable to require a very accurate orientation of the workpiece at this stage. Thus we distinguish two steps in feeding workpieces from bins into machines : we pick up a workpiece from the bin and put it on to a table, and then we are able to solve the classical problem of finding the orientation of a workpiece place in a stable position. The aim of this paper is to present a method which uses the above sensor, to solve the first step. The second step is widely exposed in the litterature [1].

Instead of recognizing a workpiece, we just want to extract some information which seems reasonably sufficient to isolate one workpiece not wedged by other -this is the object of section II- and to calculate the places where to put the fingers of the gripper system- this is the object of section III-.

Therefore, we want at first to find a part of a workpiece which is on the top of the bin and that the robot could grasp. This is performed by the algorithm briefly described below which looks for the "break points" (i.e., the points where there is a large gradient Az in z) around a given point :

i) Choose n arbitrary points in the bin, measure their coordinates and keep the one whose z is the largest, called the origin in the following. This assures that we work on a workpiece on the top of the bin presumed not to be wedged by others.

ii) Cloose an arbitrary direction.

iii) Go from the origin in this direction until you find a large Az. If the breakpoint is farther than d from the origin, go to v).

iv) Follow the break by measuring succesively top and bottom points until no break point is found.

v) Calculate the polar angles of the end points of the break which define an observed sector. If iii) failed, this is one angle.

vi) If there are observations for enough directions : end. If not choose the bissecting of the largest non-observed sector and return to iii).

\- This algorithm produces a chain of points in FT (the break points) which defines in some sense the silhouette of a workpiece. This silhouette may be a closed curve or more generally several curves corresponding to the regions with a well defined break. Of course, we are not sure that the silhouette is the silhouette of only one workpiece and that the workpiece is not wedged, but the risk is minimized.

Finally a piecewise linear approximation of the silhouette is stored for further investigations.

III. Positioning the fingers of the grasper

This section is devoted to the determination of the possible ways to grasp the workpiece assumed to be defined by its silhouette. To grip securely the workpiece we need first to put the grasper in a stable position along the silhouette and then to guarantee that the workpiece will stay in the grasper and not fall down or stay in the bin. The first problem and more difficult, is the subject of this section. The second one is solved, if necessary,by the heuristics described in section IV.

To position, without sliding, a grasper of a defined type along a silhouette is a matching problem complicated by a mechanical problem : the definition of stability. The matching problem has been extensively studied [4] but the methods used, even the most sophisticated, like relaxation in [6], are too slow to be efficient in robotics. On the other hand, the more specialised problem of stable prehension of an unknown object has received very little attention and only in particular cases [5]. [7], [11], [12].

The approach presented here is based on three simple ideas :

i) If we analyse locally the behaviour of the grasper, the problem becomes easier ; more precisely, we shall see that the different cases reduce to three.

ii) We choose a parametrisation of the silhouette more efficient that the chain of cartesian coodinates of its vertices. The parametrisation provides a simple analytic solution and a fast algorithm. Moreover, though the principle of the method is presented for a plane silhouette and a two fingers grasper, the method may easily be generalized to a number of graspers and to non-planar silhouettes [8].

iii) The stability condition will be essentially geometrical and is related to the fact that the grasper can only close, i.e., the fingers can only be brought closer together.

As mentionned in section II, the silhouette is composed of one or more non-crossing polygonal lines. By convention, the silhouette will be oriented in such a way that the normal points to the workpiece (i.e., the external contour is clockwise, the holes counter-clockwise).

The grasper is defined as an ordered set of fingers whose relative positions and directions of tightening verify some constraints.

A position of the grasper along the silhouette is said to be stable if, when tightening (i.e., when the fingers tend to move along their directions of tightening), it does not leave the workpiece.

The organisation of the section is the following ; first, we define a segmentation of the silhouette into independent primitives whose study from the point of view of stable positionnement of a finger is equivalent to the study of the whole silhouette. A unified parametrisation is then proposed which results in similar conditions for the stable positioning of one finger on each type of primitive. Finally, the positioning of the coupled fingers of the grasper is studied.

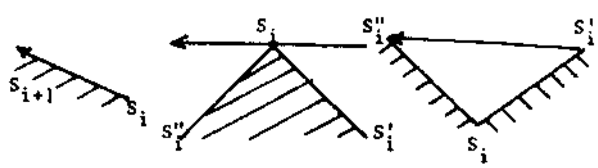
1. Classification of the stable positions of a finger along the silhouette

We consider a polygonal line $S=(S_1 \ldots, S_n)$ of the silhouette and a finger D of lenght L. We assume here, for clarity, that $||S_i S_{i+1}|| \geq L$ and $(S_i S_{i-1}, S_i S_{i+1}) \geq \frac{\pi}{2}$ [mod.2π] for every i. See for the general case [8]. The aim of this paragraph is to classify the different stable positions of D along S. This is obtained by an appropriate segmentation of S into primitives. This is quite natural for D can only touch a part of S. The primitives are defined by the following :

i) A straight primitive (noted S) is an oriented segment $(S_i S_{i+1})$.

ii) A convex primitive (noted V) -respectively: a concave primitive (noted C)- is the union of two oriented segments with a common extremity $(S'_i S_i S''_i)$ such that : $S'_i \in (S_{i-1} S_i)$, $S''_i \in (S_i S_{i+1})$, $||S_i S'_i|| = ||S_i S''_i|| = L$, $((S_i S'_i),(S_i S''_i)) > \pi$ (resp. $<\pi$).

With each primitive, an oriented segment is associated : $(S_i S_{i+1})$ in the case of a straight primitive, $(S'_i S''_i)$ in the case of a concave primitive, and the oriented segment equal to $(S'_i S''_i)$ with S_i as its middle in the case of a convexe primitive.

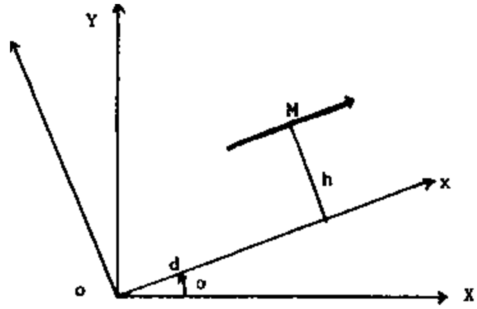


These definitions yield the trivial proposition : a finger with a lenght less than L can only touch the silhouette at points belonging to one primitive.

We now introduce a parametrisation of the primitives which corresponds to the intuitive idea that positioning the finger D on to a primitive P requires three conditions : D must be near P, must not intersect with the workpiece and must be correctly oriented.

Four parameters are sufficient to define each primitive. Thus the convex and concave primitives are characterised by their associated oriented segment. So in every case, the parametrisation of a primitive is equivalent to the parametrisation of an oriented segment.

Let {R} denote a reference frame whose origin is 0. We call the parameters of an oriented segment V the 4-tuple (l,a,d,h) where l is the euclidian norm of V, a its orientation d and h the coordinates of its middle M expressed in the frame {R} by the rotation (0,a).



The parameters of the oriented segment associated with the primitive *P* are called the parameters of *P* and we write P - (l,a,d,h).

Similarly, the parameters of the finger *D* are those of its edge oriented in such a way that it forms with the direction of tightening a direct frame. It is noted *D* - (L,6,6,E.

The stable positioning of a finger *P* on to a primitive *I'* involves three conditions : the orientation of *D* toassure the stability, the lateral positioning to assure that *V* will reach F, and the positioning normal to the orientation of the primitive of *D* to assure that *P* does not intersect with the workpiece. It is proved in [8] that, for the three types of primitives, the first condition is a fonction of 0 exclusively, the second one of 6 and 6, the third one of 6,6 and £. This property will yield an analytical solution in the case of several coupled fingers.

We give, as an example, the trivial case of a straight primitive for which the conditions are (without friction) :

i) $\theta = \alpha$

ii) $|\delta - d| \leq \frac{\ell - L}{2}$

iii) $\xi = h$.

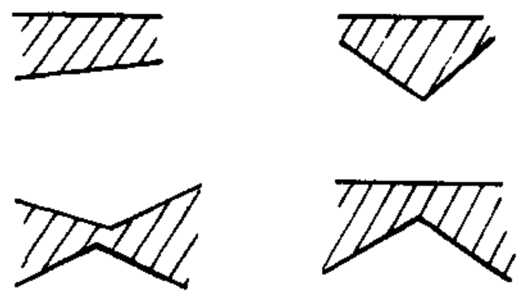
The other cases are given in the appendix and yield the classification of the stable grasps : the sets M_i of the stable positions of D on to the different primitives of the silhouette constitute a partition of the set M of the stable positions of D on to the silhouette ; i.e. $\bigcup_i M_i = M$ and $M_i \cap M_j = \emptyset$ for every i,j ($i \neq j$).

2. <u>Stable positioning of a grasper along the silhouette</u>

The problem is, now, the positioning of the different fingers of the grasper along the silhouette. We restrict our study to the case of a grasper with two identical fingers (see Figure 2). The generalisation to other types of graspers is straightforward [8].

Let $D_i = (L, \theta_i, \delta_i, \xi_i)$ be the fingers of the grasper. The constraints in the case of a grasper with two fingers are : $\theta_2 - \theta_1 = \pi$, $\delta_1 + \delta_2 = 0$, $\xi_1 + \xi_2 < 0$.

A position of the grasper will be said stable if the fingers are in stable position in the sense of §1 and if the distancebetween them passes through a local minimum different from 0. This definition implies that a grasp associates two primitives, and that some associations of primitives cannot yield a stable grasp. We only have to consider the following cases : the "trapezoid" (S,S), the "triangle" (S,V), the "butterfly" *(C,C)*, the "tunnel" *(S,C)*



Finding a grasp for the grasper is equivalent to finding the conditions under which two primitives forming one of the above configurations, make a grasp. These conditions are obtained by writing the conditions of the stable positioning of each finger and by reducing the number of variables owing to the constraints of the grasp. It is shown in [8] that for each configuration the solution is simple and analytic. A few tests on the parameters of the primitives allow to know if two primitives constitute a grasp, and, if so, the possible positions for the grasper. As an example, we give the trivial case of the trapezoid for which the conditions are :

i) $\alpha_2 - \alpha_1 = \pi$

ii) $|d_1 + d_2| \leq \frac{\ell_1 + \ell_2}{2} - L$

iii) $h_1 + h_2 < 0$.

The possible positions of the grasper are defined by : $\theta_l = \alpha_j$, $|\delta_l - d_j| \leq \frac{\ell_1 - L}{2}$, $\xi_j = h_l$ and the constraints of the grasper.

The other cases, given in the appendix, are very similar.

Two remarks must be made. Firstly, because of the simplicity of the solution, the method is very quick. Secondly, we get without any more calculation the tolerancies $\Delta\theta$ and $\Delta\delta$ on θ and δ. They are, for a given type T of configuration, a good measure of the stability and so of the quality of the grasp, useful to order the grasps. The criteria may be of the form $\lambda T + \mu\theta + \nu\Delta\delta$.

Finally the complexity of the algorithm which is, a priori $O(n^2)$ may be reduced to $O(n \log n)$ if the primitives are sorted according to their orientations [8].

IV. EXPERIMENTAL STUDY

The bin to be observed is a cubical one, 75 cm wide. For industrial reasons the whole sensor (camera, laser, and its optics) must be 4 m from the ground. To observe the whole bin whose edges are not transparent the cameras must not be more than 37.5 cm from the bin's axis. This is a very disadbantageous condition for the "z" precision because the stereoscopic angle is only 12°. The experimental sensor has 1024 photodiodes arrays and thus we obtain a precision of 0.7 mm in z and one of 0.3 mm in x and y. This is superfulous in the following example, where the maximum length of the workpieces are about 20 cm : in this case, simulation shows that a precision of 3 mm is sufficient, and hence, the length of the photodiodes arrays might be reduced.

A 100 mwatt laser is used, with a diameter equal to 1.3 mm having a divergence of 0.6 mrad. The optics composed of four lenses keep the diameter constant and equal to 0.7 mm on the entire bin.

Figure 2 shows a photograph of the bin. One notices that intensity data does not permit extraction of outlines of workpieces. In Figure 3(a), the dotted lines represent the laser beam's course from an origin to a breakpoint, and the along the outline of a workpiece on the top of the bin. The continuous line is the piecewise linear approximation of the silhouette. Figure 3(b), (c), (d) shows three possible grasps among the best ones. The criteria used to order the grasps is the criteria defined in section III2 added with some heuristics that prevent the workpiece to fall down or stay in the bin, based on the relative position of the grasp and the estimated moments of inertia of the workpiece.

V CONCLUSION

A new 3-D sensor and one of its possible applications, the bin picking, has been presented. In that application the sensor is used as a fast edge detector, allowing to isolate a workpiece or part of a workpiece on the top of the bin. Then a general algorithm defines the possible grasps along the silhouette (a representation of the object to be handled is not required); it may be used to solve many other problems of automatic prehension, when the object is unknown or when a particular orientation of the object is not needed.

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APPENDIX

Let D be the finger (L,θ,δ,ξ) and P the primitive (ℓ,α,d,h).

We note :

$$\begin{pmatrix} d(\alpha-\theta) \\ h(\alpha-\theta) \end{pmatrix} = R(\alpha-\theta)\binom{d}{h}, \begin{pmatrix} \delta(\alpha-\theta) \\ \xi(\alpha-\theta) \end{pmatrix} = R(\alpha-\theta)\binom{\delta}{\xi}, \text{ et}$$

$$\begin{pmatrix} L(\alpha-\theta) \\ H(\alpha-\theta) \end{pmatrix} = R(\alpha-\theta)\binom{L}{0}$$

Where :

$$R(.) = \begin{pmatrix} \cos(.) & \sin(.) \\ -\sin(.) & \cos(.) \end{pmatrix}$$

Three propositions give the conditions for the stable positioning of a finger (see §.III.1) on a primitive and for the stable positioning of a two fingers grasper (see §.III.2). For the proofs see [8].

Proposition 1

The finger D lies in a stable position on the primitive P iff :

i) $|\theta-\alpha| \leq \phi$ with $\cos\phi = \frac{\ell}{2L}$

ii) $|\delta - d(\alpha-\theta)| \leq \lambda(\alpha-\theta)-\mu$ with :

$\lambda(\alpha-\theta)=0$, $\mu = \frac{L-\ell}{2}$ if P is convex

$\lambda(\alpha-\theta) = \frac{\ell}{2}\cos(\theta-\alpha)$, $\mu = \frac{L}{2}$ if P is concave.

iii) $\xi=h(\alpha-\theta)$ if P is convex

$\xi(\alpha-\theta)+\varepsilon\frac{H(\alpha-\theta)}{2} = h$ if P is concave and $\varepsilon = \text{sign}(\theta-\alpha)$.

Proposition 2

In this proposition at least one primitive is a straight primitive. Such is the case for the trapezoid, the triangle and the tunnel. Say, be convention, $P_1 = S_1$. S_1 et P_2 constitute a grasp iff :

i) $|\alpha| \leq \phi_2$ with $\alpha=\alpha_1+\pi-\alpha_2$

ii) $|d_1+d_2(\alpha)| \leq \lambda_2(\alpha)-\mu_1-\mu_2$

iii) $h_1+h_2(\alpha) < 0$

The allowed positions for the grasper are defined by : $\theta_1 = \alpha_1$

$|\delta_1-d_1| \leq -\mu_1$, $\xi_1=h_1$, $\xi_2=h_2(\alpha)$ if P_2 is a straight or a convex primitive, ou $\xi_2(\alpha)+\varepsilon\frac{H(\alpha)}{2} = h_2$ if P is a concave primitive, and the constraints of the grasper (see Section III).

Proposition 3

In this propositon both primitives are concave (butterfly case). We introduce the notations :

$$\alpha=\alpha_1+\pi-\alpha_2$$

$$\binom{d}{h} = \binom{d_1}{h_1} + R(-\alpha)\binom{d_2}{h_2}$$

$$\binom{\ell}{r} = \binom{\ell_1/2}{0} + R(-\alpha)\binom{\ell_2/2}{0}$$

$$\Delta_- = (d-\ell)^2 + (h-r)^2 - L^2$$

$$\Delta_+ = (d-\ell)^2 + (h+r)^2 - L^2$$

$$t_- = \frac{-(h-r)(d-\ell)+L\sqrt{\Delta_-}}{(h-r)^2 - L^2} \quad t_+ = \frac{-(h+r)(d+\ell)-L\sqrt{\Delta_+}}{(h+r)^2 - L^2}$$

$$t' = \sup(-tg\phi_1, -tg(\phi_2+\alpha), t_-)$$

$$t'' = \inf(tg\phi_1, tg(\phi_2-\alpha), t_+)$$

$$L_i(\alpha_i-\theta_i) = \frac{\ell i\cos(\alpha i-\theta i) - L}{2} \ (i=1,2)$$

C_1 and C_2 constitute a grasp iff :

i) $t' \leq t''$

ii) $|d| < \ell$ when $h > |r| - L$

$\frac{r}{|r|} d > -\ell$ when $|h+L| < |r|$

iii) $h < 0$

The allowed positions for the grasper are defined by :

$$t' \leq tg(\alpha_1-\theta_1) \leq t''$$

$$\sup(d_1(\alpha_1\theta_1)-L_1(\alpha_1-\theta_1), -d_2(\alpha_2-\theta_2)-L_2(\alpha_2-\theta_2)) \leq$$

$$\delta_1 \leq \inf(d_1(\alpha_1-\theta_1)+L_1(\alpha_1-\theta_1), -d_2(\alpha_2-\theta_2)+L_2(\alpha_2-\theta_2))$$

$\xi_i(\alpha_i-\theta_i)+\varepsilon_i\frac{H(\alpha_i-\theta_i)}{2} = h_i$ $(i=1,2)$ and the constraints of the grasper.

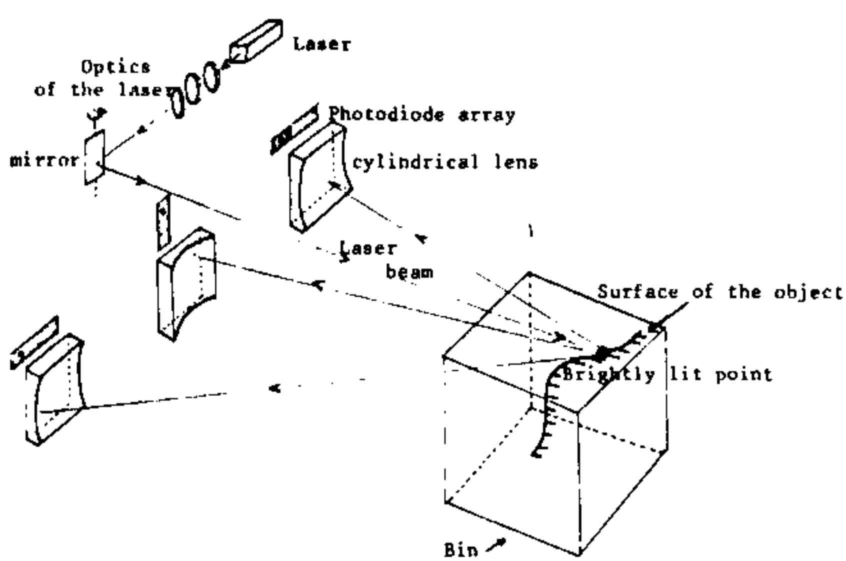

Figure 1. Basic scheme of the 3-D sensor

Figure 2. Aview of the bin.

The workpiece with a star is the first workpiece taken into account by the sensor.

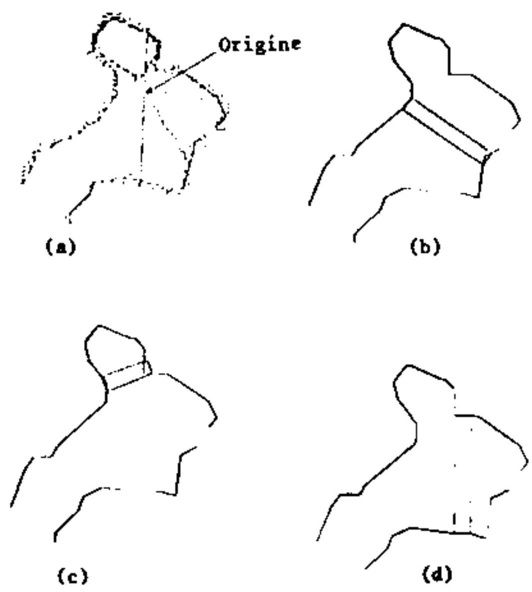

Figure 3. Extraction of a workpiece silhouette (the one with an star on Figure 2)(a) and three possible grasps (b), (d).