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An adaptive locating problem for robotic grasping

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SUMMARY
The paper addresses a problem of "in-hand" locating parts of different shapes in robotic grasping. The goal of the process is to locate a part of an arbitrary shape from an imprecisely determined initial position within a gripper to a final prescribed one. Two possible approaches to solve the problem are considered: non-adaptive, using ordinary rigid jaws of gripper and, adaptive, using an adaptive jaw which improves the performance of the locating process. The latter approach is proposed to be solved by a new type of grasping mechanism. Its theoretical analysis enables to obtain formal conditions for part behavior during the successive steps of the locating process. This process was simulated and then experimentally investigated on an actual gripper model. The proposed new class of mechanisms opens a promising avenue to the creation of a practical class of universal robotic grippers for industry.

KEYWORDS: Robotic grasping; Parts location; Gripper model.

1. INTRODUCTION
The great number of known robotic grippers do not in the least exhaust the present needs of different industries. Important characteristics of gripping devices, such as the improvement of adaption and locating properties relative to the shape of the object to be clutched, have not been efficiently analyzed and realized for industrial systems. Proper location is an important property, because it enables us to move an object from some initial state to a fixed position (base) associated with the particular coordinate system of a specific industrial robot. The adaptation property must be capable of performing a location operation for different shapes of objects in order to ensure universality of grasping processes. The development of an adaptive device is simulated by the need for flexible manufacturing systems, where a wide range of processes requires operational changes of robot gripper properties. This is why adaptive grippers have been developed,[1,2] but they have frequently been too complicated and not sufficiently reliable for industrial applications. Necessity has thus dictated the automatic changing of grippers depending on the shape of the object to be manipulated.[3] This approach is inefficient due to the high cost and losses of performance time.

Grasping an object to be manipulated when its position is imprecisely determined is another complicated robotics problem that usually requires additional sensors to determine the object's position (e.g., technical vision). Additional robot motions are needed to grasp an arbitrarily oriented object. In recent research, these grasping problems are usually solved by creating universal end-effectors in the form of multifingered hands with sensing abilities.[4] The object is then gripped only by fingertips, and this allows one to reach human-hand-like motions. However, this anthropomorphic approach is very difficult to be implemented. It requires overcoming several of theoretical and practical problems and leads to complicated hardware and software for the mechanical hand. Hence, it is not always cost effective for use in industrial robotics, which requires simple, cheap, and reliable solutions.

The problem described is very close to the problem of adaptable fixturing which was presented among the first by Asada and By.[5] As a rather promising approach to solve it, Mason's[6] pushing approach was developed being a quite effective method to solve rather simple positioning and orientation problems. However, this approach got in last years an intensive development in works directed at sensorless parts orienting. For instance, a number of these studies based on the use of fences are performed by Peshkin and Sanderson.[7,8] Recent study of Akella[9] et al. is based on the use of a simplest one-joint manipulator for that purpose.

This issue is very actual for robotics as well because it relates very closely to robotic grasping problems. Therefore, while operating with parts of different forms, in addition to the traditional approach based on the use of vision or other advanced sensor and control systems, another approach has been developed by Goldberg[10,11] and others when some simpler mechanical means are in use to operate with parts. However, while implementing this approach, the developed system structure remains relatively complex. For example, the parallel-jaw gripper system contains a simple position sensor, an additional drive, and a control system that makes a decision regarding the grasping strategy.

In this paper, two possible ways to implement "in-hand" locating are considered: The first, non-adaptive, when an ordinary gripper with rigid non-parallel jaws is in use, and the second, adaptive, using a gripper containing one ordinary, rigid jaw and another jaw with a grasping mechanism capable of adapting to the shape of part to be grasped. High-class mechanisms (HCMs), which feature of a mobile contour available from rigid links are the basis for such device,[12] and ensure properties of adaptation and

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locating. These mechanisms are named recently also as underactuated mechanisms.[13]

The purpose of this work is to establish a class of gripping devices that embody these important practical properties and to develop methods for their study and design. Computational kinematics approach[14] is applied for design of adaptive grasping devices. The adaptability features of the gripper are defined in the configuration space generated by parameters of the proper grasping mechanism and parameters of the body to be clamped. For a general consideration of the grasping mechanism design, the Plucker's coordinates matrix technique is used.

2. MATHEMATICAL DESCRIPTION OF THE LOCATING PROCESS

2.1 General definitions

Let us define two coordinate systems: motionless system S_0 (OXYZ, Figure 1) associated with end-effector *1* and movable system S' associated with body *2* to be clamped. Position and orientation of the system S′ (O′X′Y′Z) with respect to the system S_0 are given by three linear displacements *a, b, c* of the origin O′ along the X, Y, Z axes, respectively, and three Euler's angles θ, φ, ψ of rotations about the same axes. The 6×1 vector of the pose is defined as

$$\mathbf{q}=(a, b, c, \theta, \varphi, \psi)^{\mathrm{T}} \tag{1}$$

A locating mechanism has to transfer the body from a given extreme initial posture $\mathbf{q}_{ex}$ to the given final posture $\mathbf{q}_{fin}$, in which this body must be clamped. The transfer from $\mathbf{q}_{ex}$ to $\mathbf{q}_{fin}$ is carried out along the specified trajectory *T*, in all points of which vector $\mathbf{q}$ is a function of an appropriate given parameter α:

$$\mathbf{q}=\mathbf{q}(\alpha), \text{ with } \alpha \in (\alpha_{fin}, \alpha_{ex}), \mathbf{q}_{fin}=\mathbf{q}(\alpha_{fin}), \mathbf{q}_{ex}=\mathbf{q}(\alpha_{ex}) \tag{2}$$

Adaptive features of the mechanism define its capability to carry out the "in-hand" clamping process of the body when: (a) a distance between the initial and final positions of the body is not-small in comparison with dimensions of the clamped body, and/or (b) the distinctive dimensions of the clamped body have deviations from the nominal dimensions. In general case, these deviations are not small in comparison with the nominal dimensions.

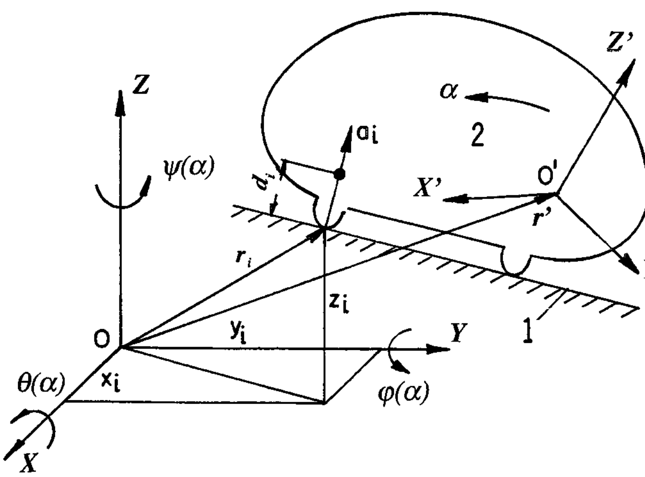

Fig. 1. Concept of a pose of a rigid body.

Quantitative characteristics of the adaptive features may be described in configuration space by two groups of the parameters: internal parameters describing the clamped part, and external parameters describing the possible postures of the part during clamping process. Configuration space is used as a tool for analysis of the tolerable parameter values. These values define the adaptive range, in which the clamping process may be performed successfully.

In some cases, the adaptive features may be characterized by external and internal numerical factors. The external adaptive factor k_{ex} depends on the capability of the gripper to perform the transfer the body 2 (Figure 1) from an arbitrary intermediate point in the interval $\alpha_{fin}\leq\alpha\leq\alpha_{ex}$ of trajectory *T*. The internal adaptive factor k_{in} depends on capability of the gripper to perform the grasping procedure successfully when the form and/or dimension of the body is different from the nominal dimensions. The corresponding adaptive factors are as follows:

$$k_{ex}=[\mathrm{F}(\alpha_{ex})-\mathrm{F}(\alpha_{fin})]/d_{nom} \tag{3}$$

$$k_{in}=(d_{max}-d_{min})/d_{nom} \tag{4}$$

where $\mathrm{F}(\alpha)$ is a function of parameter α, for example, one of the components of vector $\mathbf{q}$ [i.e., $a(\alpha), \ldots, \psi(\alpha)$]; *d* is the distinctive dimension of the clamped part; d_{max}, d_{min}, and d_{nom} are the maximal, minimal, and nominal values of the distinctive dimension *d*, respectively.

2.2 Locating conditions

The grasped body contacts with a set of point-type unilateral supports. Such support provides body movement along one specified direction. To analyze the support system, the 6×6 Jacobian matrix is used.[5] This matrix is directly built as follows. The *i*th support of rigid body 2 (Figure 1), which bears up against base *1*, is specified by a vector $\mathbf{r}_i$ of the support point and a unit vector $\mathbf{a}_i$ of the direction of the support action on the body. This pair of vectors is given in coordinate system *S* (*OXYZ*) associated, for example, with base *1* (another vector may be defined in the moving coordinate system S′ associated with clamped part 2). Let us represent a moment of vector $\mathbf{a}_i$ relative to the origin *O* of the coordinate system *S* by $\mathbf{m}_i$. Direction and position of the *i*th support is represented by vector $\mathbf{R}_i$ of Plucker's coordinates,

$$\mathbf{R}_i=(a_{xi}, a_{yi}, a_{zi}, m_{xi}, m_{yi}, m_{zi})^{\mathrm{T}}, \tag{5}$$

where a_{xi}, a_{yi}, and a_{zi} are the direction cosines of the support [i.e., coordinates of the unit vector $\mathbf{a}_i=(a_{xi}, a_{yi}, a_{zi})^{\mathrm{T}}$ of the reaction of the *i*th support]; and m_{xi}, m_{yi}, and m_{zi} are the moments of vector $\mathbf{a}_i$ relative to the *X*, *Y*, and *Z* axes, respectively; i.e., $\mathbf{m}_i=\mathbf{r}_i\times\mathbf{a}_i=(m_{xi}, m_{yi}, m_{zi})^{T}$. Note that only four of the six elements of vector $\mathbf{R}_i$ are independent of each other, since $|\mathbf{a}_i|=1$ and $\mathbf{a}_i\bullet\mathbf{m}_i=0$. The set of six supports given by Plucker's vectors $\mathbf{R}_1, \mathbf{R}_2, \ldots, \mathbf{R}_6$ according to expression (5) is characterized by the 6×6 matrix:

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$$R_d = (\mathbf{R}_1, \mathbf{R}_2, \ldots, \mathbf{R}_6)^T = \begin{pmatrix} a_{x1} & a_{y1} & a_{z1} & m_{x1} & m_{y1} & m_{z1} \\ a_{x2} & a_{y2} & a_{z2} & m_{x2} & m_{y2} & m_{z2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{x6} & a_{y6} & a_{z6} & m_{x6} & m_{y6} & m_{z6} \end{pmatrix} \quad (6)$$

It is known[5] that this matrix presents the Jacobian of the system of six linear equations:

$$\mathbf{d} = R_d \, \Delta, \quad (7)$$

where Δ and $\mathbf{d}$ are the 6×1 infinitesimal vectors; $\Delta = (\delta_x, \delta_y, \delta_z, \delta\theta, \delta\psi)^T$; δ_x, δ_y, and δ_z are the small linear displacements of the body along the X, Y, and Z axes; and $\delta\theta$, $\delta\varphi$, and $\delta\psi$ are the small angles of rotation around the same axes; $\mathbf{d} = (d_1, d_2, d_3, d_4, d_5, d_6)^T$ is the vector of the small displacements d_i of six points of the clamped body 2, which are in contact with the ith body supports. To keep the fixed position of the body at any load, the matrix R_d must be non-degenerated,

$$det\, R_d \neq 0. \quad (8)$$

When $det\, R_d = 0$, the body has N_m degrees of freedom ($N_m = 6 - rank\, R_d$), and, when small displacements of six points of the clamped body 2 are given and $det\, R_d \neq 0$, infinitesimal displacements of the body may be calculated as $\Delta = (R_d)^{-1}\, \mathbf{d}$.

A clamping force F acting on the clamped body results in reaction p_i ($i = 1, \ldots, 6$) at each of the supports. Six components of reaction p_i relative to axes of the system S are coordinates of the vector $\boldsymbol{p}_i = p_i \mathbf{R}_i$. Thus, the equilibrium conditions may be written in the form:

$$R_d\, \mathbf{P} + \mathbf{F} = 0, \text{ with } R_d \neq 0, \text{ and } \mathbf{P} > 0,$$

where $\mathbf{P} = (p_1, p_2, \ldots, p_6)^T$ is the reaction vector of the supports; $\mathbf{F}$ is the vector of clamping loads acting on the body to be clamped; $\mathbf{F} = (F_x, F_y, F_z, M_x, M_y, M_z)^T$; F_x, F_y, F_z are projections of the force vector onto the X, Y, and Z axes; and M_x, M_y, M_z are projections of the moment of the external forces.

3. A STUDY OF TWO KINDS OF LOCATING PROCESSES

There are, in principle, two possible ways to solve a problem described in Section 2. The first one is based on the use of a gripper with an ordinary rigid jaw. In this case, the locating process goes according to with the above-mentioned pushing method.[6,8] The second one can be implemented by using an adaptive jaw which is able to adapt to the shape of a part to be grasped. In this section, both these approaches are studied to reveal their features.

3.1 Locating by Means of Rigid Jaw

Let us consider a case when a rigid jaw is used to locate a part within a gripper from an arbitrary initial position to a certain base (Figure 2). Note that in practice, only the gripper with non-parallel jaws is able to perform this operation. For the sake of definiteness, we shall consider a widespread case when the axially symmetric part is clamped. The part has a convex with $l/d > 1$, where l and d are the longitudinal dimension and distinctive dimension in cross section, respectively. The triangle prismatic part of this type will be considered furthermore.

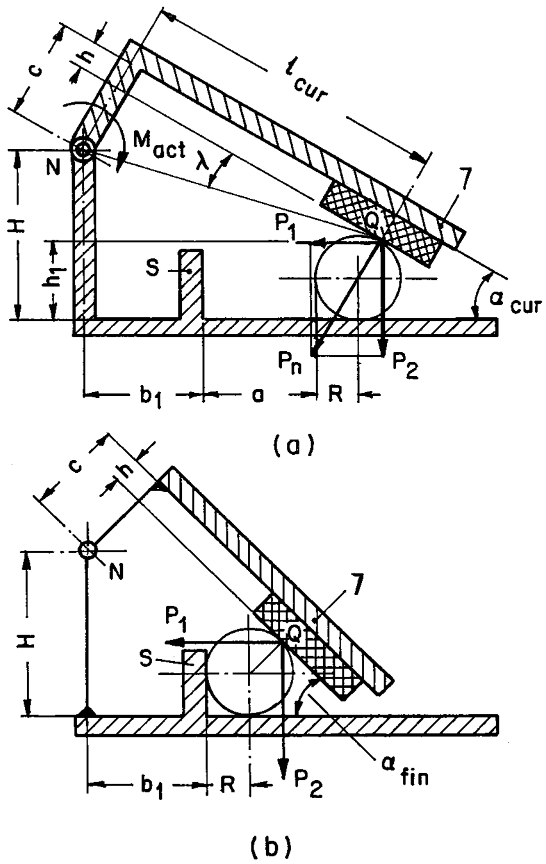

Fig. 2. Kinematics and statics of the grasping process for the cylinder part: (a) current position; (b) basing stop.

Two stages of the grasping process for the cylinder part are shown in Figure 2. The part 1 is clamped by active moment M_{act} when active link 7 is rotated around kinematic hinge N. The current stage is illustrated in Figure 2a, and the final stage, when the part is clamped, is depicted in Figure 2b. The long position of the part (Figure 3) is bounded by two walls 8 and 9.

The goal of the following analysis is to fix internal and external adaptive areas of the distinctive parameters for the design requirements. For the given structure of the gripper, an internal adaptive area is taken so that the part with dimensions within this area may be clamped by the given gripper. The external adaptive area includes "not-small" deviations of the position and orientation parameters of the

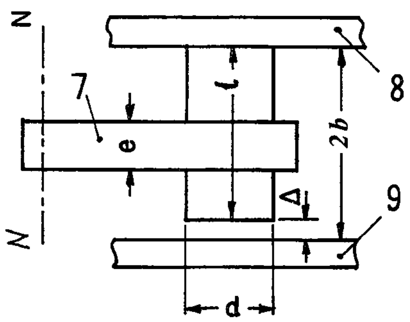

Fig. 3. Grasping the cylinder part: view from above.

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part, which do not preclude the clamping process. For the gripper structure by Figures 2 and 3 these parameters are:

- length l and cross dimension d of the part to be clamped;
- distance a between the mechanical constraint (stop S) and the initial position of the part [note that this parameter is the same X-position parameter a in formula (1)].

The simple geometrical analysis shows that the angle α between the active plane of link 7 and basis plane may be taken as a main structure parameter, formula (2), describing the clamping process. The value of this angle in the final position (when the part is clamped) is symbolized as α_{fin}, other positions are symbolized as α_{cur}.

(I) **Long position of the clamped body.** To prevent the progressive angular destination of the body axis (Figure 3), the gravity center of the body must be located in the limit of the width e of the active link 7:

$$2b - e < l < 2b, \text{ i.e.,} \quad K_{int,l} = (l_{\max} - l_{\min})/l = e/l \tag{9}$$

where $K_{int,l}$ is the internal adaptive factor relative to the length l.

To prevent self breaking the body between the walls, the distance Δ between the wall and the part must be chosen so that angle γ (Figure 4) meets the requirement $\gamma > \arctan f$, where f is the friction factor between the body and the wall.[15] This requirement corresponds to the following condition for design parameters:

$$d^2 + l^2 > 4b^2(1 + f^2) \tag{10}$$

In terms of formula (1), this inequality relates to angle ψ of part rotation about axis Z of the coordinate system associated with the part to be clamped (in this case, the Z axis is oriented perpendicularly to the drawing plane). The maximal value of the angle ψ for the part orientation may be calculated as follows:

$$\psi_{\max} \le \arctan d/l - \gamma < \arctan d/l - \arctan f$$

If $-\psi_{\max} \le \psi \le \psi_{\max}$, the part may be grasped successfully. The external adaptive factor is:

$$\begin{aligned} K_{ext,\psi} &= 2\, l \tan \psi_{\max}/d \\ &= 2\, l \tan [\arctan (d/l) - \arctan f]/d \\ &= 2\,(d - f)/[d(d/l + f)] \end{aligned}$$

(II) **Clamping the cylinder.** The adaptive properties are considered with respect to the distance a and radius R. A clamping motion (Figure 2a) is possible if the component P_1 of the active force is larger than friction forces acting along the same direction, i.e.

$$P_1 - k_f(P_2 f_2 - P_3 f_3) > 0, \text{ with} \tag{11}$$

$$P_1 = P_n \sin \alpha_{\text{cur}},\ P_2 = P_n \cos \alpha_{\text{cur}}, \text{ and} \tag{12}$$

$$P_n = M_{\text{act}} \cos \lambda / [(H - R) \sin \alpha_{\text{cur}} + (b_1 + a + R) \cos \alpha_{\text{cur}}]; \tag{13}$$

where P_1 and P_2 are the horizontal and vertical components of the normal force P_n acting on the part from the active link 7; λ is the pressure angle in the contact point Q (Figure 2a); f_2 and f_3 are factors of friction between the part and the base surface, and between the wall and the part, respectively; and k_f is the safety factor.

When the length l satisfies conditions (9) and (10), the friction force P_3 may be considered as zero. If the active moment M_{act} has the permanent direction shown in Figure 2 and the angles λ and α_{curr} meet the requirements $-\pi/2 < \lambda < \pi/2$, and $0 < \alpha_{\text{cur}} < \pi/2$, respectively, we obtain from expressions (11) and (12) that $\alpha_{\text{curr}} > \arctan (k_f f_2)$. Another bounder for α_{cur} may be obtained as follows. In the final clamping position, i.e., when $\alpha_{\text{cur}} = \alpha_{\text{fin}}$, the vertical component P_2 must be larger than friction force $F_1 = P_1 f_1$, where f_1 is factor of friction along the contact surface of stop S. Therefore, $\alpha_{\text{cur}} < \alpha_{\text{fin}} < \arctan [1/(k_f f_1)]$, i.e.,

$$\arctan (k_f f_2) < \alpha_{\text{cur}} < \arctan [1/(k_f f_1)]. \tag{14}$$

For example, if $k_f = 1.3$, and $f_1 = f_2 = 0.2$, we obtain $14.6° < \alpha_{\text{cur}} < 75.4°$. Furthermore, the current angle α_{cur} may be calculated from geometrical consideration of Figure 2a, as follows:

$$(H - R) \cos \alpha_{\text{cur}} - (b_1 + a + R) \sin \alpha_{\text{cur}} = R + h - c \tag{15}$$

This equation gives interrelationships between a and R in the domain of definition of the angle α_{cur} given by inequalities (14). Then constraints (10) with $d = 2R$ enable to calculate a range of possible values of a, R, and l, which may be defined as the area of adaptivity (AA) for the gripper according to Figures 2–4. There are two important partial cases:

- if the angle α_{cur} is constant, equation (15) gives the linear dependence between a and R:

$$\begin{aligned} a = H \cot \alpha_{\text{cur}} - b_1 + (c - h)/\sin \alpha_{\text{cur}} \\ - (1 + \cot \alpha_{\text{cur}} + 1/\sin \alpha_{\text{cur}})R \end{aligned} \tag{16}$$

- if $a = 0$ (it is the position, in which the part is clamped, and, therefore, the angle $\alpha_{\text{cur}} = \alpha_{\text{fin}}$) equation (15) gives the radius R as a function of α_{fin} as follows:

$$R = (H \cos \alpha_{\text{fin}} - b_1 \sin \alpha_{\text{fin}} + c - h)/(1 + \cos \alpha_{\text{fin}} + \sin \alpha_{\text{fin}}) \tag{17}$$

Numerical example. Parameters in Figure 4 are $35 \le l \le 40$ mm, and $e = 5$ mm, parameters in Figure 2 are $b = 20$ mm, $c = 21$ mm, $h = 6$ mm, $b_1 = 26$ mm, $H = 35$ mm, horizontal displacement a (Figure 2a) lies in-between $0 \le a \le 80$ mm, friction factors are $f_1 = f_2 = 0.2$, and safety factor is $k_f = 1.3$.

The calculations are performed in two stages:

(1) Configuration space for parameters d and l met the requirements (9) and (10) is shown in Figure 5 (cross-

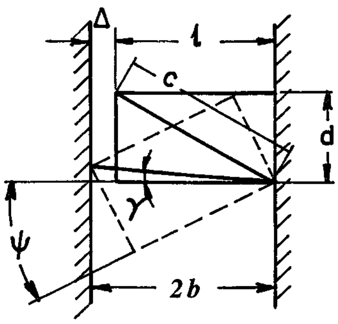

Fig. 4. A limiting position of the cylinder part in the horizontal plane.

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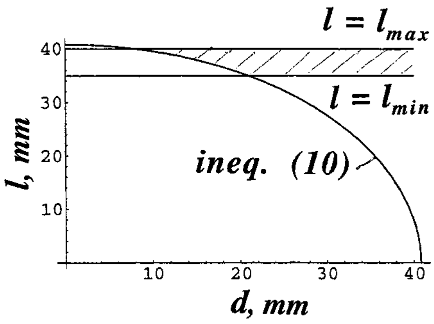

Fig. 5. Configuration space for combinations of lengths l and diameters d for the cylinder part.

hatched region). The adaptable area (AA) is located between two horizontal straight lines $l_{max} = 40$ mm, and $l_{min} = 35$ mm obtained from inequalities (9) and bounded below by the circle defined by inequality (10).

(2) Configuration space for parameters a and R met the requirements (9), (10), (14), and equation (16) is shown in Figure 6. The AA is bounded:

- to its right by vertical lines $R = R(l)$ obtained from condition (10) for $35 \le l \le 40$ mm;
- to its left by a line $a(R)$ obtained from condition (16) taking into account the left side of inequality (14), ie., $\alpha_{cur} > 14.6°$; an equation of this line is: $a = 168.27 - 8.8237\,R$.
- above and below by horizontal lines $a = 0$ and $a = 80$ mm.

For example, the AA when $l = 35$ mm is triangle ABC and the AA when $l = 40$ mm is quadrangle CDEF.

In the partial case when $a = 0$, condition (17) describes the clamped position of the body. In this case, $4.0 < R < 19.1$ mm. The internal adaptive factor with respect to the nominal radius R_{nom} is $K_{int,R} = (R_{max} - R_{min})/R_{nom}$. If, for example, $R_{nom} = 10$ mm, we have $K_{int,R} = (19.1 - 4.0)/10 = 1.51$. The external adaptive factor with respect to the distance a is $K_{ex,a} = (a_{max} - a_{min})/R_{nom} = (80 - 0)/10 = 8$.

(III) **Clamping the prismatic part** (Figure 7). The adaptive properties are considered with respect to length d of the

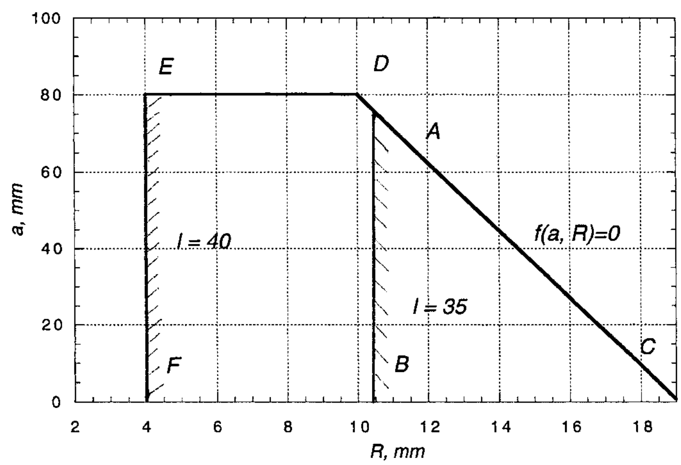

Fig. 6. Configuration space for combinations of maximal distances a from stop point S and diameters $2R$ for the cylinder part.

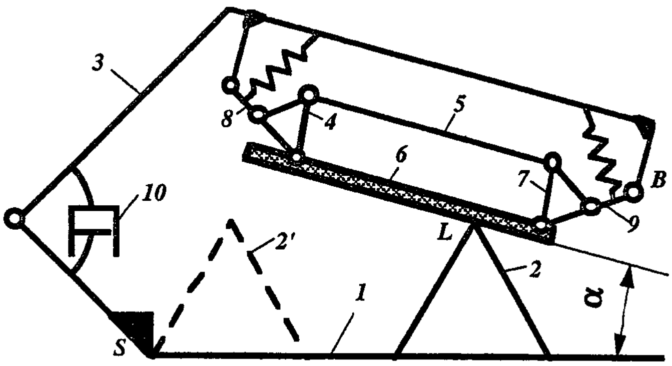

Fig. 7. An adaptive grasping device.

equilateral triangle in the cross-section of the clamped part. In this case, equations (9)–(14) remain unchanged, and conditions (15) has the form:

$$(H - d\sqrt{3}/2)\cos\alpha_{cur} - (b_1 + a + d/2)\sin\alpha_{cur} = h - c$$

Additionally, these conditions must be complemented by condition for preventing the upset of the part during motion:

$$\tan\alpha < k_b\, b_2/h_2 = k_b\sqrt{3}$$

where k_b is the safety factor; and α is either α_{fin} or α_{cur}. As usually, this constraint is harder than the right side of inequality (14).

3.2 Adaptive Locating

The locating process can be essentially intensified while an adaptive gripping device is used. The adaptive properties of the devices developed in this work are provided by automatic changing a shape of its jaw. A special kind of these mechanisms, which allows to solve the problem under consideration, is related to those called recently as under-actuated mechanisms.[13] The purpose of our present work is the development of our previous results[16–18] to establish the important practical properties of adaptation and location and to develop methods for study and design of this class of gripping devices.

An example of an adaptive gripping device layout is shown in Figure 7. One jaw 1 of this gripper is ordinary and rigid and contains a basing stop (point **S**). An object 2 must be moved from some arbitrary initial state and be fixed at point **S**. Another jaw contains the group of IV-class[4] of the second order (links *4*, *5*, *6*, and *7*), as well as fitted with springs links *8* and *9*, which connect the group to input link *3*. The springs are intended to maintain the group at a stable state when it is not in contact with the manipulation object, as well as to close a kinematic chain at point ***L*** (kinematic pair between object *2* and contact link *6*). The gripper also contains drive motor *10*.

To analyze the operations,[16–17], we first replace the higher kinematic pair at point ***L*** by lower kinematic pairs; namely, the revolute and prismatic pairs of the 5th class. The resulting mechanism (Figure 8) has three DOFs and does not work; note that link 1 is considered as motionless. To ensure the mechanism's workability, it is necessary to eliminate extra DOFs by fixing two of the joints. There are several ways to perform this.

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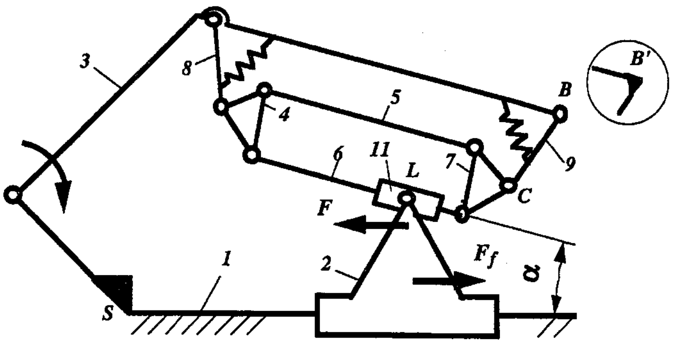

Fig. 8. Gripper with rubber contact plate.

Gripper with rubber contact plate. First of all, we may put a rubber plate on link *6* so that the plate makes contact with part 2 and prevents link *11* (Figure 8) from moving on guide *6*. Note that natural friction between materials of details *6* and *2* may play the same role. We then perform a fixation of a linear joint at point ***L***.

Let us consider the work process of such a device while gripping an object for manipulation. We will assume that a frictional force has previously acted on object *2* and prevented its motion on jaw *1*. The resulting mechanism has then the mobility $W=1$, and it may be used for adaptive locating. This process consists of several stages:

(i) *Stage 1*. At the initial gripping stage, a small force acts on object 2 from jaw *3* and a IV-class mechanism. The pressure from object *2* (namely, a reaction ***F***) does not surpass the value of the frictional force $F_f (F < F_f)$, and object *2* is at rest. Thus, the planar linkage takes place with the structural formula *I*(3)→*IV*(4, 5, 6, 7, 8, 9). Under the motion of the mechanism's driving link *3*, input link *6* rotates about point ***L*** as long as it is tight against the surface of object *2*. This stage of mechanism adaptation may be even completed earlier, when force ***F*** begins to surpass the frictional force $(F < F_f)$. Thus, object *2* starts to move along guide *1*.

(ii) *Stage 2*. The proper location stage begins. In the movement process, a mechanism is formed where link *6* and *2* are rigidly bound by means of the rubber plate. In this case also, $W=1$, and the mechanism structure is *I*(3)→*IV*(4, 5, 6+2, 7, 8, 9), with input link *6+2* connected by a prismatic pair to guide *1*. When object *2* reaches stop ***S***, it is fixed. The instance will be more precisely determined below. This reasoning is suitable if the need is to locate the object to the left (Figure 8).

An opportunity to improve this device is contained in the combination of the two described above regimes of adaptation and locating. This can result in fast-operation, since both adaptation and location processes could be conducted simultaneously. However, such a combination of regimes is presently impossible because of the redundant structure of the initial mechanism (Figure 8). There are several ways to obtain the workability of the initial mechanism by removing its extra DOFs using fixation of some joints of the mechanism.

Adaptive grippers with fixed joints. To eliminate extra DOFs from the mechanism, it is possible, first, to make the connection of links *3* and *9* rigid. The mobility of the obtained mechanism (see a balloon with point ***B′*** in Figure 8) is $W=1$, when one accounts for the frictional force between links *2* and *11*, and the mechanism is then efficient. Its structural formula is *I*(3)→*IV*(4, 5, 6, 7, 8, 2). When input link *3* of the linkage is moved, gripper output link *6* is rotated about point ***L***. The adaptation process then occurs, and, simultaneously, object *2* is located along jaw *1* to stop *S*.

An approach with the joint ***B*** fixation may be developed, while at the same time fixing, for example, joint ***C*** to eliminate extra DOFs. This solution is theoretically possible, but it makes the high-class group immobile. In this case, the studied HCM is reduced to an ordinary gripper with two rigid fingers where the grasping process occurs, as it was considered in Section 3.1. It is clear that this grasping process is not adaptive and also not universal, because it depends very much on the frictional and geometrical characteristics of the jaws and the object to be manipulated. It may be seen that the above considerations have a general form and are valid for different shapes of manipulation objects.

Example. Let us consider an arbitrary position of the object (Figure 9). It has one DOF in the position in the Figure, since it can move along the Y axes of the tool coordinate system connected with the end-effector. The object is stopped at the extreme left by means of support *6*. Guideways of the object may be described as a set of five supports 1, . . . , 5 shown in Figure 9. Vectors $\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$, $\mathbf{R}_4$, and $\mathbf{R}_5$ are described by Plucker's coordinates of these supports.

For **Stage 1** of the grasping process, the support matrix compose of vectors $\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$, $\mathbf{R}_4$, and $\mathbf{R}_5$, and part 2 has one DOF. For **Stage 2** (the part 2 is clamped), the support matrix is formed by the addition of vector $\mathbf{R}_6$:

$$\mathrm{R}_d = (\mathbf{R}_1, \ldots, \mathbf{R}_5, \mathbf{R}_6)^{\mathrm{T}} = \begin{pmatrix} 0 & 0 & 1 & c & b & 0 \\ 0 & 0 & 1 & v & b & 0 \\ 0 & 0 & 1 & v & -b & 0 \\ 1 & 0 & 0 & 0 & 0 & -c \\ 1 & 0 & 0 & 0 & 0 & -v \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix},$$

with $v=c+d$, $det\ \mathrm{R}_{dl} = -2bd^2 \neq 0$, i.e., the location process

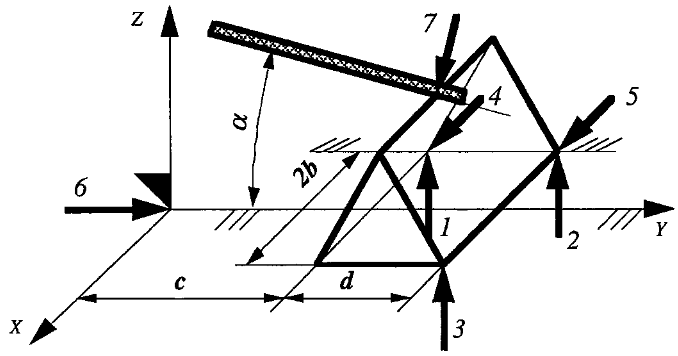

Fig. 9. Formal interpretation of the supports set.

is finished. Since the force acting along direction *7* (Figure 9) is non-zero, reactions p_1, p_2, p_3, and p_6 are positive. Note that matrix R_d presents one of the versions of the well-known 3 + 2 + 1 locating system.

4. SIMULATION OF AN ADAPTIVE GRIPPER

4.1. Graphic Simulation Model

Existing robotic simulation packages allow one to simulate robots and other multiple-DOF mechanisms and provide rapid workcell layout and automatic program generation and verification.[19] Using graphic simulators, cycle times can be predicted and different scenarios can be evaluated not only for technical feasibility, but for optimum plans and maximizing utilization and efficiency. In addition, graphic simulation is an essential step for initiating the design process and enabling assessment of alternative concepts and designs in a timely manner. Another advantage is that it provides a realistic, visual, easy to understand model of the actual operations.

The model of adaptive gripper was developed using RobCad,[20] a CAPE (Computer Aided Production Engineering) system on a Silicon Graphics Iris workstation. A full 3D model of the gripper structure was implemented and analyzed. Graphic simulation of locating processes of different objects was performed. To construct the graphic simulation model, the following steps were conducted:

(a) **Geometric model of the system.** All the gripper components were drawn separately as solids with actual dimensions.
(b) **Kinematics definitions.** The kinematic parameters (joint type, range, speed, acceleration and motion type) were defined for each joint. The kinematic structure was built by defining the relationship between every pair of joints. Implementation of the closed-link structure required the use of special functions that connected the parallel links, in addition to the standard definition of parent-child linkages. Inverse kinematics of the structure was then computed automatically by the software package.
(c) **Workcell design.** To design the task, it was necessary to combine all the components into the desirable workcell and check its validity. Workcell design included the definition of locations of the gripper's path from its initial location, down to its contact with the object, and final basing stop.
(d) **Task definition.** A task program was written in TDL (task description language) for the gripper and for the object moved. This was achieved by a sequence of move commands to locations along the path.

4.2 Results and Discussion

Figure 10 shows the animation of two of the objects simulated – a risosceles triangle (the angles of the triangles are 35° and 90°, the height is 25 mm), and a cylinder with a radius of 25 mm. Graphic simulation of the model prior to prototyping made it possible to visualize and understand the grasping process. The kinematic model was designed accurately by developing a CAD model of the system components and then defining the kinematic relations between each joint. There was no need to compute the kinematic equations of the complex gripper structure. The kinematic equations are then generated automatically by the software based on the kinematic structure definition. This enabled fast evaluation of different link dimensions and connections between them, in parallel to the actual development of the mathematical model.

The model demonstrated the feasibility of the proposed adaptive grasping technique and enabled the evaluation of alternative kinematic structures in a timely manner. Further simulations can be performed using this tool to evaluate and optimize the proposed universal gripper, for example, to select optimal link lengths and to determine optimum motor speeds.

5. DEVICE PROTOTYPING

A practical part of the investigation consisted of designing and building an operational gripper model. The model (Figure 11) was built from a plastic material and driven by a DC motor (10A, 12V). Experiments were conducted to evaluate performance based on different operational characteristics. The spatial objects with following cross-sections were used for the experiments:

- T1 – "golden triangle" with angles 30°, 60°, 90° (height is 44 mm and base is 50 mm);
- T2 – risosceles triangle with angles 35°, 55°, and 90° (height is 25 mm and base is 50 mm);
- C – cylinder with radius 25 mm;
- P – pentagon with height 47 mm.

The time of location from a certain initial position of each object was experimentally studied. The changed parameter of interest was mobility in joint ***B***; that is, our theoretical considerations about location process acceleration while fixing this joint were checked. Results (Table I) indicate that the location time is reduced for the second scheme by an average of 34% as compared with the first scheme. This confirms results determined from the above structural-kinematic analysis. Based on the evaluations above, a gripper was designed and fitted for a 5-DOF articulated robot. It was implemented (Figure 12) specifically for the case of a parallel shift of robot jaws. The preliminary tests indicated the workability of our approach.

6. CONCLUSION

The "in-hand" locating problem of robotic grasping is considered. Two approaches based on the use of non-adaptive and adaptive locating processes are analyzed. Methods for design of corresponding technical means are developed. The non-adaptive locating process can be performed when using the most simple device – the ordinary gripper with rigid, non-parallel jaws. However, this kind of locating process is not universal and depends very

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much on frictional and force characteristics of interactive bodies (jaws and the object to be manipulated).

Another approach is based on the use of an adaptive jaw, which is capable of change of its shape resulting from a contact with the part to be located. A relative new type of grasping mechanisms are proposed for this purpose. These mechanisms fall in the group known as HCMs[12] or underactuated mechanisms.[13]

The new class of mechanisms used allowed to perform a location process, combined with an adaptation process, with imprecisely determined initial coordinates of a manipulation object. This opens the possibility of implementing a practical class of universal robotic grippers for industry. The proposed solution uses simple technical means (based on an ordinary linkage and one drive motor in the main version) and requires no sensing. The adaptive gripper considered in the paper is, in fact, an example of the whole class of such mechanisms capable of solving not only planar but also 3D locating tasks.

Structural-kinematic and static relationships were obtained in order to explain the theoretical basis of adaptive grasping processes. Performed simulation and prototyping confirmed the workability of this approach and indicated achievement of the desired properties. The described grippers allow one to reduce the number of grippers with which a robot is equipped. This reduces robot cost and the

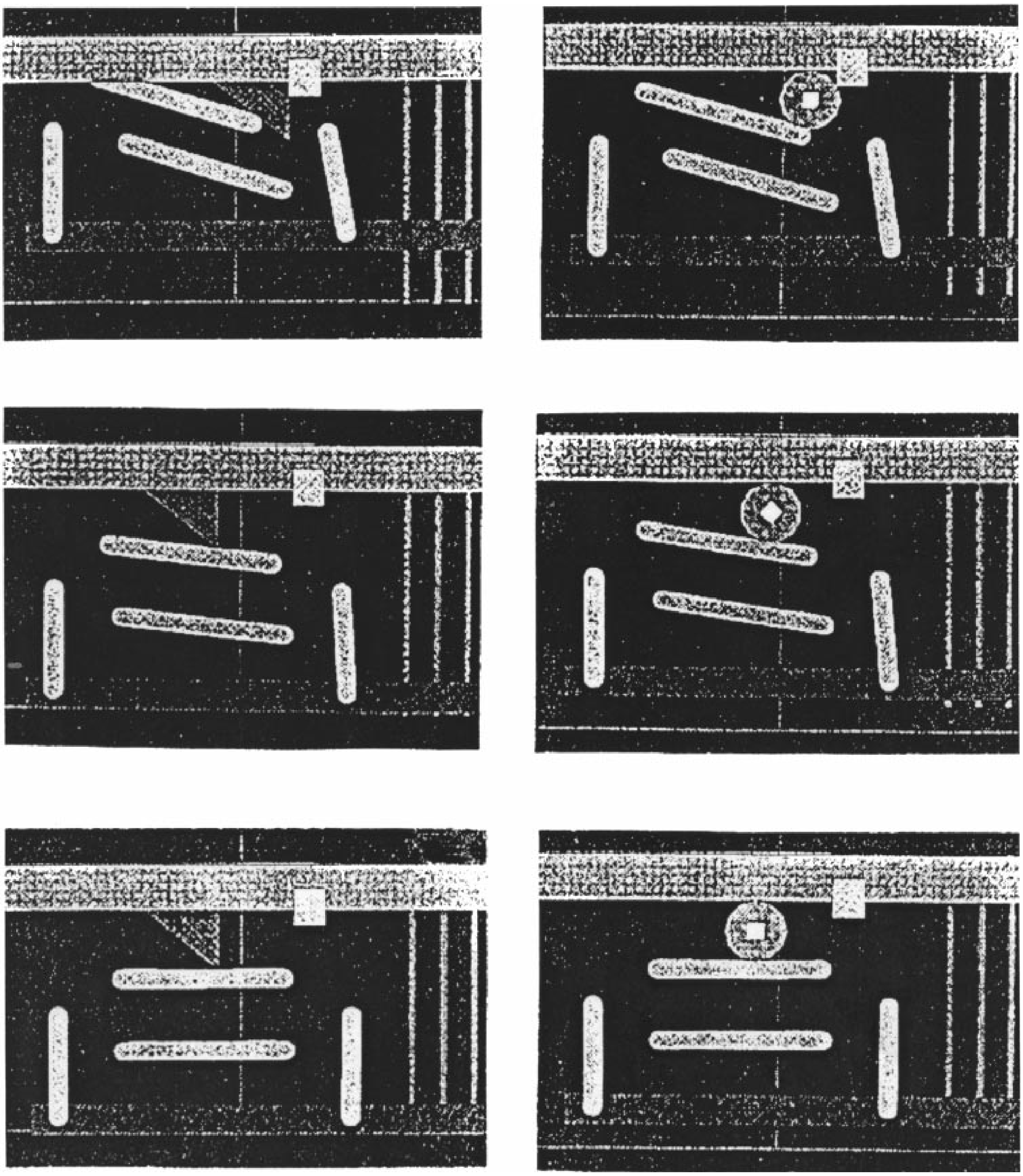

Fig. 10. Graphic simulation of a universal gripper grasping (a) a cylinder object and (b) a risosceles triangle: upper row – the contact point; intermediate row – the current step; the bottom row – the basing stop.

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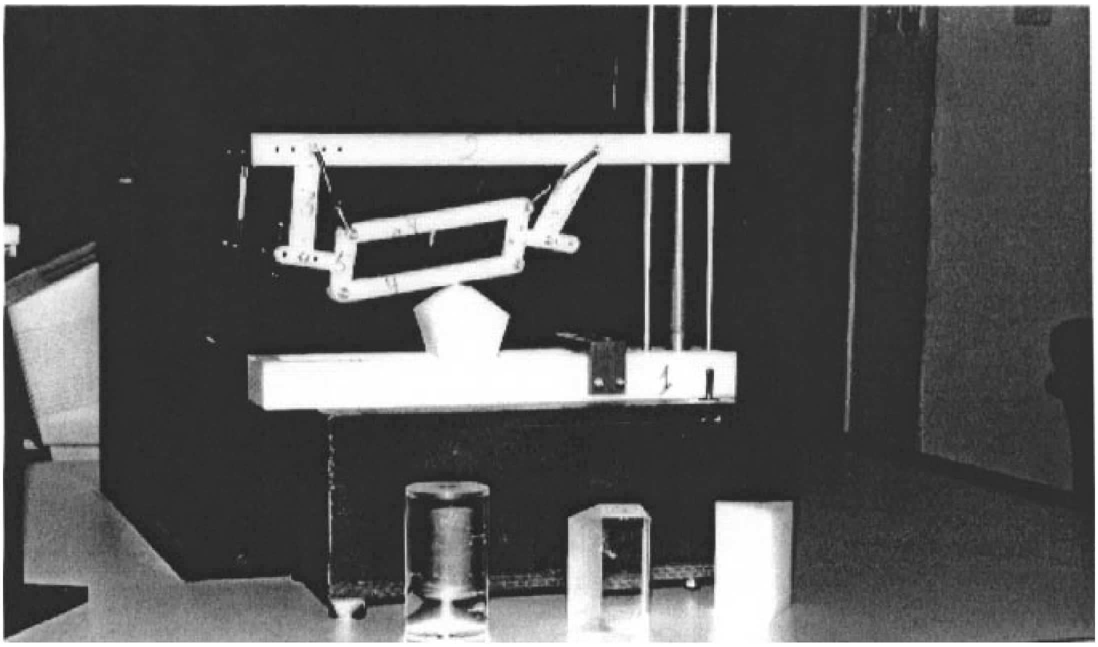

Fig. 11. An acting gripper model.

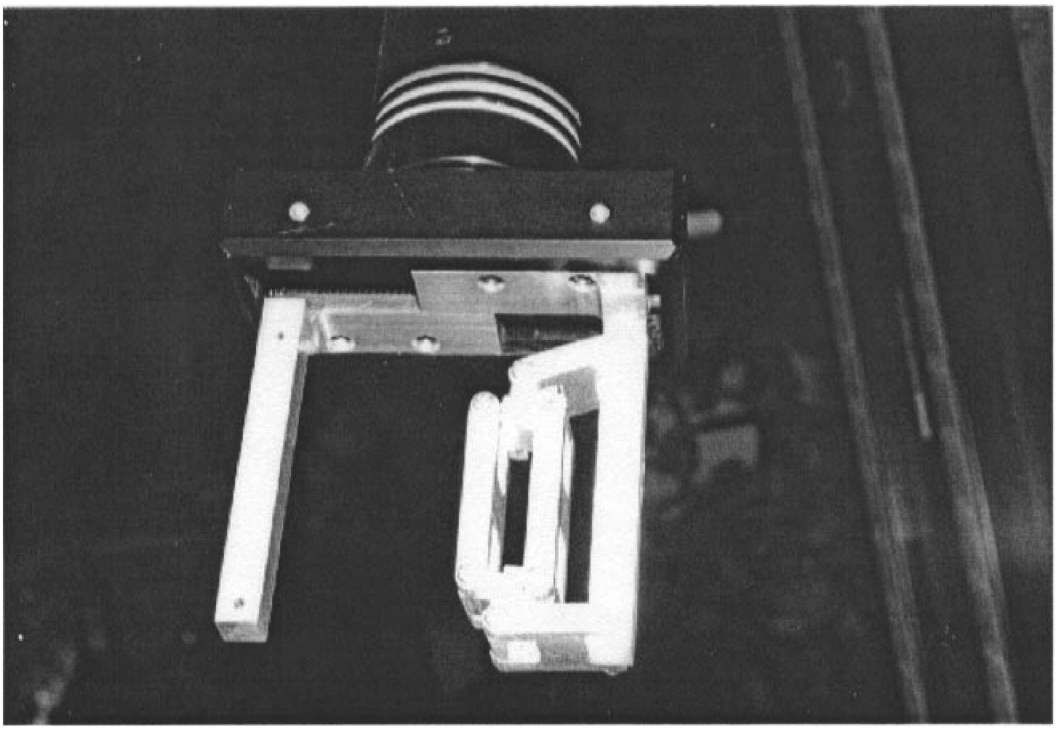

Fig. 12. A gripper for a 5-DOF articulated robot.

time to re-adjust the robot to a new technological operation. Hence, it may ensure high efficiency in industrial robotics.

Table I. Experimental location duration (sec) for different objects.

Object type	T1	T2	C	P	Average
Basic scheme	15	14	7	11	11.75
Scheme with joint ***B*** fixation	8	10	5	8	7.75

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