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Robotized Peg-in-Hole Task Involving the Needle-Like and Pill-Like Objects with Tight Tolerances

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Abstract

Handling and assembly of the needle-like and pill-like objects is a delicate task, particularly if tight clearances are involved. In both cases the key issue is a compromise between the opposite requirements of holding firmly the object and, at same time, allowing it to have the adequate properties of passive compliance. In this paper we describe our approach to achieving this for both type of objects using the sensors with soft contact surfaces (SwSCS) [5-7]. *For insertion of needle-like objects we take advantage of using soft rubber layers placed on top of the sensors composed in such a way to ensure the object's desired behaviour. During assembly we applied variable grasping force to overcome critical situations when the object motion inside the hole is limited by clearance while, the resolution of the robot's motion is lower compared to it. In case of the pill-like object we constructed a special device for parallel grasping, to decouple the sensor cells for sensing forces in the grasping phase from those involved in the assembly itself. Both approaches were successfully tested by experiment.*

1. Introduction

A compliant behaviour of the object in contact with the environment can be achieved by various control techniques. This is a key issue in robotized realization of any type of contact tasks. By eliminating rigid contact surfaces of the gripper grasping the object, i.e. by using elastic material between the hard object and the gripper "skeleton" [1,2] (soft grasping) a passive compliant behaviour can be achieved. It is also important to enable on-line measurement of the grasping forces between the gripper and the object. The idea of soft sensors enabling compliant behaviour of the grasped object was initially proposed in [3]. In [4], an improved design of the sensor was presented which minimizes the number of necessary sensing elements and improves the overall information relevant to the realization of contact tasks. Further development of this idea yielded the realization of a new sensor in which soft and elastic elements cover the whole body of the sensor, and with optocouplers as non-contact sensing elements [5-7].

Such sensors are capable of fulfilling various requirements arising from the application in different tasks. In assembly of small pill-like objects it is how to make a compromise between the opposite requirements of holding the object firmly enough (relatively large grasping forces are needed) and at the same time, allowing it to have the properties of passive compliance. In case of inserting the needle-like objects with tight clearances it is how to realize compensational motion if the resolution of robot motion is below the allowable object motion limited by clearance. In this paper we propose an approach to the realization of insertion of the objects of both types.

1. SwSCS with optocouplers as sensing elements

The basic idea of the sensor design [5-7] is illustrated in Fig. 1. The body of the sensor (3) is made of rubber of the appropriate hardness, sandwiched between two rigid plates (2,4), whereas the top layer of soft rubber (1) ensures adaptation of the contact surface to the local object shape. In this design, relative displacements of the rigid plates in normal and tangential directions are measured. Holes of appropriate shapes are made inside the hard rubber. They are used for placing the sensing elements. Reflexive optocouplers, each consisting of an in

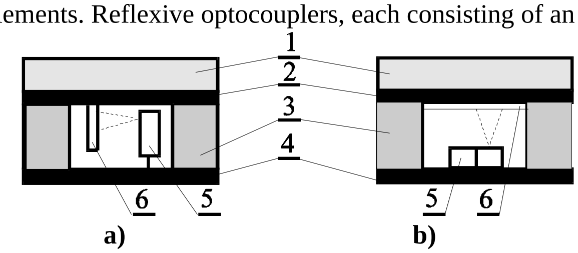

Fig. 1. Sensing cells

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plane mounted light emitting diode and a phototransistor (5) are used as sensing elements. They are fixed to the lower rigid plate, which is connected to the finger hard core, while the reflexive surfaces (white paper) (6) are attached to the inner side of the upper rigid plate. In Fig. 1 are shown the sensing cells for measuring the normal (a) and tangential (b) deformation. Both cells are of identical shape, only the disposition of optocouplers and reflexive surfaces is different. The modular design using sensing cells for measuring force in a certain direction enables us to compose a sensor of desired complexity. Two versions of such sensors with three [6] and eight [7] sensing cells

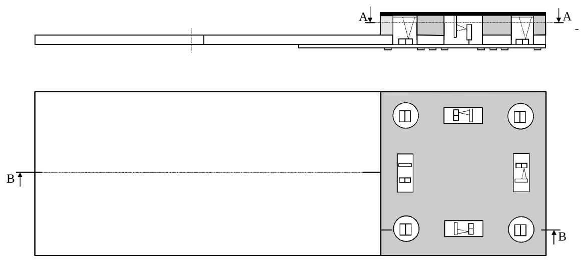


Fig. 2. Sensor composed of eight sensing cells

have been realized, the latter one having especially good characteristics. In Fig. 2 is sketched a sensor composed of eight sensing cells. The sensor is capable of measuring normal force at four points in the corners of the sensing area, while the other four places are filled with the cells for measuring of tangential forces in two mutually orthogonal directions. Such sensor is capable of measuring inclination of the contact surface, axial forces in two mutually orthogonal directions, as well as the torque applied in the direction orthogonal onto the contact surface. (In Fig. 2 is not shown the soft rubber layer (layer 1 in Fig. 1)).

3. Assembly of needle-like objects

3.1. Basic characteristics of the peg-in-hole task

The most relevant information for realization of the "peg-in-hole" task is the type of contact and intensity of contact forces between the object and the hole. Initial contact usually takes place in the chamfering cone (Fig. 3a) and the main problem in this phase is how to eliminate positional Δa and angular α deviations and introduce the object tip into the hole. In the second phase, insertion is initiated. In this phase, contact of the object and the hole is at one point and, to balance the object (usually with large inclination) a moment should be applied on the grasped object end (Fig. 3c). As insertion is progressing the alowable inclination angle decreases (Fig. 3b), and at a certain depth, two-point contact will occur. Then, the compensational gripper motion will change the normal forces (not the moment as in the prevous phase) applied on each of the fingers by the object grasped end. Usually, both fingers remain in contact, but in Fig. 3d is shown the

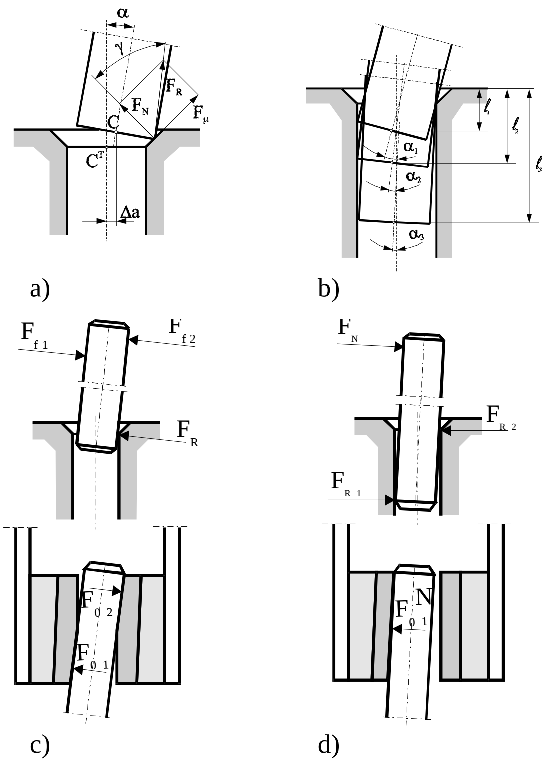


Fig. 3. Phases of the "peg-in-hole" task

extreme situation when only one finger is in contact with the object. If resolution of the robot motion is lower than the allowable object motion the main contribution in task continuation is played by soft and elastic top layer, as desribed in the followig section.

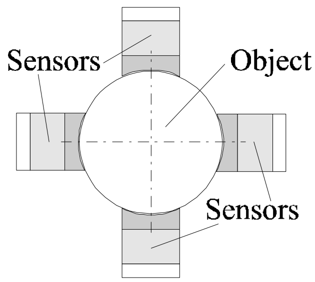
Additional problem relating the needle-like objects is grasping. In our previous experiments with the objects of "normal" size we used four SwSCS of three sensing cells disposed as in Fig. 4a [6]. It is practically impossible to apply the same approach in case when the object diameter is too small. Instead, we used two SwSCS with eight sensing cells each (Fig. 4b) and two-fingers parallel gripper. The sensor's design [7] enables acquisition of all the necessary information for task realization.

3.2. Task realization

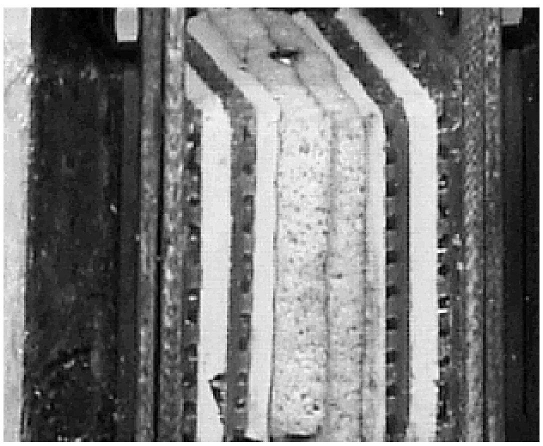
We performed the "peg-in-hole" experiment with the needle-like object [8] whereby the clearance between the object and the hole is smaller than the resolution of the robot motion (62.5μm). The object length was 90 mm, with diameter of 3.5 mm and clearance about 30 μm. The hole was made in a 20 mm thick steel block. After the initial contact, the robot was commanded to insert the object for 30 mm, to make it visible when the object's lower tip comes out of the block at the end of the task execution.

The object is grasped softly with the fingers having the sensors with soft contact surfaces enabling the object to move within the gripper and simultaneous measurement of the contact forces acting on each of the gripper fingers.

The soft layer placed on top of the basic sensor structure (shown in Fig. 2) was composed of three rubber layers: two layers of the table tennis racquet rubber and the top layer of very soft and elastic expanded rubber (Fig. 4). During the task execution we applied variable grasping force to change the grasping stiffness of the object, aiming at the control of excessive contact force between the object and the hole, to avoid the occurrence of a too high



a)



b)

Fig. 4. Grasping of the object

friction force. The task itself is realized in three main phases: elimination of the initial positionning and inclination error, “shallow-insertion”, and “deep-insertion” phase. In the first phase, which usually takes place in the chamfering cone, large initial positional Δa and angular α deviations (Fig. 3a) should be compensated. In the second phase, the insertion itself is initiated. In this phase, the contact of the object and the hole is still at one point, and large inclination of the object is still possible (insertion depth l_1 and inclination angle α_1 in Fig. 3b). As insertion is progressing the allowable inclination angle decreases. Thus, for "deep-insertion" the maximal transversal displacement of the object's grasped end is dominantly limited by the magnitude of clearance. At a certain depth, two-point contact occurs, which marks the beginning of the third phase. It should be mentioned that during the task execution the insertion force F_{IN} in the direction of the object axis is constantly applied. Force intensity is monitored and kept within the predefined region $F_{IN}^{min} < F_{IN} < F_{IN}^{max}$. This force causes elastic deformation of the soft layer, enabling thus instantaneous partial insertion if $F_{res} < F_{IN}$ (F_{res} is the force resisting insertion).

Phase 1

Initial contact in the first phase usually takes place within the chamfering cone, and both the object inclinati-

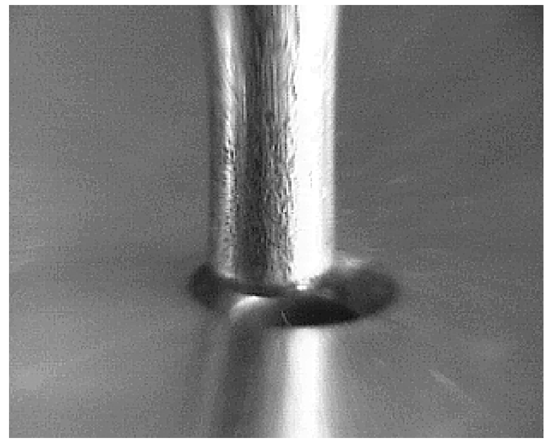


Fig. 5. Initial contact in the chamfering cone

on and positional deviation of the object tip should be compensated (Fig.5). First, the gripper rotates to achieve a parallel position of the sensor's surface to the tangent at the contact point of the object and chamfering cone. Then, to realize more precise centering the gripper partially opens, to lower grasping force. After that the gripper travels across the hole till the opposite side of the chamfering cone is detected, and then the object has to be centered.

Phase 2

Because the expected insertion resistance is low, the second phase starts by resuming the initial grasping force. The object is in contact with the hole at one point only, and the sensors measure the moment applied by the grasped object end on the gripper fingers. Compensational movement of the gripper (it is orthogonal to the hole axis, i.e. in our example it is horizontal) decreases this moment, as well as the object inclination, which enables progressing of the insertion. The insertion step is inversely proportional to the insertion resistance, while the step of the gripper performing horizontal compensation movements is directly proportional to it.

Phase 3

At a certain depth, due to low clearance and insufficient robot resolution, the object jamming at two points occurs (as shown in Fig. 3d). This situation is detected by measuring the rapidly increasing force in insertion direction caused by the insertion resistance. The previous algorithm becomes inappropriate to achieve again a low insertion resistance. Instead of measuring the moment applied by the gripper fingers, we measure now the total normal force on each of the fingers (Fig. 3d). The corrective horizontal motion in the direction of the larger force makes the contact point of the object and the hole to shift to the opposite hole wall. During this transition period the inclination of the object decreases while the object axis gets closer to the hole axis, and then it increases till the object hits the opposite side of the hole. While the object axis is close to the hole axis, the two-point contact becomes one-point contact, the resistant force decreases, and the elastic force of the soft material performs partial

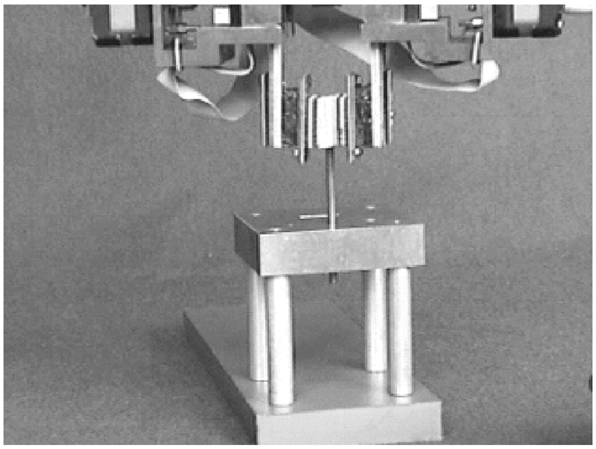


Fig. 6. Task execution

insertion of the object at the moment when insertion resistance is low. In this stage, the magnitude of the vertical insertion step changes exponentially and it is inversely proportional to the insertion resistance. In case of jamming, the grasping force and, consequently, the grasping stiffness, is lowered, to decrease contact friction force between the object and the hole. The procedure is repeated till the task is completed (Fig.6).

4.0. Assembly of pill-like object

4.1. Grasping

Let us consider the problem of grasping a thin pill-like object (Fig. 7) which has to be inserted into the hole of the same nominal diameter with tight tolerances. A serious problem arises as the parts are small and there is no enough space for classical grasping as in the previous example. Furthermore, grasping of the object has to be performed in such a way that the object's height H is not occupied completely with the fingers: In case of using of SwSCS to grasp the object directly (the object is in a direct contact with the sensor's top layer (layer 1 in Fig. 1)) the grasping subtask is performed by the sensor edges (Fig. 8). However, this way of grasping is not reliable because the object can easily slip out of the fingers. Additional problem is the initial inclination of the sensor surface and consequently, the activation of all sensing cells already in the grasping phase. To achieve a stable grasp we designed special rigid "fingers" (Fig. 9) capable of applying larger grasping forces. The fingertips are co-

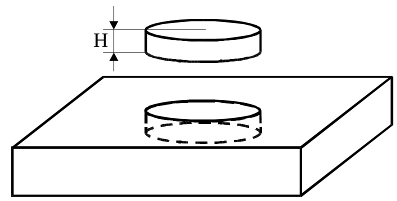


Fig. 7 Small planar pill-like objects

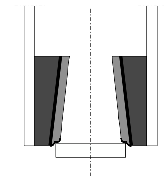


Fig 8. Inclination of the contact surfaces in direct grasping

vered with rubber to ensure sufficiently large friction force for reliable grasping. Each finger has additional limiter, to prevent the object slippage in the axial direction and leave a free portion of the object's height H needed for partial insertion of the object into the hole while it is grasped.

Let us suppose that the sensor surfaces remain parallel in the course of grasping. In such a case, only the normal sensing cells (four cells in the corners, Fig. 2) are activated, the other four cells remaining available for the

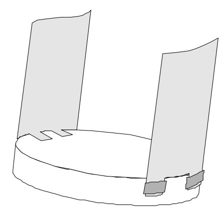
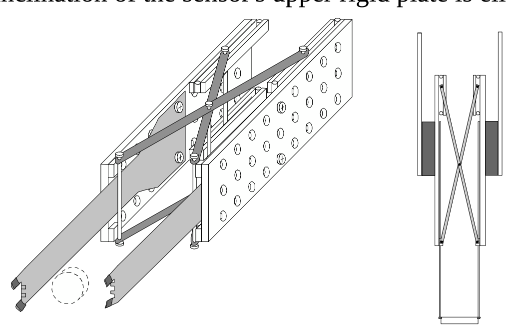


Fig. 9. "Fingers" for object grasping

rest of the process. To achieve such allotted use of the sensing cells we constructed a special device for parallel grasping (Fig. 10a), to which the already described rigid fingers for object grasping are attached.

During the device closing and object grasping with a desired grasping force, despite of the fact that the grasping action takes place out of the sensors, the parallelism of the mechanism plates is preserved. It ensures that the inclination of the sensor's upper rigid plate is eliminated**,**



a) b)

Fig. 10. Parallel mechanism with "fingers " for object grasping and the mechanism built in the gripper

i.e. they are loaded by pure normal force. Thus, the sensing cells for axial forces are not involved in grasping. Such "decoupling" of the grasping process from the rest of the task ensures that one set of sensing cells is used for the assembly subtask only. Because the object is not in a direct contact with the sensor, the top soft rubber layer (layer 1 in Fig. 1) could be removed and the device attached directly to the upper rigid plates (position 2 in Fig. 1), as shown in Fig. 10b.

4.2. Object centering

Centering is a very delicate step in the task execution because of the object's shape, size, and tolerances (small inclination causes jamming). The centering procedure is described in the text to follow.

4.3. Task execution

To perform assembly, the initial angular and positional deviations between the object and the hole (Figs. 11 and 12) have to be eliminated. Centering has to be achieved on

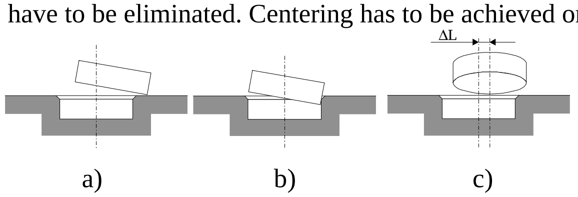


Fig. 11. Object inclination and centering deviation at initial moment

the basis of the sensors readings when the object touches the hole. The task is performed in five steps:

1. grasping,
2. detection of the surface of the object with hole (as sketched in Fig. 11a),
3. hole finding (as sketched in Fig. 11b),
4. centering (elimination of positional devation, (as sketched in Fig. 11c, for 90 deg rotated wiev),
5. elimination of angular devation and insertion.

Each step will be described separately.

Step 1

The object grasping is performed manually. During this, all sensing cells are offset, i.e. all current readings from the sensing cells are considered zero. After that, 50 readings are performed and the average value is taken as the starting value for all sensing cells.

Step 2

The gripper with the grasped object moves down till contact with the object surface occurs. When comes close to the object surface, the gripper moves in the increments of 0.1 mm. After each increment, the force in the insertion direction is checked. When the contact is achieved, the gripper stops.

Step 3

The next action is the motion toward the expected hole position (to left in Fig. 11.a). When the hole edge is detected, the motion is continued to the occurrence of the moment decrease, which ensures the object enter the hole. The insertion depth is defined by the intensity of elastic deformation of the sensor body occuring when the contact of the grasped object with the environment is established.

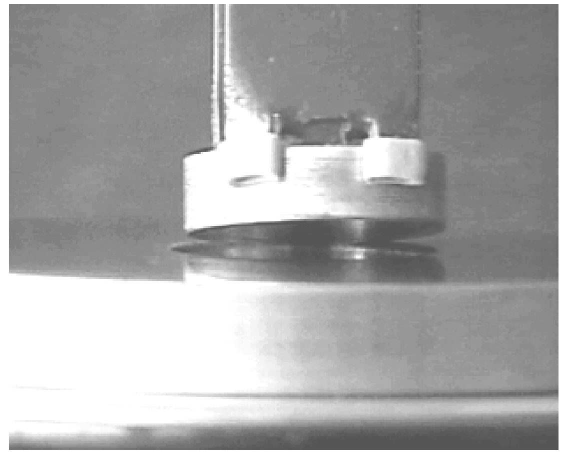


Fig. 9. Relative positions of the object and the hole during centering

Then, the object is moved down by 0.2 mm, to ensure a stable contact and reliable execution of the next phase.

Step 4

Because of the very tight tolerance it is necessary to ensure in this phase the best possible centering of the object within the hole, i.e. the centering deviation, ΔL, should be as small as possible. For this purpose, the gripper moves laterally in one direction till the desired moment intensity is attained. Then, the gripper position is recorded and the procedure repeated, but in the opposite direction. The centering position is determined as the position in the middle between the two recorded positions. This procedure is repeated till the difference between two successive centering operations is small enough.

Step 5

The last phase is the insertion itself. The object inclination has to be eliminated first. This is performed in the increments of 0.5 deg, and after each correctional action, the moment acting in the plane of correction is checked. If the moment is increased, the gripper moves by 0.1 mm in the direction yielding its decrease. Then, the insertion is attempted in the object's axial direction. If the axial force exceeds the predefined intensity, the object is pulled out for 0.5 mm, correction is repeated and the procedure is continued till the final insertion.

Another experiment with the same object and hole was also performed, but with the initial displacement and angular deviation changed to match closer a situation in industial applications. The initial angular deviation was eliminated, while positional displacement was set at random within the chamfering cone. The initial position of the objects is shown in Fig. 13. As could be expected, the

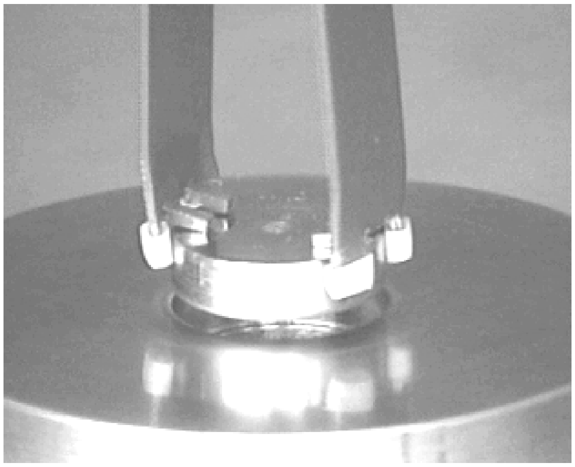


Fig. 13. The assembly experiment with smaller initial deviations

assembly task was now accomplished very fast, which suggests the approach could be potentially interesting for the real industrial use.

5. Conclusion

We described a procedure for performing the "peg-in-hole" task involving two quite different types of objects (needle-like and pill-like), with tight clearances. We showed that the use of sensors with soft contact surfaces placed on each gripper finger enables successful task execution. For inserting the needle-like objects we added a layer of very soft and elastic rubber on the top of the sensor. During the task execution we applied variable grasping force to change the grasping stiffness of the object, for the purpose of controlling the excessive contact force between the object and the hole, to avoid the appearance of a too high friction force. During the gripper motion, when the allowable object motion was lower than the robot's resolution, the elastic force of the soft material performes passive partial insertion at the moment when insertion resistance is low. This enables to prevent jamming. To insert small pill-like objects we constructed a special device for parallel grasping which enables additional decoupling of the sensing cells (one set of cells is used in the grasping subtask and the other one in the assembly itself) and the firm grasping while allowing the necessary passive compliance behaviour of the object. Both experiments were performed with success.

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