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Behaviour-based peg-in-hole

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SUMMARY
Given the high occurence rate in assembly industry, mating a peg into a hole can be considered as one of the most classic problem in robotics. Such a task has been extensively examined by many researchers who have repeatedly attempted to find out a general solution for it. Peg in hole, which is, needlessly to mention, extremely trivial for any human operator, is surprisingly difficult to have it carried out by a robot manipulator. The reason is partly due to a physical limitation of the mechanical compliance of the robot wrist and arm and partly to a lack of a mating strategy allowing the successful execution of the task whatever the initial position of peg and hole axes is. The work presented in this paper tackles a particular class of peg-in-hole (tandem peg-in-hole) and proposes within the behaviour-based paradigm a solution to its two main components (hole search and peg insertion) loosely modeled on the equivalent strategies performed by a blind human being in possess solely of the same sensing capability (*i.e.* a simple differential touch sensor).

KEYWORDS: Peg-in-hole problem; Assembly robotics: Behaviour-based approach.

1. INTRODUCTION
As soon as we as human beings talk about putting a peg in a hole, we think of an extremely simple and trivial task which any normal human being can perform without particular problems. However, when an operator tries to have the very same task carried out by a robot, surprisingly he or she incurs enormous difficulties, difficulties which clearly show how complex apparently simple tasks such as this really are. My interest for peg-in-hole, though, is not confined just to this realisation. Such a task is one of the most common in manufacturing assembly industry,[1] and at the same time one which hides in its simplicity most of the difficulties of assembling parts. But why is it so hard for a robot to carry it out? One of the reasons lies in its limitations in sensing the surrounding environment,[2] but yet it is not the main one.

Any robot is not conscious of what it is doing:[3] the only thing that matters is moving its end-effector to a well specified position and once there performing any eventual action like screwing, grasping, spraying, or whatever. In the specific case of peg-in-hole, if a peg is for some accidental reasons wrongly gripped, or if a hole is not exactly in the location expected, a manipulator would be most of the time unable to mate successfully the parts without any human help. What is really missing is a description of the task in terms which enables the robot to cope with the uncertainty embedded in the world.[4] The Behaviour-based assembly approach, which assumes a plan to be expressed in terms of task-achieving units called behavioural modules, may be a possible answer and here I show that peg-in-hole can actually be reliably accomplished within the terms of such a paradigm.

The work presented here in this paper is organised as follows: section 2 describes related research works; section 3 states clearly the assumptions underlying the investigation carried out and its limitations; section 4 presents the experimental setup employed; section 5 outlines my implementation of peg-in-hole within the behaviour-based paradigm; section 6 and section 7 describe then the strategies to find a hole and insert a peg, respectively; and finally section 8 draws conclusions.

2. RELATED RESEARCH
As can be easily gathered by its name, peg-in-hole consists essentially in inserting a peg into a hole.[5] In this regard, I assume, as most of the researchers tacitly do, to deal just with rigid parts. The reason is that, despite the fact that they do actually occur,[6,7] flexible parts matings are not so common in manufacturing assembly industry. Thus, it does not constitute a big limitation in the following discussion assuming to disregard them.

The great majority of the relevant literature views peg-in-hole as a four-stage process:[8] approach, chamfer crossing, one-point contact, and two-point contact (Figure 1).

During this last a peg may get stuck and two situations may arise: jamming and wedging. The former occurs because of wrongly proportioned forces and moments applied to the peg through the support, and the latter because of linear dependency of the resultant forces at the constraints.[9]

In order to limit the occurrence of these situations and to increase peg-in-hole mating success rate, special hardware devices exploiting mechanical compliance have been introduced: the remote centre compliance (RCC) for passive part mating,[10] and the instrumented remote centre compliance.[11] The latter, which enhances the former by adding active force

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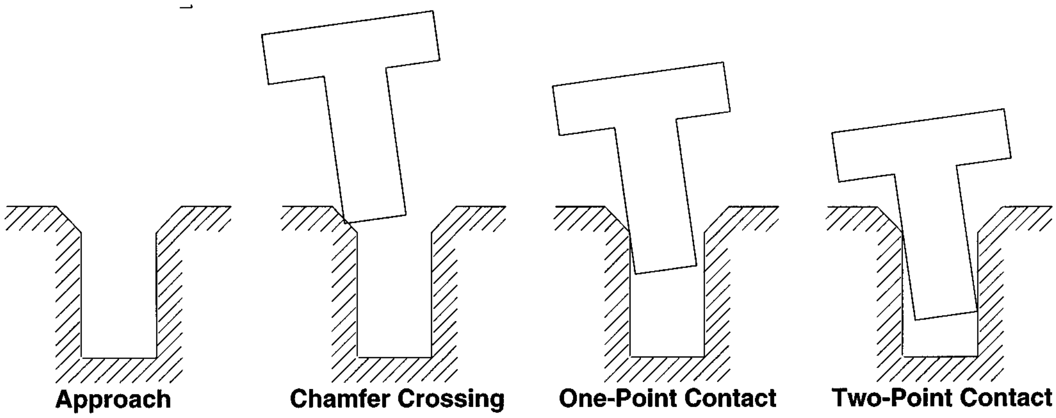

Fig. 1. Peg-in-hole mating stages.

sensing to correct the insertion, may be viewed as a hybrid between passive and active part mating. In this regard, proper active part mating, which fully exploits sensory data to drive the peg inside the hole, has been the subject of extensive research. Söderqvist and Wernersson[12] introduced a method for gathering information about mating from force sensor. A high-precision, self-calibrating insertion strategy was proposed by Paulos and Canny[13] for cylindrical pegs, which exploits simple and accurate optical sensors. A modular approach for solving the peg-in-hole problem using a camera has also been presented by Kleimann *et al.*[14] Such a work, which was devloped for a complex system made of a 6 degree of freedom manipulator and a dextrous three-fingered gripper, proposed to divide the mating process in three parts: a module responsible for classifying the position of peg and hole with respect to each other, a second module for selecting the right insertion strategy according to the classification, and finally a module for handling the actual insertion by means of 5 primitives (lowering, displacement, shaking, hole-search, and lifting).

3. RESEARCH ASSUMPTIONS

Before presenting and discussing the research carried out in this work, it is important to state clearly the asumptions I made and the scope within which the results I obtained are valid.

The first point I intend to raise concerns the task itself. A first rough classification of peg-in-hole divides it in two different families: single and multiple peg-in-hole. What I report here, given the higher occurrence rate,[1] focusses just on the former. This last in turn may be further refined in two classes: round peg in round hole and orientation dependent peg in a matching hole. In this regard, a general treatment on assembly strategies based on bybrid force/position control is presented by Aspragathos[15] for the large class of peg-in-hole assemblies having a plane of symmetry passing through the insertion axis. My investigation, however, concerns just round peg-in-hole. In this respect, I need to distinguish two important varieties whose assembly strategies have been extensively analyzed by Wu and Hopkins:[16]

- peg into a single hole and
- peg into two coaxial holes with different diameters.

The latter, also known as tandem peg-in-hole*, assumes to have the hole with the small diameter lying below the hole with the bigger one. Since this last may be viewed as a generalization of the former, and since a general-purpose module performing this task should be capable of coping with the former as well as with the latter, it is important to study such a variety.

Having clearly stated the specific kind of peg-in-hole which I assumed to work with, the next point I would like to raise concerns the experimental test-bed. In this regard, I assume to use an assembly kit made of three kinds of part (a `peg`, a `plate`, and an `L-shape`) to be assembled onto a slanted `jig`. In order to test the generality of the solution proposed, I employ two similar but not equal sets of parts: a metallic one (aluminium) and wooden one (Figure 2).

Notice that each set involves a generalised form of the specific peg-in-hole assumed above. In this case the mating task requires in fact the peg to be inserted into two coaxial holes located on two loose, separate parts. The research I am reporting here is concerned with developing a general behaviour-based peg-in-hole capable of dealing with such a form of mating process.

Summarising what discussed above, the kind of peg-in-hole I am assuming to deal with consists in inserting a round peg into a round hole. Such an extremely trivial description, though, is very deceiving because it hides an awful amount of unpredicted difficulties caused by uncertainties in the parts, misalignments, friction, *etc*. (cf. Caine *et al.*[17] and Wilson and Latombe[18]). But if the description is simple, why do all these difficulties arise? The answer is that the real world is not perfect and an agent operating in it has to cope with the various uncertainties embedded in its environment in order to accomplish useful physical tasks. In this case mating a peg with a hole, although simple to describe, is very hard to be reliably carried out by a machine. Several works have studied how to reduce or at least constrain uncertainty. It was shown that, except for an irreducible 180° ambiguity, some polygonal shapes can be

* Tandem peg-in-hole may be generalized to an *N*-tandem peg-in-hole by assuming a sequence of coaxial holes with decreasing diameters. However, this more complex form will not be considered here, because the strategy to accomplish it may be trivially deducted from the one to accomplish the simple tandem one.

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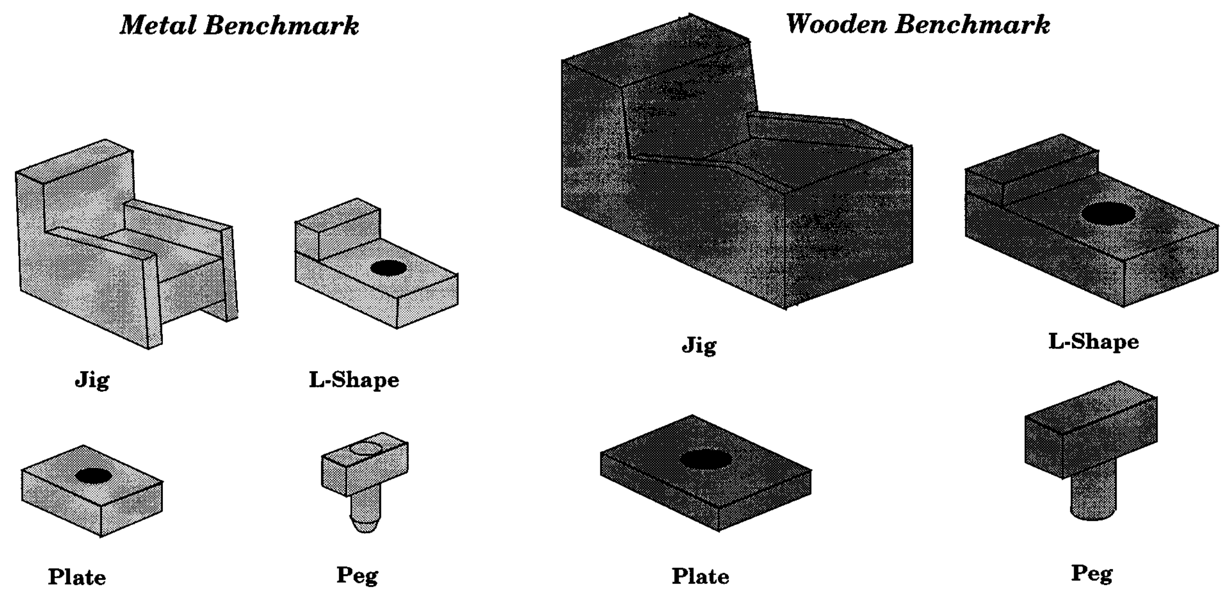

Fig. 2. Benchmark family parts.

stably grasped in a completely determined orientation without any sensing by performing a sequence of just two squeezes.[19,20] Another interesting work presented a sophisticated two-arm robot system equipped with a vision system (camera) and two force-torque sensors.[21] Such a system was capable, by fusing its sensory readings, of planning a sequence of robot commands for grasping and manipulating parts placed in any orientation within its vision field. In this regard, a method of systematically generating visual sensing strategies based on knowledge of the task to be performed was proposed by Miura and Ikeuchi.[22]

4. WORK-CELL SETUP

Since the features of a work cell characterize the kind of jobs a robot manipulator can deal with, and since I want to be as general as possible, I make very plain assumptions about the work-cell. To start with I assume to work with a rather common basic set up: a robot manipulator, its relative controller, a terminal, and an end-effector (Figure 3.).

As regards the manipulator itself, I assume to use a Cartesian robot with a SCARA configuration (*Adept 1*) and with 5 d.o.f.: which means that the robot arm can any time be moved anywhere in the work-cell envelope (i.e. working volume) simply by specifying the Cartesian coordinates of the target point with respect to the robot frame system.

As regards the robot controller, I assume to program it with a textual programming language (*VAL II*) as well as with a teach-pendant. In this way the manipulator can be moved to a target location either manually or with textual commands by specifying a 6-dimensional vector whose components are the Cartisian 3D space coordinates, and the yaw, pitch and roll angles.

As regards the controller terminal, I assume to use a Sun 3/160 workstation. However, in order to maintain generality, I use the workstation as a mere terminal with nothing more than what might be found on a usual robot video terminal.

As regards the end-effector, I have to say that a general-purpose multi-fingered gripper given its versatility would be

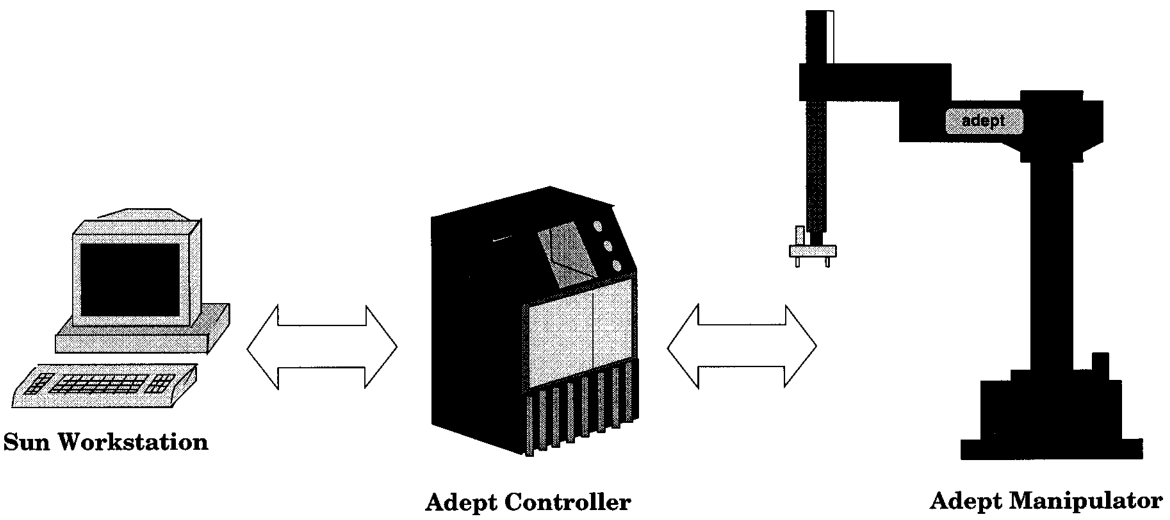

Fig. 3. Robot System used for the project.

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a perfect choice, but unfortunately the few that have been developed are still nothing more than mere research prototypes, and indeed this is still today a subject of extensive research.[23,25]

Considering the kind of objects of the experimental setup and assuming to restrict the robot to deal just with prisms with parallel faces and to cylinders, a two-fingered gripper with parallel jaws would suffice the needs. In this regard, I developed an electric gripper (Edinburgh Gripper[26]) to be mounted onto the robot wrist and to be directly driven by the robot controller via parallel binary output lines. Such an end-effector is capable of gripping objects by opening or closing its jaw-fingers according if the object is gripped from inside, as it may be in the case of a hollow cylinder, or from outside, as in the case of a prism.

Considering the operations involved in putting a peg into a hole and all the hardware which I assumed to make use of, I have to point out that there is no need to provide the robot with any sensing capability in order to accomplish them. However, it would be of great help to provide it with a sensor which would allow to adapt its behaviour according to the particular part it is currently dealing with. This leads to the problem of choosing an appropriate sensor. Roughly speaking the simpler it is, the faster the data gained from it can be processed. Analyzing the kind of tasks which my robot has to perform, I observe that it needs to pick up objects of different sizes from a work-cell location, move them about, and lay them down at another location. Thus, in order to enable more general positions and sizes to be handled, the environment information I require to get from a sensor should consist basically in detecting contact event signatures.

Among all the senses possessed by human beings vision is surely the most powerful one, but also the most complicated and expensive to reproduce in the artificial. Besides, many high precision cameras, which may be regarded as a rough approximation of a human eye, have not sufficient resolution to cope with very tiny robot moves. In fact part mating would typically require motions with accuracy less than 0.1 mm, whereas cameras in typical assembly work can only offer a resolution greater than 1 mm.

Vision is no doubt a powerful tool for driving a peg towards a hole during the approaching stage (cf. Figure 1), but it is unable by itself to solve jamming and wedging during the stage of the two-point contact. In this respect, as mentioned above, force-torque sensors can help to overcome these problems, however, as pointed out earlier, these sensing devices provide far more information than it is actually required out of a sensor. Considering then their relatively high cost, they do not represent a perfect choice. An interesting solution to the problem of finding a suitable sensor is proposed Kim *et al*.[27] He suggests to use an event signature sensor, that is a device capable of notifying events' occurrences. Physically it is made of a piezo-film, wrapped around the fingers of the robot (Figure 4). Since every bending of the piezo-film produces a voltage, every time one occurs, a signal can be sent to the controller warning that a contact has taken place. In this way the two fingers may be used to detect contacts with other surfaces.[28]

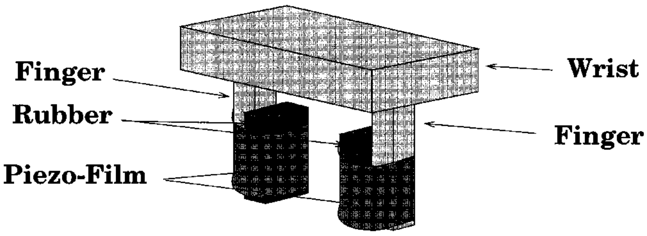

Fig. 4. Gripper equipped with Kim's Piezo-Film Sensor.

Taking into account what information is needed out of a sensor, I notice that Kim's sensor, although being very simple and crude, provides reliably and robustly the robot with the minimum information it requires (contact detections) in a very inexpensive way, and this characteristic makes it very appealing. Of course, it cannot be the ultimate solution for every assembly task, but it can greatly and cheaply help in many situations. For these reasons I decided to equip the fingers of the Edinburgh gripper with this kind of sensing device.

5. PEG-IN-HOLE

Having stated in the previous two sections the assumptions concerning the research and the experimental set-up which I based my investigation on, I can start now presenting the strategy I adopted to accomplish peg-in-hole.

Observing the way in which human beings insert a peg into a hole, I notice that such a task is accomplished first by locating the hole, and then by performing the mating. I label these two task components with the names *hole search* and *peg insertion*, respectively. However, since I rely very much on my eyes to locate the hole, and since I am assuming to equip my agent with a simple touch sensor and no visual sensing (cf. section 4), I need to find a better example for modeling peg-in-hole.

A blind man may in a certain way represent a better model to follow: he does not know where exactly the hole is but he may have a rough idea where it may be found. Thus, first he tries to put the peg there, and then, in case of failure, he starts searching for the hole in the surrounding area until he finds it and proceeds with the insertion of the peg.

Following the line of this example and assuming my agent to have already moved its gripper above the location where the hole is supposed to be, I can model peg-in-hole with three components:

(i) putting the peg down inside the hole,
(ii) searching for the hole, and
(iii) peg insertion.

The first module component attempt the insertion simply by putting the peg down. In case the peg shaft as a result of this action is at least 95% inside the hole, I can consider the peg fully mated with the hole. Notice that I did not want to define a successful insertion when the peg is 100% inside the hole because it is important to leave some room for tolerance. In case, instead, this does not happen, the agent should start looking for the hole in the neighbouring vicinity until one of the following situations occurs:

(i) a hole is found,

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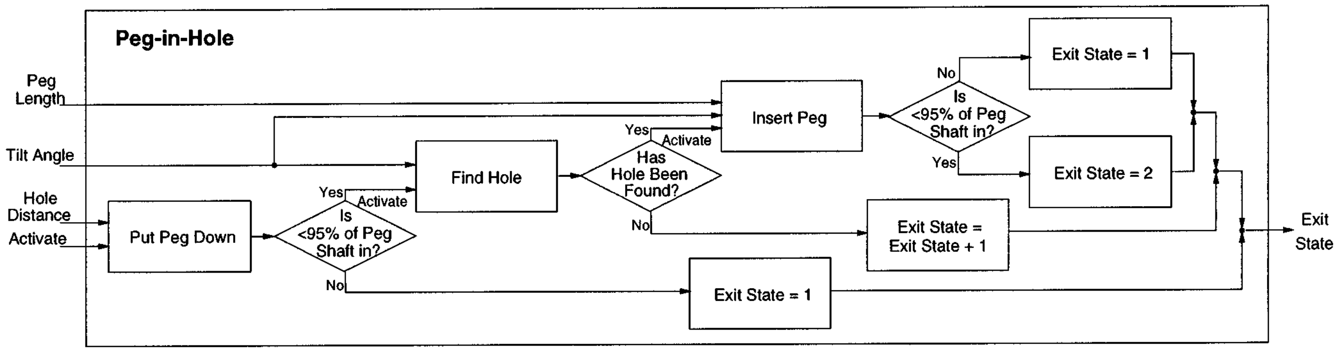

Fig. 5. Peg-in-hole diagram.

(ii) search failed because of an obstacle, or
(iii) search ended without finding a hole.

In case a hole is found, an insertion module, whose outcome may be either peg successfully mated or insertion failed, is then performed. Summarising, I can classify the possible assembly situations in which the agent may be left at the end as follows:
(i) peg successfully mated with a hole,
(ii) peg insertion aborted,
(iii) obstacle detected during search for hole,
(iv) hole not found.

Since I am not employing sophisticated sensory equipment such as, for instance, a vision system, each module component has to rely on some knowledge which has to be given as input. The first one requires to know the distance between the peg head and the surface whereon the hole is located, the second one needs to know the tilt angle between the plane of the hole and the X-Y plane of the robot frame, finally the last one requires to know the length of the peg shaft (Figure 5).

Notice that the module *Find Hole* returns always an exit state code (i.e. 1, 2, or 3) which is then attributed to the variable *Exit State*. Thus, such a variable does not require to be initially set. In case the outcome of the search for the hole is positive (*Exit State* = *1*), then the diamond box activates the execution of the insertion module, otherwise it just increments the variable *Exit State* by 1, whose value may be 2 or 3, in order to discriminate these outcomes from those in the other branch of the diamond box.

Notice also that if the peg shaft is not almost totally inside the hole, it is better to take it out and proceed to the search for the hole even if that had already been found. The reason is that the little impacts caused by the hopping search (cf. section 6) can help to realign the two detached coaxial holes.

As a last remark, I would like to point out that I used in the diagram of Figure 5 an input line to the three modules which I labelled with activate. Such a line should be interpreted as the flow of the control of the robot manipulator.

The strategy synthesised by the aforementioned diagram let clearly emerge the two main components of peg-in-hole: finding the hole and inserting the peg. The next two sections are dedicated to explain a possible solution for each of them.

Notice that thanks to the behaviour-based paradigm the implementations of the two aforementioned components can always be changed with improved versions without affecting or changing the structure of the entire task (cf. Figure 5).

6. PROBLEM OF FINDING A HOLE

Searching for a hole may be regarded as the approaching stage in the classic peg-in-hole decomposition in four steps discussed earlier (cf. Figure 1 in section 2). Most of the research has mainly concentrated on the stages involving the insertion leaving this specific sub-problem quite unexplored. However locating a hole is as important as the actual insertion of a peg, because a good localization avoids most of the difficulties caused by jamming and wedging in later stages. In this regard, a special purpose hardware module was developed by Martínez and Llario[29] to identify and locate round holes in three dimension by employing a stereo vision system. The strategy used was based on the matching of virtual points corresponding to the centres of the holes in the stereo pair. Another interesting technique for a round peg-in-hole was presented by Paulos and Canny.[30] The approach they proposed centred around recording the location of four points on the edge of the hole using a reflective optical sensor placed in an opportune position below the manipulator gripper. The sliding motion of the beam emitted by the optical source first along the X-axis and then along the Y-axis allows to find these four points. Once they have been recorded, the boundary of the hole, and therefore its centre, is determined. However, in case no edge point is initially detected, a spiral or grid based search strategy was performed in the neighbourhood until one was found. Following this method, a similar technique employing a force-torque sensor was developed for round peg-in-hole by Bruyninckx *et al.*[31] The strategy he proposed required to lean a peg so that its axis and that of the hole are largely misaligned. Once the contact between peg and hole has taken place, three points are located on the rim of the hole by reading the sensory data of the force-torque sensor placed beneath the assembly (Figure 6).

At this point, using their position coordinates, he can determine the location of the centre of the hole with respect to the robot frame axes, and then carefully align the peg with the hole axis. This method is quite effective, however it is limited by the tacit assumption to have a peg located above its matching hole. The method does not in fact

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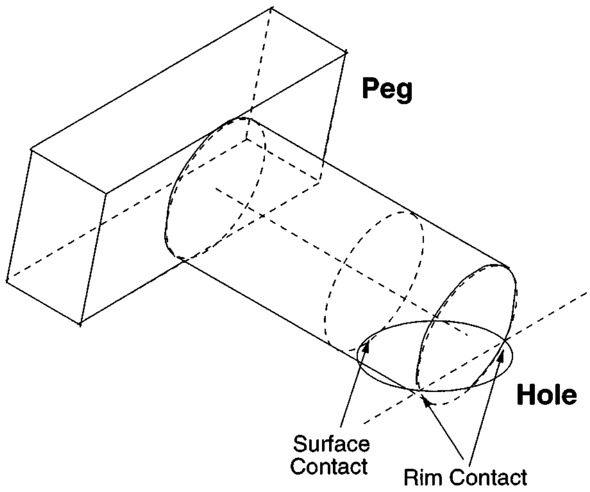

Fig. 6. Peg on hole.

undertake any search for the hole in case this does not lie beneath the peg.

The strategy I am proposing is based on some ideas from the works outlined above. First of all, let me stress the point that I am not employing any vision, optical or proximity sensors: I am simply using a cheap differential touch sensor wrapped around the fingers of my robot gripper. Such a sensor is capable of detecting just variation of forces, in other words contact events. Thus, the search is bound to be performed by exploiting on/off information from impacts between parts. In this respect, several solutions are possible using this kind of sensor, but they all require to scan the surface where the hole is, and therefore testing its presence, by hitting either directly the surface along its normal axis with a finger, if this is thin enough, or indirectly with a thin stick (probe), in which case contacts are sensed as forces propagated through the probe. Since the fingers I am employing are very crude tools to be used for such a search, I opt for the second solution. If a peg tip is sharp, I can actually use the peg itself as a probe. Unfortunately, in general this is not the case, nevertheless I can still use it as a probe by leaning it with respect to the normal to the surface of the hole. This always guarantees a sharp contact edge for both chamfered and chamferless pegs.

At this point, before discussing a few relevant solutions to the problem of search for the hole, let me make one more remark. As detailed above, any search is bound to be made by hopping along the surface of the hole and sensing any contact event between probe and surface. A hole would be detected by the absence of any impact within a certain distance. As mentioned above, I supposed the surface of the hole to be tilted with respect to the X-Y plane of the robot frame axes. In this regard, I have to point out that slopes greater than 15° allow the metal parts of our benchmark under the push of gravity to overcome friction and slip upon the slope, whereas slopes smaller than 15° are not enough to allow any slipping to take place. This is an important observation, because the aluminium assembly I chose to experiment with (cf. Figure 1 in section 3) has a hole which lie on a slope of 15° which is just on the edge of making any part (peg included) slip upon the surface. Thus, I should not be thinking of the peg shaft as an accurate probe device for the search.

Each time, in fact, an impact takes place, the peg tip under the downwards push of the robot arm undergoes a surface force which makes the tip slightly slip along the slope and the peg rotate about the Y-axis of its head (Figure 7),* and this in a long run may well cause the agent to tilt the peg so much that it will acknowledge a hole where there is not one, simply because it cannot detect a contact between peg tip and slope. Unfortunately, such a problem cannot be avoided by alternating tip side because this would introduce more uncertainty, nor by aligning the peg orthogonal to the slope, because, as mentioned earlier, a peg tip is relatively large and therefore not a very accurate tool to be used for a search.

Let me now return to focus the attention to the search strategy itself. I mentioned above that several search path solutions are possible. In this respect, I notice that they may be performed following any trajectory. However, the easiest ones to implement are those which are shaped along regular lines, and, among these, those particularly appealing to us are zigzag and spiral paths (cf. Figure 8).

The following two subsections will present these particular solutions, whereas the last subsection will discuss and compare the two of them. In any case, it is worth recalling that a hole search is triggered only if a peg does not find a hole straight away. However, in order to avoid never ending loops, once any search is started, it has somehow to terminate with an exit state of either hole *found* or *search failed.*

6.1 Zigzag search

This kind of search is very simple (Figure 8) but not very practical because of its relatively slow speed to converge to the target (hole).

In order to test this strategy I set two kinds of experiments involving an L-shape part and a plate (cf. section 3) which are made of metal in the first experiment and of wood in the second one. The two parts are in each case placed on a tilted jig made of the same material.

I started with the metal parts and, by running 40 searches, I recorded 38 successes distributed as follows: 10 after 9 steps, 18 after 14 steps, 6 after 20 steps, and 2 after 26 steps. The two failures were due to a wrong acknowledgement of a hole caused by a peg overtilted because of the high number of contacts.

I repeated the same experiment using wooden parts, and again, by running 40 searches, I recorded 39 successes distributed as follows: 11 after 8 steps, 19 after 13 steps, 7 after 21 steps, and 2 after 25 steps. The only failure recorded was once again caused by a wrong acknowledgement of a hole for the same reason.

6.2 Spiral search

This strategy pursue the search for a hole by following a spiral path. There are many kinds of spirals (e.g. ellipsoidal, circular, square, rectangular), but just two of them are very easy to implement: square and rectangular spirals (Figure 8). The former, since it is not particularly biased on any

* Notice that an equivalent diagram applies for a chamfered peg.

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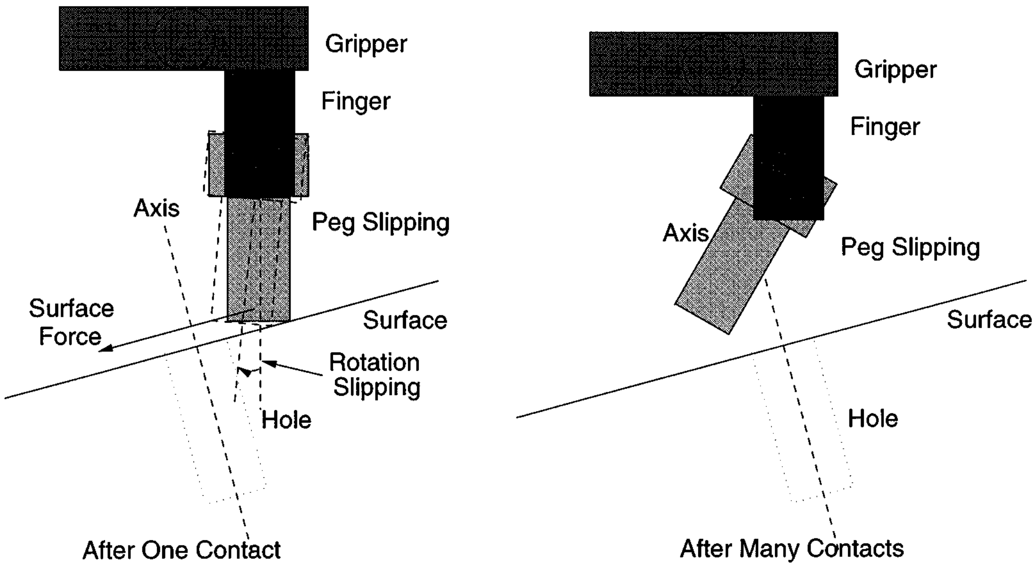

Fig. 7. Example of chamferless peg tilting because of a contact.

directions, has in general better performance than the latter. The spiral is carried out by hopping along the surface in the same fashion as a zigzag search, but with the difference of turning direction of hops 90° clockwise after a certain number of them has occurred. This number is progressively increased after a direction turning has taken place until a limit number of hops, which can be passed as an input parameter, is reached.

In order to test this strategy, I set two experiments similar to those made for the zigzag strategy using metal and wooden parts. I started by placing the metal parts containing the holes on a tilted jig. As done before, I ran 40 searches and recorded 40 successes distributed as follows: 2 after 1 step, 19 after 3 steps, 16 after 6 steps, and 3 after 10 steps. I repeated the same experiment using wooden parts and recorded again 40 successes distributed as follows: 4 after 1 step, 21 after 3 steps, 14 after 5 steps, and 1 after 11 steps (cf. Table I).

6.3 Comparison of search strategies

Considering the two search for hole strategies discussed in the previous two subsections, I need to make a few comments. First of all, I have to point out that zigzag requires in general a large number of contact events to be detected. This is particularly important because, as observed earlier in this section, a peg may get more and more tilted each time an impact takes place, and it may happen that in the long run a hole is wrongly acknowledged (Figure 9).

This drawback is difficult to be avoided even using more sophisticated strategies, because it is intrinsic of the kind of sensor used. The solution of having tighter grips is not very effective both because of the small friction between peg head and fingers' skin, and because of the small area actually gripped. Increasing friction does not avoid peg slippings when each impact takes place, therefore the best way to limit its negative effects, i.e. the failure rate, and improve the reliability of the solution is by drastically reducing the number of hops required for the search, in other words, by switching to a better search path. In this respect, a spiral search is in general far better than a zigzag search, because it optimizes the area of the search (Table I).

In fact, assuming to start in the proximity of a hole, I will not need to complete the entire path in order to find a hole.

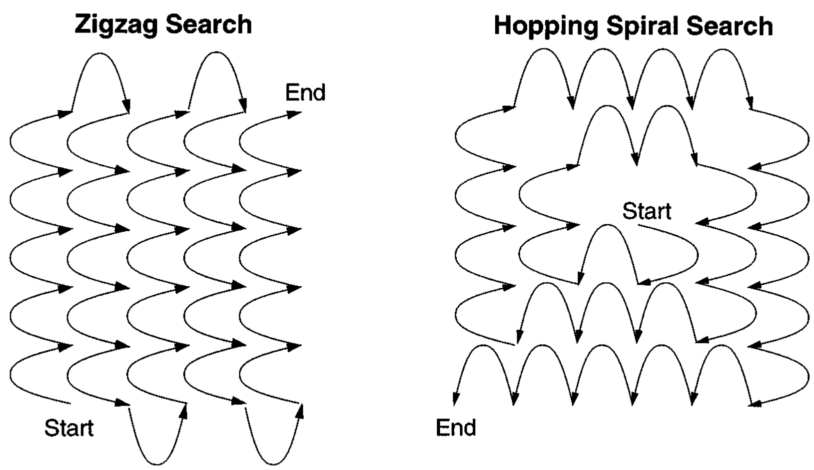

Fig. 8. Zigzag and spiral searches paths.

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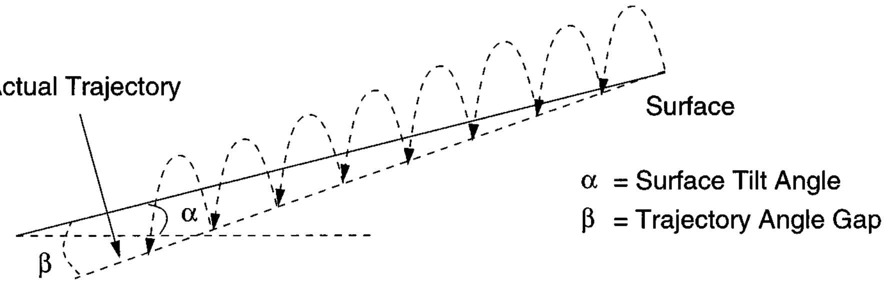

Fig. 9. Trajectory followed during the search which wrongly acknowledges a Hole.

The worst case occurs only when a hole is located very far away from the centre of the spiral, in which case a zigzag search is more efficient. Thus, in general a spiral search outperforms a zigzag one. However, I have to point out that, although following a better path, it does not resolve the problem of unwanted supplementary peg tilting, which always lurks and may lead any search to a failure. The reason is that the optimization regards just the search and not the way in which the presence of a hole is tested.

7. PROBLEM OF INSERTING A PEG

Peg insertion is the other major research topic of the peg-in-hole problem and may be regarded as the one- and two-point contact stages of the classic decomposition discussed in section 2. The particular task carried out in this phase consists in actively inserting a peg (in this case a round one) into a matching hole. In this respect, I need to distinguish two relevant outcomes: successful insertion, or failure caused by jamming, wedging, or unpredicted situations.

Although the location of the hole at this stage of the task is assumed to be known, mating a peg with its correspondent hole is not as trivial as it may appear at first. It involves many complex operations whose accomplishment is too often taken for granted. The main difficulty in solving the peg-in-hole problem is to find strategies which are robust and reliable enough so that to lead the agent to a successful accomplishment of the task regardless of unforcast and potentially failing situations which may surprisingly arise during execution time. In other words, the difficulty is to define back-up procedures general enough so as to allow the agent to recover from the various error situations which may arise.

The relevant literature reports many solutions to the peg insertion problem, but they all resort to more or less complex hardware. Some techniques employing hybrid force-position control were described by Strip[32] for a wide variety of shaped pegs, whereas some strategies for chamferless insertion of planar and prismatic rectangle pegs were instead proposed by de Fazio *et al.*[17] Other research studies tackled the insertion problem more theoretically by conducting analytical work on the various difficulties involved with insertions. In this regard, an interesting analysis of the dynamics of peg-in-hole insertion was carried out by Shahinpur and Zohoor[33] who showed that the conditions of a successful insertion were determined by a set of generalized inequalities. Another work analyzing uncertainties involved with peg insertion was presented by Patsch and von Wichert[34] who proposed the use of a force feedback loop for driving a multifingered gripper as a solution for resolving them. As a general remark I have to point out that all the works outlined above share the tacit assumption of dealing with rigid parts. In this respect, a study involving compliant parts worth mentioning is the one performed by Meitinger and Pfeiffer[35] who extensively model and analyze the forces and torques acting on a gripper during the mating process.

As realized from the few examples mentioned above, there is a great variety of strategies resolving the insertion problem. However, there is not as yet any robust and reliable general solution to such a problem. The great majority of those proposed and developed applies to a particular class of peg shapes and relies on more or less sophisticated sensor availability. In this respect, as stated earlier, I am employing a very simple touch sensor and I am restricting my investigation just to round peg insertions (cf. section 3). Notice, however, that my concern is not limited with what I labelled as simple peg-in-hole, but it extends to cover a form of tandem peg-in-hole involving two loose parts tilted with respect to the X-Y plane of the robot frame system. In this regard, recalling the general structure of the task outlined earlier (cf. section 5), I have to point out that a peg insertion would be initiated just after search for a hole, which, if successful, implies part of the tip of the peg to be inside the hole. Thus, I can assume without any loss of generality to start the insertion process with a peg partially inserted.

As mentioned in section 5, I need two parameters* as

Table I Search strategies experimental data

	Metal Parts		Wooden Parts	
	Search Strategies		Search Strategies	
Steps	Zigzag n°	Spiral n°	Zigzag n°	Spiral n°
1–5	0	21	0	39
6–10	10	19	11	1
11–15	18	0	19	0
16–20	6	0	0	0
21–	2	0	9	0
Success Rate	38/40	40/40	39/40	40/40

* Notice that the assumption of using a vision system would make these parameter redundant.

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input: the length of the peg shaft and the tilt angle. The latter is necessary in order to derive the insertion axis, whereas the former in order to realize when a peg is successfully inserted. In this respect, the test of successful insertion is accomplished by comparing the distance travelled by the manipulator wrist with the rest of the peg shaft length which at the beginning is still out of the hole.

The rest of this subsection is dedicated to present and discuss three different possible solutions to the round peg insertion problem (Figure 10), which will be opportunely compared in order to select the one which best guarantees robustness and reliability. For sake of generality I assume in the rest of this discussion to carry out the insertion $\alpha°$ tilted with respect to the X-Y plane of the robot frame system.

7.1 *Straight thrusting*

The first solution I examine consists in thrusting a peg into a hole directly without caring of any possible jamming or wedging. If a peg gets stuck inside a hole, its insertion is aborted and the whole task has to be repeated.

In order to test this solution, I set two different experiments using two kinds of parts (L-shape and plate) made of different material (metal and wood) and having coaxial holes of the same diameter.

To start with, I placed the two metal parts one above the other on a jig 15° tilted with respect to the table, and, in line with the assumption of working with loose tandem peg-in-hole (cf. section 3), I did not fix them to each other. As regards the peg, I assumed it to have its tip slightly dipped inside the hole (Figure 10). I ran a set of 50 trials for this experiment and I observed 39 successful matings of both holes (78% success rate). The 11 failures recorded were caused partly by a misalignment of the two holes' axes and partly by jamming and wedging. Indeed, I noticed that the metal peg successfully penetrated completely the first hole in 5 out of the 11 failures, but it got stuck at the rim of the second hole because of the misalignment. Thus, considering just the first hole, I may say that I recorded 44 complete matings of metal peg in one hole (88% success rate). As regards the remaining 6 failures, I noticed that four of them were caused by wedging and the other two of them by jamming.

As mentioned above, I ran a second experiment involving similar parts made of wood placed on a jig 10° tilted with respect to the table. By running a set of 50 insertion trials as done before, I observed 41 successful matings of both holes (82% success rate). Analyzing the 9 failures recorded, I noticed that they were caused this time by axis misalignment (5 failures), jamming (1 failure), and wedging (3 failures). Thus, considering just one hole, I may say that I recorded 46 successful wooden peg in one hole (92% success rate).

The results of these experiments are all reported in Table II.

7.2 *Wobbling technique*

The second solution I consider is what I may label as insertion by wobbling. It consists in deliberately changing the direction of peg insertion by rotating a peg about both the insertion axis and its tip. The algorithm describing it may be outlined as follows:

- tilt peg with respect to the surface of the hole,
- repeat
  - push peg inside hole,
  - rotate peg anti-clockwise slightly about the hole axis,

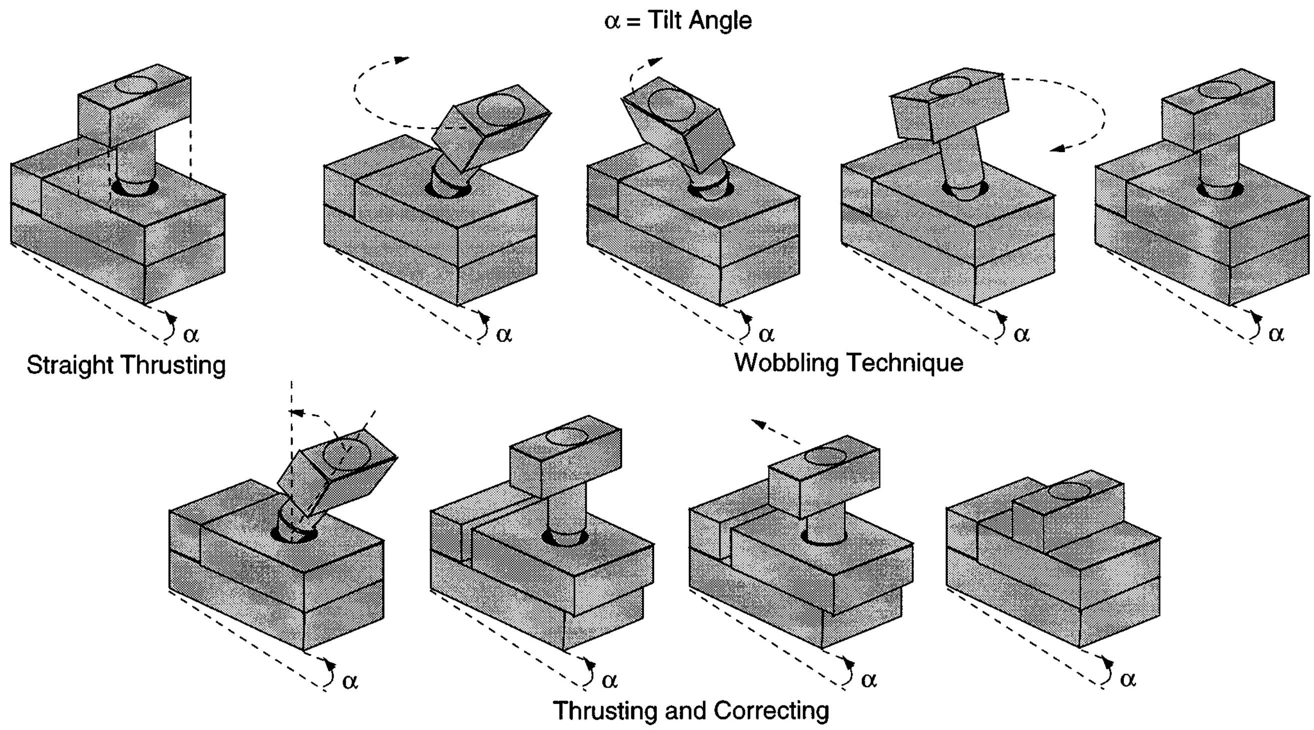

Fig. 10. Different Strategies for solving the peg insertion problem for a chamfered peg, but a similar diagram applies for a chamferless one.

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- increase peg tilting,
- until most of the peg shaft is inside the hole.

The idea behind this technique is to resolve jamming and wedging by taking advantage of the coupling between peg and hole. As a remark, I have in fact to point out that every time a direction of insertion takes place, a different two-point contact is determined, and in turn this last allows more peg shaft to slip inside. At the end of the wobbling process most of the shaft is inside the hole and both peg and insertion axes are aligned.

In order to test this technique, I set two experiments similar to those described before for the straight thrusting solution. I started with the metal parts on the metal jig and, by performing 50 wobbling insertions, I recorded 44 successful matings of the two holes (88% success rate). As regards the 6 failure cases, I observed that 3 were due to axis misalignment, 1 to jamming, and 2 to wedging. Thus, considering just the first hole, I recorded 47 successful insertions by wobbling (94% success rate).

The second set of 56 wobbling insertions performed with the wooden parts on the wooden jig showed similar results: 44 successful matings of both holes (88% success rate) and 6 failures of which 4 were due to axes misalignment, 1 to jamming, and 1 to wedging. As far as the first hole is concerned, I recorded 48 successful insertions by wobbling (95% success rate).

Also in this case the results of these experiments are all reported in Table II.

7.3 Thrusting and correcting

The third solution I examine may be regarded as an optimized version of straight thrusting whose main drawback, as showed earlier, was its inability to resolve a stuck situation which mainly happens at the rim of the second hole (Figure 11).

This strategy, which assumes that any misalignment between the two parts involved with the peg mating is within 1/2 mm along the X-axis or Y-axis but not along both,* adds the capability of adjusting a peg with the axis of

* This assumption is consistent with the fact that some misalignments are caused by rotations of the peg about its tip along the X-axis after a search for a hole has succeeded.

Table II Experimental data of tandem peg insertion

Insertion Strategies	Successes		Failures					
			Misalignment		Jamming		Wedging	
	n°	Rates	n°	Rates	n°	Rates	n°	Rates
Metal Tandem Peg-in-Hole								
Straight Thrust	39	78%	5	10%	2	4%	4	8%
Wobbling Technique	44	88%	3	6%	1	2%	2	4%
Thrust & Correct	48	96%	1	2%	0	0%	1	2%
Wooden Tandem Peg-in-Hole								
Straight Thrust	41	82%	5	10%	1	2%	3	6%
Wobbling Technique	44	88%	4	8%	1	2%	1	2%
Thrust & Correct	49	98%	0	0%	0	0%	1	2%

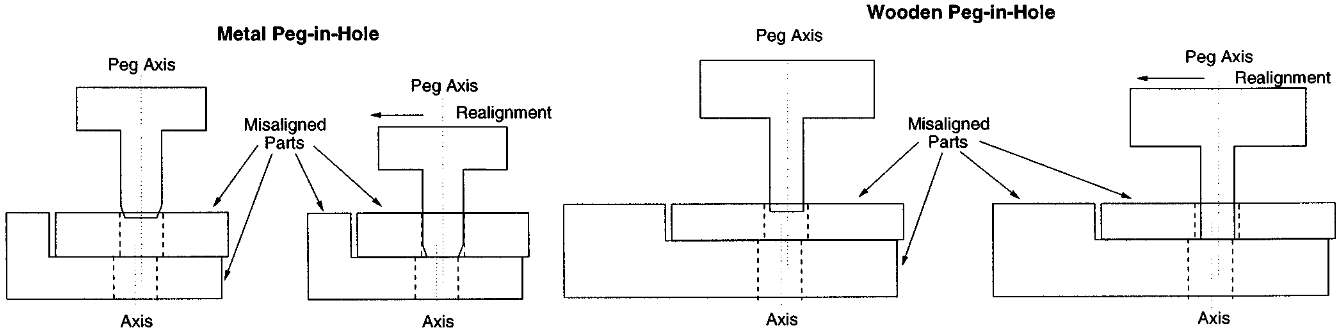

Fig. 11. Diagram of the stuck situation.

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the second hole when a stuck situation caused by misalignment occurs (Figure 10). This is achieved by attempting in sequence at most four shiftings of a peg from its initial position: one of 1/2 mm along the X-axis, one of − 1/2 mm along the X-axis, one of 1/2 mm along the Y-axis and finally one of − 1/2 mm along the Y-axis (Figures 12).

In order to test this solution, I set the same two experiments I did for the other two insertion strategies discussed earlier: two parts with coaxial holes placed loosely on a tilted jig and a peg with its tip slightly dipped inside the hole. I started with performing 50 insertions with the metal parts and I recorded 48 successful matings of both holes (95% success rate). The two failures were due to wedging and one to an axis misalignment larger than 1/2 mm. Thus, considering just the first hole, I may say that we obtained 49 successful matings of peg in one hole (98% success rate). By repeating the previous experiment with wooden parts, I recorded 49 successful matings of both holes (98% success rate). The only failure recorded was due to wedging.

The results of these experiments are all reported in Table II.

7.4 Comparison of insertion strategies

Having described the three insertion strategies in the previous three paragraphs, I can now compare and discuss the experimental results I obtained. First of all, let me summarize the data for the metal and wooden tandem peg-in-hole remembering that the total number of trials for each strategy was 50 Table II).

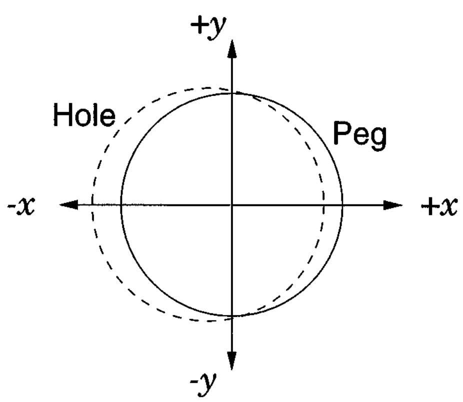

Fig. 12. Diagram of shifting directions.

As a general comment on the results shown there, I have to say that the material which the parts were made of affects the performance of the three strategies. The insertions performed using the wooden parts showed a relatively higher success rate and lower failure rate caused by jamming and wedging. I can explain such an outcome by observing that wood, despite having a coefficient of friction higher than metal, is actually softer than this last. Thus, several cases of jamming and wedging are resolved by a little deformation of the peg at the level of its tip.

As regards the strategies themselves, there are a few remarks which I need to point out. Straight thrust may be regarded as the simplest of the three strategies from the implementation point of view, however, as can be seen from the table above, it is neither very reliable nor very robust. In this respect, wobbling showed better performance, but it is unfortunately more complex to be implemented and requires a manipulator agent which is capable of at least two rotations at the wrist level: one along the Z-axis and one along the X- or Y-axes. This characteristic makes it not so appealing to be developed as a more general tandem peg insertion. The third strategy examined (thrusting and correcting) retains the simplicity of the straight thrust but, besides, it adds the capability of resolving slight axis misalignment between peg and second hole, which were one of the main causes of failure. However, the misalignments which can be corrected are limited to 1/2 mm along the X-axis or Y-axis but not along both. Notice that the success rate also depends on the relative peg and hole sizes, the amount of peg tapering and hole beveling. In this regard, I have to say that the strategy was tested on rather short peg shafts with a diameter/length ratio of about 0.4.

At this point, let me summarize the experimental data relative to the first hole (Table III).

As already stressed earlier, considering just the first of the two tandem peg insertions, I notice that the three strategies have a higher success rate, and once again thrust and correct outperformed the others. Indeed, this last within its limits of applicability* was the only one among the three of them which was not affected by the specific material of the parts. This particular characteristic makes such a strategy very appealing.

* Misalignments of the coaxial holes within 1/2 mm along either the X-axis or the Y-axis.

Table III Simple peg in one hole experimental data

Insertion Strategies	Simple Peg-in-Hole							
	Metal				Wooden			
	Successes		Failures		Successes		Failures	
	n°	Rates	n°	Rates	n°	Rates	n°	Rates
Straight Thrust	44	88%	6	12%	46	92%	4	8%
Wobbling Technique	47	94%	3	6%	48	96%	2	4%
Thrust & Correct	49	98%	1	2%	49	98%	1	2%

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Now, taking into account the different success rates for both tandem and simple peg-in-hole relative to each strategy reported in Tables II and III, I conclude that thrust and correct is the most reliable and robust among them, and, because of this, it is the one which I select as my peg insertion submodule (cf. peg-in-hole diagram in Figure 5).

8. CONCLUSIONS

The work described in this paper tackles the problem of putting peg into a hole by proposing a solution embracing the behavioural approach for one particular class of peg-in-hole tasks: the tandem peg-in-hole, that is inserting a peg into loose coaxial holes. The strategy to accomplish the task was loosely modeled on how a blind human operator would perform the same task.

The solution outlined, which is however limited to rigid parts and to misalignment between the two holes of at most 1/2 mm, was divided into two main modules and a solution for each of them was proposed. Experimental tests for the whole peg-in-hole behaviour showed clear interesting performance with respect both to reliability and robustness.

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