PRECISION ROBOTIC ASSEMBLY USING ATTRACTIVE REGIONS

Matteo Gilli,¹ and Ron Lumia,² and Stefano Pastorelli¹

¹Mech Eng. Dept., Politecnico de Torino, Torino, Italy

²Mech Eng. Dept. University of New Mexico, Albuquerque, NM, USA

Abstract

This paper describes a method for peg-in-hole insertion based on attractive regions a new approach to decompose 6D configuration space into two 3D subspaces. An impedance controller, in combination with the attractive regions, is integrated in a novel controller whereby human-like assembly performance is achieved without using a force sensor. In this paper, the insertion task uses three different pegs, as shown in Fig. 1. The strategy is to decompose the 6 DOF space in which the peg moves into two low-dimensional subspaces. The controller uses stereo-triangulation and a k nearest-neighbor (k -NN) algorithm to identify the parts. An impedance controller monitors the forces (estimated by motor current rather than a force transducer) applied to the system and uses events rather than time to determine the state and the evolution of the assembly process. The approach is experimentally verified using a Barrett Technology's WAM Arm, a backdrivable 7 DOF robotic manipulator.

Keywords

robotic assembly, attractive regions, decomposition of configuration space, impedance control

1. INTRODUCTION

Although robots have become increasingly common in manufacturing environments, they cannot currently be used to perform the vast majority of assembly operations. The general peg and hole assembly problem embodies many aspects that are difficult for robots to perform. For example, insertion tasks often require high precision where the position error of the robot is larger than the clearance of the peg and hole. In addition, many advanced assembly operations require high speed, high accuracy, repeatability and low cost. The challenge is to find a way to reduce uncertainties that prevent the robot from successfully accomplishing a task in a highly constrained environment.

Figure 1: Pegs and base with dimensions in mm. The upper surface of the non-axially-symmetric pegs has a tag whereby information on their orientation is obtained

1.1.RELATED WORK

The peg-in-hole insertion problem covers more than 40 years of research and technology developments, yet remains one of the fundamental challenges for robotic assembly.

1.1.1.Passive compliance

The elimination of uncertainty in the insertion process has been addressed by the development of compliant fixtures [1] such as the remote center compliance device (RCC)[2][3]. The RCC is a compliant wrist that is attached to the robot end effector. It acts as an error absorber in peg and hole insertion operations. The major limitation of this method is that the peg must be moved in a predetermined direction (usually vertical) to touch the hole, which has to be chamfered. Specific modes of failure such as wedging and jamming been thoughtfully examined in [4] and [5] but Whitney et al. [2] where diagrams determine failure boundaries, which are a function of geometry and coefficient of friction.

1.1.2.Active compliance

Force sensors are commonly used in assembly operations. These sensors allow the peg to follow automatic search patterns[6][7][8]. These techniques are all gathered under the terms of active compliance and impedance control. Mason [9] developed a technique based on force control, whereby theoretical definitions such as *ideal effector* and *ideal surfaces* are used to model the behavior of the manipulator. Raibert and Craig [10] were among the first to accomplish this goal with a hybrid force and position robot controller. Hogan [11] and Whitney [12] summarized the state of the art that led to impedance control. Inoue [13] and Merlet [14] proposed peg rotation (with respect to an axis normal to the peg axis) in order to ensure that the projection of the lowest point of the peg surface is on the hole mouth. The peg is moved to touch the edge of the hole, detected by force sensors, and then rotated back and inserted into the hole. The additional rotation increases the range from which the peg can perform a successful insertion. Caine et al. [4] studied the assembly strategies for chamferless squared parts using a limited number of initial contact cases. Several types of impedance control have been developed for specific tasks, such as the position-based impedance controller proposed by Heinrichs et al. [15] based on a hydraulic manipulator.

1.1.3.Visual servoing and object recognition

Vision is a useful robotic sensor because it allows for noncontact measurement of the environment. Shirai et al. [16] paved the way to use vision as a reliable and efficient part of robot control. Typically, visual sensing and manipulation are combined in an open loop strategy (a *look-then-act* behavior) but the most significant results have been obtained by providing closed-loop position control, often referred to as visual servo control. Progress in visual servo control accelerated after the early 1980s, mostly the result of improved computational power over the last two decades. Prior to this, researchers required specialized and expensive pipelined pixel processing hardware, e.g., PIPE[17]. Visual servoing is the fusion of results from many elemental areas including high-speed image processing, kinematics, dynamics, control theory, and real-time computing. Pattern recognition is an essential part of any high-level image analysis system. Most of these systems share a general structure that outlines the strategy process: image acquisition, pre-processing of the images, feature extraction, and classification[18]. A central problem in pattern recognition and computer vision is determining how one shape differs from another. The most popular and widely used contour-based shape descriptor is a set of moment invariants derived by Hu[19]. Hu moments are invariant to Euclidean or affine transformations of the data

set and have been used successfully in the recognition and classification of 3D surfaces [20][21] and aircraft [22].

1.1.4.Pre-images and back-projections

Lozano-Perez et al. [5] defined the *pre-image* of a system goal as a set of positions from which a particular command can recognizably achieve the target with the allowed sensory, control and model errors. Each pre-image can be considered as a new sub-goal to reach the desired target. The back-projection concept was developed by Erdmann[23]. The *back-projection* of a goal is the set of positions from which the system can achieve the goal with the same commanded velocity. For the robotic peg-hole insertion task, if all pre-images in one strategy can be replaced by their back-projections, the operation can be achieved without the need for additional sensing. The introduction of the back-projections separated the issues of goal reachability and recognition. Lozano-Perez et al. [5] and Erdmann [23] reached the following conclusions:

- Within some bounded regions, it is possible to fully orient and position an object without using force sensors even when the initial configuration is completely unknown.
- Before building a sensorless system, it is necessary to analyze the dynamics of the domain to ensure that the predictive power of the robot planner can detect information and produce actions.
- There is a trade-off between sensing and action.

1.1.5.Attractive regions

An innovative approach to the peg-in-hole insertion strategy has been suggested by Qiao[24], who introduced the concept of the *attractive region* as a powerful implementation derived from the concept of the back-projections. An attractive region is a portion of the configuration space in which the system can reduce its uncertainty with a constant external force using the environment rather than signals from force sensors. The environmental conditions, which can form attractive regions, have been systematically analyzed in theory[25]. The attractive regions can be used as *potential functions* where the system can be pushed toward its minimum with a single, simple input. This method has several advantages:

- It is possible to achieve high-precision tasks directly using a sequence of *pushing* inputs. When the goal region of the system is described with respect to the environment, the stable state in the attractive region can be one sub-goal of the system.
- The input simply pushes the system in given direction and keeps other degrees of freedom free of control or fixed (according to the feature of the attractive region).
- The initial area of attraction is large as the mouth of the hole: if the projection of the lowest point of the peg is within this area, the system can reach a new equilibrium state with a single input.

The concept illustrated above has been tested successfully in specific industrial tasks that require high tolerance, e.g. an insertion of a peg in a piston rod hole [26] and a bearing assembly on a crankshaft[27]. These results suggest that a general and reliable method can be designed and applied to a wide range of peg shapes, without the need to develop the correct strategy on a case-to-case basis. The presence of an integrated impedance controller would add strength and reliability to the attractive regions method, by constantly monitoring the forces and the insertion state.

1.1.6. The purpose of this paper

One of the major difficulties in sensor-less peg-hole insertion is to be sure that the planned trajectory is compliant with the desired contact state. This is difficult because the configuration space of this contact state is hard to describe analytically due to high dimensionality and lack of symmetry. Insertion tasks often require tolerances that are smaller than the sensitivity of the sensors. This means that a strategy cannot rely exclusively on sensors; there must be a way to describe analytically precisely how the peg reaches the desired state. The concept of the attractive region can be used in an impedance-based control approach. The decomposition of high-dimensional space and the use of simple inputs, combined with an active-compliance based controller, can greatly enhance the robustness of the insertion process.

The main contributions of this paper are:

- A new decomposition method is proposed to divide the high-dimensional configuration space into two low-dimensional subspaces. The attractive regions formed in these subspaces are analyzed.
- A peg-in-hole strategy is designed based on the decomposition of the configuration space.
- A stereo-triangulation vision system is used to identify the peg type and its position inside the working space.
- A robotic system is used to verify the approach experimentally. The system can insert three different prismatic pegs in their respective holes on a base fixed to a working table. The system includes a seven DOF robotic arm with a three-fingered robotic hand at the end effector.

The addition of an integrated impedance controller permits changes stiffness and damping coefficients and thus, indirectly, the forces applied to the parts. The previous strategies were based on time: the system switched from a stage to another after a certain amount of time[26][27]. With this novel controller, *events* are used as end conditions for triggering the state changes. Force and torque thresholds are set on each axis and a suitable strategy can be developed in order to change the input after that some threshold is crossed. The controller, developed in MATLAB, relies both on analytical considerations about the geometry of the parts that have to be assembled and on data acquired from the impedance model, such as Cartesian forces and pose location.

2. ROBOTIC SYSTEM STRUCTURE

The system developed in this paper includes one WAM Arm manipulator with a Barrett Hand robotic hand attached at the end effector, one control computer that communicates with a reflective memory and a target real-time computer, two CMOS Basler cameras for the stereo-vision (plus one used to monitor the process), and finally three pegs and one base (that contains the respective holes) made out of ABS, a thermoplastic known for its impact resistance and toughness. A schematic of the equipment used in this paper is seen in Figure 2.

Figure 2: Hardware organization and communication lines

The robot used for the insertion operations is the Barrett Technology 7-DOF WAM Arm. The WAM Arm is a redundant backdrivable lightweight robot. The robotic arm communicates with an individual Linux-based target computer that runs compiled *Simulink* control models. In addition to communicating with the WAM, the target computer is also able to read from and write to specific memory addresses (called nodes) in the GE Fanuc Reflective Memory interface. This is where the WAM writes joint position and joint torque data to the control computer and reads commands and control parameters from the control computer. The image processing unit used in this system consists of two Basler color progressive scan CMOS cameras attached to movable, flexible supports.

3. MATERIALS AND METHODS

The concept of an *attractive region* is now introduced. The formulation has some features similar to Lyapunov's function. Assume that there is a nonlinear system $\frac{dX}{dt} = f(X, u, t)$, where

$X \in \mathbb{R}^n$ is the state of the system, u is the input to the system and t the time variable. If there is a function $g(X)$, which, for some real number $\varepsilon > 0$, satisfies the following properties for all X in the region $\|X - X_0\| < \varepsilon$, where X_0 is a state of the system:

$$\begin{cases} g(X) > g(X_0), & X \neq X_0 \\ g(X) = g(X_0), & X = X_0 \end{cases};$$

$g(X)$ has continuous partial derivatives with respect to all components of X ;

$$\frac{dg(X)}{dt} < 0.$$

Then, $\|X - X_0\| < \varepsilon$ is an attractive region. The attractive region provides insight into the object's dynamic motion configurations. The main differences between the function $g(X)$ defined above and Lyapunov's functions are:

- The function $g(X)$ is one independent element of the states rather than an arbitrary designed function and it can be negative;

- The input system can be designed in order that $\frac{dg(X)}{dt} < 0$.

In the following subsection the role of the attractive regions in the decomposition of the configuration space is illustrated.

3.1. Configuration space of the peg

The following analysis focuses on the round peg. At a later stage, the approach will be extended to encompass other peg shapes.

There are four coordinate frames, shown in Figure 3 used in the analysis of the insertion process :

- {R} coordinate frame (also called world frame) is fixed to the robot base, which does not move during the insertion process.
- {H} coordinate frame is fixed to the hole. The origin O_h is defined as the center of the upper surface of the hole, and its axes are parallel to the R-coordinate frame, i.e., there is a constant distance between {R} and {H} coordinate frames.
- {P} coordinate frame is fixed to the peg. The origin O_p is defined as the center of the lower surface of the peg, $O_p Y_p$ is defined as the line from O_p to the lowest point of the peg surface, $O_p Z_p$ is along the vertical axis of the peg directed upwards and $O_p X_p$ is perpendicular to $O_p Y_p$ and $O_p Z_p$.
- {HP} coordinate frame is fixed to the hole. The origin O_{hp} is defined as the center of the upper surface of the hole, $O_{hp} Y_{hp}$ is defined as the line from O_{hp} to the projection of the lowest point of the peg surface, $O_{hp} Z_{hp}$ is along the vertical axis of the peg directed upwards and $O_{hp} X_{hp}$ is perpendicular to $O_{hp} Y_{hp}$ and $O_{hp} Z_{hp}$.

Figure3: Coordinate frames attached to the hole and the peg

The pose of the peg can be defined by:

$$X_{peg} = (x_p, y_p, z_p, \alpha_p, \beta_p, \gamma_p) \quad (1)$$

where (x_p, y_p, z_p) is the position of O_p in H-coordinate and $\alpha_p, \beta_p, \gamma_p$ are the roll, pitch and yaw angles of the peg in H-coordinate, i.e., they define the rotations of X_p, Y_p, Z_p with respect to X_h, Y_h, Z_h . The translation vector x_{hp}, y_{hp}, z_{hp} and the rotation angles R_x, R_y, R_z indicate the position of the peg in HP-coordinate. It should be noted that this convention implies a constant translation from the base to the actual position of the hole (which is fixed). Figure 3 also illustrates the relationship between the poses defined above: ${}^A\xi_B$ describes the pose of B with respect to A.

The round peg has only five-DOF in a 3D space because a rotation of the yaw angle (around the Z_p axis) does not change its configuration by virtue of axial symmetry. We define the attractive function as the distance between O_p and O_h

$$D_g = g(x_p, y_p, \alpha_p, \beta_p) \quad (2)$$

where x_p, y_p is the position of the peg on the horizontal hole plane in H-coordinate and α_p, β_p , are the roll and pitch angles of the peg in H-coordinate. The coordinate z_p becomes here the function $g(X) = D_g$ described in the previous section.

It is difficult to design the robotic manipulation in a high dimensional configuration space $(x_p, y_p, z_p, \alpha_p, \beta_p)$. In the following subsection, we discuss a method to decompose this 5-dimensional configuration space into two low-dimensional configuration subspaces. The assembly strategy can be designed independently for each of the two subspaces.

3.2. The decomposition of the configuration space

In this subsection, a method to decompose the configuration space into two subspaces is discussed. Set $(\alpha_p, \beta_p) = (\alpha_p^*, \beta_p^*)$ where (α_p^*, β_p^*) is a constant. The minimum of the function g can be written as

$$g(x_p^*, y_p^*, \alpha_p^*, \beta_p^*) = \min_{x_p, y_p} g(x_p, y_p, \alpha_p^*, \beta_p^*). \quad (3)$$

If the configuration space described by $(x_p, y_p, \alpha_p, \beta_p, D_g)$ is a *convex* set, a differentiable mapping function m can be obtained such as

$$m : (\alpha_p^*, \beta_p^*) \rightarrow (x_p^*, y_p^*). \quad (4)$$

Therefore, for a constant (α_p^*, β_p^*) , the function $g(x_p, y_p, \alpha_p^*, \beta_p^*)$ always reaches its minimum at (x_p^*, y_p^*) .

It should be noted that if the constant set changes from (α_p^*, β_p^*) to $(\alpha_{p'}, \beta_{p'})$, the function m reaches the same minimum:

$$g(m(\alpha_{p'}, \beta_{p'}), \alpha_{p'}, \beta_{p'}) = \min_{x_p, y_p} g(x_p, y_p, \alpha_{p'}, \beta_{p'}) \quad (5)$$

$$m(\alpha_{p'}, \beta_{p'}) = (x_{p'}, y_{p'}) \quad (6)$$

i.e., for any fixed set (α_p, β_p) , at the minimum of the function $D_g = g(x_p, y_p, \alpha_p, \beta_p)$, the vector (x_p, y_p) always reaches its minimum (x_p^*, y_p^*) .

Thus, the configuration space can be decomposed into two independent low-dimensional subspaces, each of which has a suitable strategy:

- For a fixed vector (α_p^*, β_p^*) , a three-dimensional configuration space is obtained by:

$$(x_p, y_p, D_g) |_{(\alpha_p, \beta_p) = (\alpha_p^*, \beta_p^*)} \quad (7)$$

Then, the same logic can be applied to another set of variables. The vector (x_{hp}, R_y) is kept at a fixed value and a strategy can be designed to move (y_{hp}, R_x) to a desired state. The desired state, in this case, corresponds to the peg fully inserted into the hole. The subspace is established by:

$$(y_{hp}, R_x, D_g) |_{(x_{hp}, R_y) = (x_{hp}^*, R_y^*)} \quad (8)$$

Attractive regions formed in the subspaces

In this subsection, the insertion strategy is analyzed according to the attractive regions and it is divided into two stages.

Stage 1

In the following, one of the attractive regions formed in the subspace $(x_p, y_p, D_g) |_{(\alpha_p, \beta_p) = (\alpha_p^*, \beta_p^*)}$ is analyzed through numerical simulation. The results are shown in Fig. 4. The minimum of the function D_g is reached in the configuration that corresponds to a three-point contact between the peg surface and the mouth of the hole. This is a stable state and it can be reached with a single input as shown in the following section. A negative value of D_g means that the center of the lower surface of the peg is below the upper surface of the hole. It should be noted that this value depends on the initial values of (α_p, β_p) . Different initial values lead to different attractive regions and different goal conditions, but the strategy used to reach this condition is the same. The attractive region here formed satisfies the properties introduced in the previous section:

- The function $D_g = g(x_p, y_p) = g(X)$ has a minimum in $D_{g0} = g(x_{p0}, y_{p0}) = g(X_0)$, defined as the bottom of the cone-shaped attractive region in Fig. 4. $D_g > D_{g0}$ for each $X \neq X_0$.
- D_g is continuous and has continuous partial derivatives.

- $\frac{dD_g(X)}{dt} < 0$ when the input pushes downwards the system toward its minimum.

Therefore, under the action of the input, the peg can slide down to the attractive region and reach the minimum. The initial position of the peg should be within an area as large as the hole area, that is, the projection of the lowest point of the peg surface must lie inside the hole. When a downward force is applied to the peg under these conditions, the center of the peg mouth follows a trajectory along the attractive region in Fig. 4. Stage 1 is finished when the peg reaches the bottom of the attractive region.

Figure 4: The attractive region formed in the first configuration space

Stage 2

In this stage, the uncertainty of (y_{hp}, R_x) can be eliminated by another input that allows the system to maintain the three-point contact and rotates to align the peg. The attractive region is now formed in the subspace (y_{hp}, R_x, D_g) . It should be noted that even though the origin of the attractive function has the same definition that had in the first stage (the distance between the center of the lower surface of the peg and the center of the upper surface of the hole), the peg reduces the uncertainty both in translation and rotation until the insertion is reached. Moreover, the function D_g now depends on a different state, i.e., $D_g = g(y_{hp}, R_x)$. Since it is more difficult to comprehend what the goal of the second attractive region means, Figure 5 shows a two-dimensional state representation of a three-point contact, where the angle R_x has been called θ to lighten the notation. According to this scheme, the attractive region formed in this configuration has a minimum where the following conditions are reached and the peg can be pushed into the hole:

$$|y_{hp}| < r_{hole} - r_{peg} = 0.1015 \text{ mm}$$

$$|\theta| < \arccos\left(\frac{r_{hole} - r_{peg}}{r_{hole}}\right) = 0.0064 \text{ rad}$$

Figure 5: Two-dimensional state representation during three point contact

Figure 6. The attractive region formed in the second configuration space

These conditions come from simple geometrical considerations on the state of the peg in Figure 5. It is interesting to compare these conditions to the numerical results shown in Figure 6. The center of the zone of the attractive region shows a steep zone that corresponds to the condition by which insertion can occur.

The simulation suggests a linear relationship between the variables θ and y_{hp} , which are bounded in a box where $|y_{hp}|_{exp} \leq 0.05 \text{ mm}$ and $|\theta|_{exp} \leq 0.025 \text{ rad}$. The differences are due to a two-dimensional simplification in the analytical study and to the discrete simulation step and contact detection method used in the numerical simulation. The following section will discuss a method and an input to reach these goal conditions. The end of the Stage 2 corresponds to the end of the insertion process.

Figure 6 shows a wide range of positions for the peg but not all of them are arbitrarily reachable. The path followed by the peg depends on the input. The starting point depends both on the initial conditions and on the final position at the end of Stage 1.

4. STRATEGY ANALYSIS

4.1. Recognize the target with the aid of stereo-vision

Using vision the centroid of a peg is determined. This allows us to identify its position on the working table. The process that leads to the stereo triangulation is shown in Figure 7. The images

are acquired by the cameras at the beginning of the insertion process and the features are extracted as follows:

- Each image is classified according to the *k-means clustering* algorithm: the pixels are clustered in *k* groups. The group that includes the color of the peg is analyzed.
- Since the segmentation is not perfect, the image obtained contains noise and other objects that happen to be included inside the peg cluster. The noise can be removed with morphological cleanup.
- After noise removal, as in can be seen in Figure 7 , there are still unwanted blobs in the frame.
- The following step is used to identify the correct blob by using a k-NN algorithm based on Hu moment invariants [19] : each blob in the frame is compared to a library and, the blob closest to the peg is chosen its centroid is computed.
- Finally, stereo-triangulation uses intrinsic camera calibration data as well as extrinsic parameters. The extrinsic parameters are essential because they tie the relative results of the cameras to a fixed point on the working table. Therefore, the position of the peg according to the robot coordinate frame can be determined.

Figure 7: The steps to identify and locate the target peg

When the pose of the peg is determined, the robotic hand can be guided to grasp the peg and to position it above the hole.

4.2.Orientation computation for non axial-symmetric pegs

The pegs that are not considered axial-symmetric are provided with a blue tag on their lower surface, as shown in Figure 1. This tag is used to identify and to compute, by feature extraction, the peg orientation. Then, it is possible to add a rotation before the first stage of the strategy so that the peg orientation aligns with that of the hole. This is due to the fact that the strategy needs the $Z_{hp}Y_{hp}$ plane (the plane that passes through the center and the lower point of the peg) to be symmetric in order to reach a stable three contact point and to work on a two-dimensional plane during the latter part of the strategy. The orientation is computed by analyzing the tag's equivalent ellipse, after having conveniently rotated the peg towards the camera.

Stage 1: Eliminating the uncertainties of (x_p, y_p)

In this subsection, we design a controller that reduces the uncertainty of the system and reaches the minimum of the attractive function in **Error! Reference source not found.** In order to push the peg to the three-contact state, the following conditions should be satisfied:

- The center of the lower surface of the peg is inside the range of the allowable location, from which the attractive region can be used to reduce uncertainties;
- The contact force must overcome the frictional force at any point of the trajectory of the peg to guide the peg to the goal by following the environmental boundary.

The allowable range can be obtained through the analysis of the force acting on the peg during a one-point contact, as shown in Figure 8.

Figure 8: Forces acting on the peg. The forces are applied at the boundary of the peg allowable movements

To make the peg move along the attractive region, the projection of the pushing force on the tangential plane should overcome the frictional force:

$$F_z \cos \alpha_f > \mu F_c = \mu F_z \sin \alpha_f \quad (9)$$

where F_z is the pushing force and F_c is the contact force acting on the peg, which is normal to the plane tangential to the boundary. α_f is the angle between the tangential plane and the Z_h axis and F_f is the frictional force. Thus, the condition required to deal with friction is:

$$\tan \alpha_f < \frac{1}{\mu} \rightarrow \alpha_f < \arctan \frac{1}{\mu}.$$

Given the peg and the base, the friction coefficient of $\mu = 0.2$ dictates the following condition: $\alpha_f < 78.69^\circ$. This condition is satisfied everywhere inside the attractive region: if the projection of the lowest point of the peg lies within the hole mouth, the system will reach the bottom with a single downward input.

Therefore, the strategy for the first step can be the following:

- Move the peg above the hole and adjust the orientation to $(\alpha_p, \beta_p) = (0.3, -0.3)$.

- Translate the peg on the horizontal plane in order to be sure that the projection of the center of the peg falls in the range of the allowable positions explained above.
- Lower the peg until it reaches the stable three-point contact.

The strategy is shown in Figure 9

Figure 9 : Strategy steps

An impedance controller is used to determine when the peg reaches the goal point. At the minimum of the attractive region the contact force is entirely vertical and this particular condition can be used as a fast and reliable end condition determine.

In this first stage, the translational DOFs are set to be compliant in the xy -plane while the vertical and rotational DOFs are set to be stiff in order to reach the three-point contact without losing the initial alignment.

Stage 2: Eliminating the uncertainties of (y_{hp}, θ) and achieving peg insertion

In this subsection a strategy is designed to move the peg from the three-point contact, as shown in Figure 5, to the final position, where it is completely inserted into the base. The main goals during this stage are:

- maintaining three-point contact in order to assure that the vector (x_{hp}, R_y) remains constant;
- reducing the uncertainty of (y_{hp}, θ) until the insertion condition is reached.
-

In this stage it is essential to avoid some conditions that arise from the interaction of forces between the peg and the base: *wedging* and *jamming*. The definitions used in the discussion are shown in Figure 10. The analysis is carried out on a two-dimensional representation.

Figure 10: Forces and moments on a peg during insertion

Wedging occurs when contact forces point directly toward each other. Nevins and Whitney [3] used a diagram that limits the allowable peg position in both translation and rotation in order to avoid wedging. The diagram was designed for chamfered part but the condition on the maximum allowed wobble angle is still valid for chamferless insertion as well. In order to avoid wedging

the following equation must be satisfied: $\theta < \theta_w = \frac{c}{\mu} = 0.0319 \text{ rad}$, where $c = \frac{r_{hole} - r_{peg}}{r_{hole}}$ and

$\mu = 0.2$. It should be noted that this condition is satisfied in the goal region of the attractive region in Figure 6, as discussed in the previous section. When the peg reaches the bottom of the attractive region, the angle θ is smaller than the maximum allowed wobble angle and wedging is avoided.

Jamming occurs when the resultant insertion force direction deviates too far from the insertion axis. Figure 11 illustrates the combination of the forces F_x, F_z, M required to avoid jamming.

The diagram is built on the variable λ , which is defined as $\lambda = \frac{l}{2\mu r_{hole}}$, where l is the insertion depth.

Figure 11: The jamming diagram. The diagram, developed by Nevins and Whitney[3], shows the allowable combinations of applied forces and moments on the peg that permit assembly without jamming

If the forces acting on the peg stay within the boundary set by the box of Figure 11, the system avoids jamming and the insertion can be performed.

Figure 12: Tolerances on the non axial-symmetric pegs

To achieve these goals, the input to the system consists now of a constant downward F_z force and a torque M_{hz} directed along the X_{hp} axis and applied on the grasping point (robotic hand), that becomes the center of compliance of the system. Figure 9 illustrates the second stage of the insertion. The insertion is considered done when the peg reaches the bottom and the vertical force exceeds a threshold.

5. RESULTS AND DISCUSSION

The insertion method based on the decomposition of the configuration space is experimentally verified in this section. Experiments are carried out with the three pegs shown in Figure 1 and the output data for the round peg is analyzed below. The experiment for non axial-symmetric pegs requires an adjustment on the yaw angle of the peg as explained in the previous section. Figure 12 shows the range of error in the computation of the orientation angles where the insertion is still successful. It should be noted that after the robotic hand grasps the peg, it can assume only a limited set of orientations because of the geometry of the parts. If the vision system fails to determine the correct angle, there is still a small range in which the insertion can still be performed correctly because the stiffness on the z -axis is kept slightly compliant in order to adjust for small errors when the peg begins to contact the hole. Since the tolerances on the 2nd peg are small, the tolerances angles are small as well. It is important to underline that the precision of computer vision does not directly affect the method efficiency. The strategy developed here allows the system to perform the most important part of the insertion process without relying on vision. The attractive region is used to reduce system uncertainty in a range of sub-millimeter and sub-degree by using environmental constraints. Vision is only used in the phase before the actual insertion.

In Figure 13 the end condition that permits the controller to switch between the two stages is clearly shown: *end value* = 1 means that the stage 1 is completed and the system is in the stage 2. Similarly, *end value* = 2 tells us that the insertion is complete.

Figure 14 and Figure 15 show forces and moments acting on the peg during the insertion process. When the controller switches state, the force F_z reaches its maximum. This is an essential point in the controller because the limit of the force can be set according to the parts that have to be assembled. This saturation value is a safety measure so that expensive parts are not damaged. Three-point contact is reached at $t = 7.35s$. After this point the forces acting on the peg fall. Then, the second part of the strategy starts to act on the system, until the insertion conditions are met and the second stage is completed. At the end of the second step, the presence of saturation on the force F_z does not stop the system. The insertion is considered completed only when the peg reaches the bottom of the hole. Before this point the forces act in order to avoid jamming. At $t = 14.60s$ the force F_z drops and the peg is lowered significantly, as seen in Figure 16. This corresponds to the most important stage of the insertion, when the peg slides into the hole. After this moment the peg is still being lowered into the hole, and the insertion is considered completed when the peg is at the bottom of the hole and the force F_z reaches the saturation limit, at $t = 15.80s$. The roll, pitch and yaw rotation, shown in Figure 17, give us insight into how the peg is rotated to achieve the different steps of the process. After switching from stage 1 to stage 2, the peg rotates along the axis X_{hp} (which is not parallel to X_h) and this is the reason why the roll and pitch rotations move together. Also, α and β trends appear symmetric because of the particular initial choice of $(\alpha, \beta) = (0.3, -0.3)$. The alternate change in rotation at the end of the stage 2 corresponds to an easy way to avoid jamming: the peg wobbles along the X_{hp} axis in order to produce the effect of a slight vibration.

Fig. 18 shows a sequence of the most important steps of the insertion process. The robot starts from its initial front position (a). It is then moved and rotated so that the peg's lowest point lies within the hole mouth (b). After three point contact (c), a moment and a downward force act on the peg in order to maintain the contact and align the peg to the hole. The dynamic actions between the peg and the hole keep changing (d) until the insertion conditions are all met and the peg is pushed to the bottom of the hole (e).

Figure 13 : End value

Figure 14 : Forces

Figure 15: Moments

Figure 16: Peg insertion depth. The hole height is represented by the dotted line

Figure 17: Rotation angles in R-coordinates

Figure 18: Insertion process

6. CONCLUSIONS

In this paper, the analysis and experimental verification for the assembly operation of different pegs is presented. The proposed strategy divides the insertion task into two stages in which only some variables of the configuration space change while others remain constant. In each of these two stages, the configuration space of the peg is reduced from 5 DOF to 3 DOF and each has a simple yet robust strategy to reach its determined goal. The subspaces greatly reduce the difficulty of planning the insertion because it is possible to work with fewer variables. The robot moves along virtual boundaries that limit its degrees of freedom. Moreover, this strategy can be applied to any shape of peg that has at least one plane of symmetry that passes through the peg axis.

The compliant robot varies the compliance of its axes in order to control the stiffness of the insertion during different stages of the strategy. The controller uses events, rather than time, to switch states and acts on different subspaces. The goal region of the first subspace becomes the starting position for the second one. In this manner, the process and the forces between the parts are constantly monitored until the insertion is considered complete.

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REFERENCES

- [1] S. Simunovic, "Force information in assembly processes," in 5th International Symposium on Industrial Robots, 1975, pp. 415-431.
- [2] D. E. Whitney, "Quasi-Static Assembly of Compliantly Supported Rigid Parts," *Journal of Dynamic Systems, Measurement, and Control*, vol. 104, pp. 65-77, 1982.
- [3] J. L. Nevins and D. E. Whitney, *Concurrent Design of Products and Processes: A strategy for the next generation in manufacturing*: McGraw-Hill 1989.
- [4] M. E. Caine, T. Lozano-Perez, and W. P. Seering, "Assembly strategies for chamferless parts," in *Robotics and Automation, 1989. Proceedings., 1989 IEEE International Conference on*, 1989, pp. 472-477.
- [5] T. Lozano-Perez, M. T. Mason, and R. H. Taylor, "Automatic synthesis of fine-motion strategies for robots," *The International Journal of Robotics Research*, vol. 3, pp. 3-24, 1984.
- [6] D. E. Whitney, "Force feedback control of manipulator fine motions," *Journal of Dynamic Systems, Measurement, and Control*, vol. 99, pp. 91-97, 1977.
- [7] N. Hogan, "Impedance control: An approach to manipulation," in *American Control Conference, Boston, MA 1985*, pp. 304-313.
- [8] S. Hopkins, C. Bland, and M. Wu, "Force sensing as an aid to assembly," *The International Journal of Production Research*, vol. 29, pp. 293-301, 1991.
- [9] M. T. Mason, "Compliance and force control for computer controlled manipulators," *Systems, Man and Cybernetics, IEEE Transactions on*, vol. 11, pp. 418-432, 1981.
- [10] M. H. Raibert and J. J. Craig, "Hybrid position/force control of manipulators," *Journal of Dynamic Systems, Measurement, and Control*, vol. 103, pp. 126-133, 1981.
- [11] N. Hogan, "Impedance control: An approach to manipulation: Part III - applications," *Journal of Dynamic Systems, Measurement, and Control*, vol. 107, p. 17, 1985.
- [12] D. Whitney, "Historical perspective and state of the art in robot force control," in *Robotics and Automation. Proceedings. 1985 IEEE International Conference on*, 1985, pp. 262-268.
- [13] H. Inoue, "Force feedback in precise assembly tasks," DTIC Document 1974.
- [14] J.-P. Merlet, "A Control Law for the Insertion of a Flexible, Cylindrical Peg using a Robot," in *1983 Cambridge Symposium*, 1984, pp. 297-304.
- [15] B. Heinrichs, N. Sepehri, and A. Thornton-Trump, "Position-based impedance control of an industrial hydraulic manipulator," *Control Systems, IEEE*, vol. 17, pp. 46-52, 1997.
- [16] Y. Shirai and H. Inoue, "Guiding a robot by visual feedback in assembling tasks," *Pattern recognition*, vol. 5, pp. 99-108, 1973.
- [17] E. W. Kent, M. O. Shneier, and R. Lumia, "PIPE (pipelined image-processing engine)," *Journal of Parallel and Distributed Computing*, vol. 2, pp. 50-78, 1985.
- [18] A. Khotanad and J.-H. Lu, "Classification of invariant image representations using a neural network," *Acoustics, Speech and Signal Processing, IEEE Transactions on*, vol. 38, pp. 1028-1038, 1990.
- [19] M.-K. Hu, "Visual pattern recognition by moment invariants," *Information Theory, IRE Transactions on*, vol. 8, pp. 179-187, 1962.
- [20] G. Taubin and D. B. Cooper, *Object recognition based on moment (or algebraic) invariants*: IBM TJ Watson Research Center, 1991.
- [21] M. Mercimek, K. Gulez, and T. V. Mumcu, "Real object recognition using moment invariants," *Sadhana*, vol. 30, pp. 765-775, 2005.
- [22] S. A. Dudani, K. J. Breeding, and R. B. McGhee, "Aircraft identification by moment invariants," *Computers, IEEE Transactions on*, vol. 100, pp. 39-46, 1977.
- [23] M. Erdmann, "Using backprojections for fine motion planning with uncertainty," *The International Journal of Robotics Research*, vol. 5, pp. 19-45, 1986.
- [24] H. Qiao, "Attractive regions in the environment [motion planning]," in *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on*, 2000, pp. 1420-1427.
- [25] H. Qiao, "Strategy investigation with generalized attractive regions," in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, 2002, pp. 3315-3320.
- [26] J. Su, H. Qiao, C. Liu, and Z. Ou, "A new insertion strategy for a peg in an unfixed hole of the piston rod assembly," *The International Journal of Advanced Manufacturing Technology*, vol. 59, pp. 1211-1225, 2012.

- [27] J. Su, H. Qiao, Z. Ou, and Y. Zhang, "Sensor-less insertion strategy for an eccentric peg in a hole of the crankshaft and bearing assembly," *Assembly Automation*, vol. 32, pp. 86-99, 2012.

Authors

Matteo Gilli received the B.S. and M.S. degree in mechanical engineering from the Politecnico di Torino, Italy, in 2010 and 2013 respectively. His interests lie in the general area of robotics and mechatronics and include vibration mechanics and numerical modeling. He has been a member of the Politecnico di Torino's Isaac Team student research group.

Ron Lumia received the BS degree in electrical engineering from Cornell University, Ithaca, NY, in 1972. He received the MS and PhD, both in electrical engineering, from the University of Virginia, Charlottesville, VA, in 1977 and 1979, respectively. His technical interests include computer vision, microrobotics, robot control, and manufacturing. He has been a Professor in the Mechanical Engineering Department at the University of New Mexico, Albuquerque, NM since 1994. From 1986-94, he was Group Leader of the Intelligent Control Group at the National Institute of Standards and Technology (NIST). Previously, he held academic positions at VA Tech in Blacksburg, VA, and the National University of Singapore. Professor Lumia remains active in IEEE Conference organization, serving IROS 2003 as Chair of Special Sessions, IROS 2007 as Finance Chair, ICRA1997 and ICRA 2006 as Exhibits Chair and ICRA 2010 as Finance Chair.

Stefano Pastorelli received the M.S. degree in mechanical engineering and the Ph.D. degree in applied mechanics from Politecnico di Torino, Turin, Italy, in 1992 and 1996, respectively. From 1995 to 1997 he operates as technical consultant for a high-tech aeronautical company. He is currently an Associate Professor of Applied Mechanics in the Department of Mechanical and Aerospace Engineering at the Politecnico di Torino, Italy. His main research interests include analysis of functional behavior of mechanical systems, power transmission and actuation servo-systems, kinematics and dynamics of robots, motion capture techniques and active human modeling for biomechanics.