# Robustifying force-controlled insertion skills by increasing attraction regions in single DoF contact transitions

Federico Ulloa[1], Wilm Decré [1], Erwin Aertbeliën [1], and Herman Bruyninckx [1,2]

***Abstract*— This paper presents a methodology for robust insertion skill definitions, that allows developers to exploit their insights in (i) the (active and passive) compliance properties of both robot and environment, and (ii) the source and magnitude of geometrical uncertainties. The core ideas behind the methodology are (i) it is always easier to deal with geometrical uncertainties one degree of freedom at a time than several together, and (ii) the passive compliance in the assembly parts can be used as a feature instead of as a bug, most notably in the case of *engineered* compliances such as snap fits.**

## I. Introduction

In the last decades, robots have been widely used in industrial automation due to their relatively high accuracy and speed. They have been commonly deployed and used to perform repetitive tasks in constant and predictable environments. However, with the increasing tendency of product customization that lead to small batch production, robot automation solutions are still a challenging and expensive solution due to the need to create structured environments and the variability in the parts.

In the assembly context, an important and common operation is part insertion. Dealing with product variability and unstructured environments is challenging for insertion operations that involve tight tolerances, and/or multiple mating relations between objects, since the error in the information about part location and geometry, among others, can be higher than the insertion geometrical tolerances.

Some works have explored robotic insertions skills in unstructured environments. In [1], a model-based solution that exploits the geometrical properties of a peg-in-hole insertion is presented. In [2], authors present a fuzzy logic approach to multi-peg-in-hole insertion.

The main contribution of this work is the proposition of a methodology to specify compliant insertion skills, that exploits specific geometrical features of the parts to sequentially create attraction regions with single degree of freedom (DoF) contact transitions. Resolving the geometrical uncertainties one degree of freedom at a time, provides more opportunities *to increase robustness*, in a trade-off with (i) *execution speed*, and (ii) *level of expertise* in the skill developers.

The paper is structure as follows. In section II the skill methodology to specify skills is explained, section III shows the obtained results of applying the methodology to three low-tolerance insertion cases. Finally, in section IV the results are discussed and extensions are mentioned as possible future work.

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[1]Department of Mechanical Engineering, KU Leuven, Belgium, Core Lab ROB, Flanders Make, http://www.mech.kuleuven.be/robotics. Corresponding author: federico.ulloarios@kuleuven.be

[2]Department of Mechanical Engineering, TU Eindhoven, the Netherlands

## II. Methodology

This section presents a general methodology for robust insertion skill definitions, that allows developers to exploit their insights in (i) the (active and passive) compliance properties of both robot and environment, and (ii) the source and magnitude of geometrical uncertainties. An insertion is represented by a set $\mathbb{F}$ of feature frames $\{\text{Ft}_i\}$ located on the relevant geometrical features connecting the parts.

Figure 1 shows the sequence of actions that form a skill's generic structure. It consists of four actions. In the first one, the part to be assembled ($\text{Obj}_1$) is placed on top of the housing part ($\text{Obj}_2$). Then in action 2, offsets are added to $\text{Obj}_1$ in directions that later on can be reduced by compliantly interacting with the environment. There are two reasons for which a particular offset is introduced to the skill,

(i) to generate a *contact attraction region*, i.e. a physical region where the contact reaction forces guide the part towards the correct final position in the assembly.

(ii) to *isolate* a mating feature, i.e. to ensure geometrically that some feature will be in contact first.

A total of six offsets can be applied to the part, three translations $x_{\text{off}}$, $y_{\text{off}}$, $z_{\text{off}}$, and three Euler angles $\phi_{\text{off}}$, $\theta_{\text{off}}$, $\psi_{\text{off}}$ in orientation.

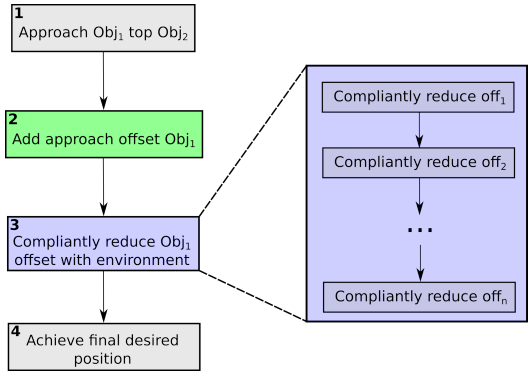



Fig. 1: Generic structure of a skill.

In the next generic action, these offsets are reduced one by one, by means of a sequence of active compliant motions where contact attraction regions are used to reduce each DoF of $\text{Obj}_1$. Of course, each particular assembly task only partially conforms to the generic skill structure, so skill

developers must decide on both the selection and order of the approach offsets. That choice is based on:

(i) the *information gained* in each step, defined as the number of DoF reduced in the action, and

(ii) the *stability* in maintaining the contact state realized thus far, over the subsequent actions.

For example, for the case of a single peg in hole insertion (see Fig. 2a), there is no information gained on reducing $\theta_{\text{off}}$ before $z_{\text{off}}$ since there is not yet interaction with the environment. Information on the gained contact states is taken into account in the subsequent offset reduction action, so existing contacts are maintained while the next offset is being reduced.

A task function approach is used to define the compliant offset reduction actions. A set of force/torque constraints in the frames of set $\mathbb{F}$ are implemented using an admittance control strategy, similar to the task frame formalism [3], [4], but allowing the addition of composing constraints in different part feature frames in the same specification.

The expertise of the skill developers is important to choose the right control stiffness values for each force/torque constraint: these values depend on both the *directions* in which forces are required to reduce the "gap", and the *stiffness* of the expected contact situation. The trade-off is between fast reactions of the robot in the "attraction" directions, and control stability in the (possibly already mechanically constrained) other directions.

In a similar way, the developers insights are essential in deciding which force/torque and pose monitoring to add, in the direction in which a transition to a new contact situation is expected, as well as in the already established partial contact situation directions.

## III. Results

Three industrial type insertion tasks with low geometrical tolerances were performed and implemented using the open source constraint-based task specification and control framework eTaSL [5]. The tasks were executed by a seven DoF KUKA LBR iiwa and a six DoF UR10 robot, both equipped with an external F/T sensor.

| Insertion case | $x_{\text{off}}$ | $y_{\text{off}}$ | $z_{\text{off}}$ | $\phi_{\text{off}}$ | $\theta_{\text{off}}$ | $\psi_{\text{off}}$ |
|---|---|---|---|---|---|---|
| Single peg-in-hole | | | 1 | | 2 | |
| Dual peg-in-hole | | | 1 | 2 | 3 | |
| PCB Insertion | 1 | 3 | 2 | 4 | 5 | |

TABLE I: Applied approach offsets for each insertion case and reduce order.

Table I gives a summary of the offsets applied for each of the insertion cases, as well as the order on which the offsets were reduced.

### A. Single Peg-in-Hole

A single peg-in-hole task Fig. 2a, with hole diameter $h_d = 25$ mm, *H7/d9* tolerance, and *1mm x 45°* chamfer was inserted.

Only one feature $\{\text{Ft}_1\}$ is present in this insertion, so the two applied offsets (Table I) are to increase the attraction region of the insertion. Fig. 3a shows the different execution stages of the task. From timestamp I to II, the offsets are added to the peg. From II to III, $z_{\text{off}}$ is reduced gaining information on the $x$, $y$, $z$ location of the hole. Later from III to IV $\theta_{\text{off}}$ is reduced gaining information on $\theta$ and $\phi$ angles. Finally, from IV to V the part achieves the final assembled position.

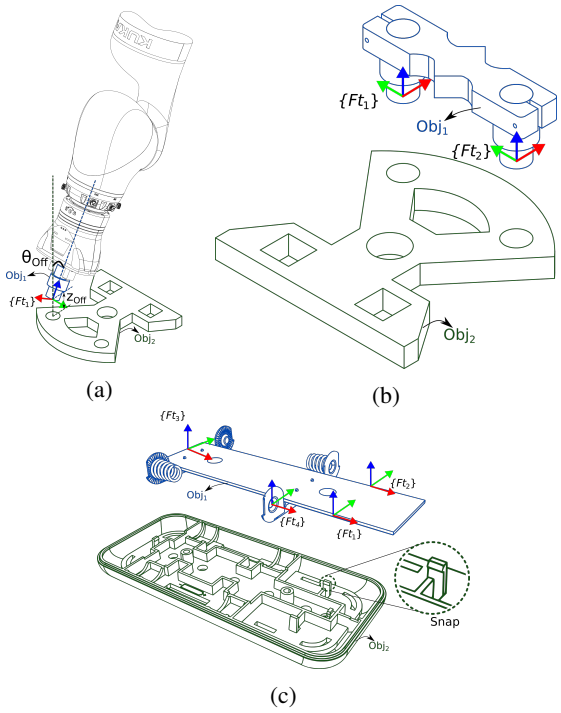



Fig. 2: Insertion tasks with selected feature frames (a) Single peg-in-hole with two offsets, (b) dual peg-in-hole, (c) three snap-fitting PCB insertion *(Frames follow the color convention RGB for XYZ axis).*

### B. Dual Peg-in-Hole

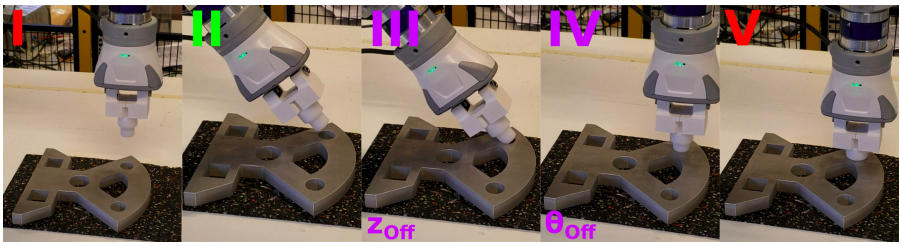
A dual peg-in-hole task, depicted in Fig. 2b, in which each peg has the same geometrical properties as in the single peg-in-hole case was inserted. The pegs are connected at a distance $p_d = 120$ mm.

In this case, apart from the offsets to increase the attraction region, one more offset $\phi_{\text{off}}$ is introduced in order to isolate the first feature $\{\text{Ft}_1\}$.

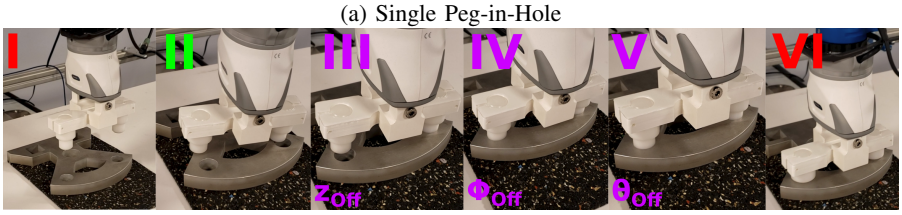
Fig. 3b shows the robot execution of the task. From timestamp I to II, the offsets are added. From II to III, $z_{\text{off}}$ is reduced gaining information on the $x$, $y$, $z$ by using the attraction forces in $\{\text{Ft}_1\}$. Later from III to IV $\phi_{\text{off}}$ is reduced by compliantly controlling $\{\text{Ft}_2\}$. From IV to V, $\theta_{\text{off}}$ is reduced gaining information in the last remaining DoF $\theta$. Finally, from V to VI the part achieves the final assembled position.

### C. PCB Insertion

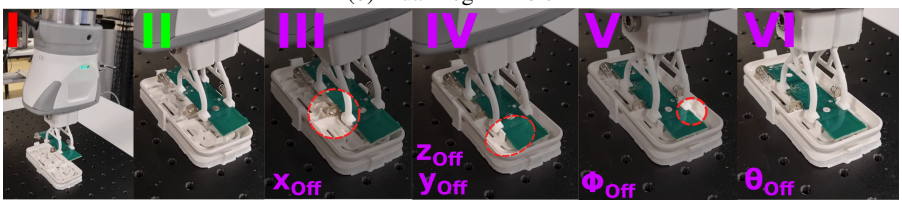
A 20x80x2 mm PCB insertion task, depicted in Fig. 2c, with three deformable snap-fitting features was accomplished.




(a) Single Peg-in-Hole




(b) Dual Peg-in-Hole




(c) PCB Insertion

Fig. 3: Robot Execution of Insertion Tasks.

In addition to the three feature frames corresponding to each snap-fit location, $\{\text{Ft}_4\}$ is introduced since three snap-fit relations doesn't completely constraint the +x direction of $\text{Obj}_1$. Five approach offsets are used, three position offsets, are introduced to create contact attraction regions and two orientation offsets to isolate $\{\text{Ft}_4\}$ from the rest of features.

Fig. 3c shows the robot execution of the task. From timestamp I to II, the offsets are added to the PCB. Compliance in the PCB is exploited to keep feature $\{\text{Ft}_3\}$ isolated until timestamp V. From II to III, $x_{\text{off}}$ is reduced by making a plane-plane contact at $\{\text{Ft}_4\}$. Then from III to IV $\{\text{Ft}_1\}$ is compliantly controlled to reduce $y_{\text{off}}$ and $z_{\text{off}}$, while $\{\text{Ft}_4\}$ is constrained to maintain $x$ contact. From IV to V, $\phi_{\text{off}}$ is reduced and the snap at $\{\text{Ft}_2\}$ is deformed to fit. Finally, from V to VI the deformation on the PCB is taken back and $\{\text{Ft}_3\}$ is moved towards the final position.

## IV. Discussion and Conclusions

The proposed methodology was used to achieve three different low-tolerance insertion tasks, in situations where the uncertainty in the position was larger than the geometrical tolerances, and validated using two different robot manipulators. By applying approach offsets, attraction regions are generated that guide the compliant manipulator towards the correct end pose in single DoF contact transitions.

The possibility to define force/torque constraints with different stiffness on multiple frames and directions is exploited by the methodology to maintain contact situations while reducing an offset to gain a new contact.

Stiffness values in the constraint directions are currently defined based on the expertise of the skill developer. However, these parameters can be fine-tuned during robot execution with an Iterative Learning Control scheme [6]. This is considered as future work.

Due to the hardware-independent nature of the skill definitions in the methodology, different mechatronics can be used. For example, by adding active compliance in the robot hand, comparable or better results can be achieved with possibly less effort. This can be explored in the future.

It was shown that having passive compliance in the assembly parts eases the insertion process, since it allows to further isolate features. This is particularly interesting in insertion cases where the end condition of the part is in a hyper-static contact state, since the nature of the contact makes the final connection stiff.

## References

[1] H. Bruyninckx, S. Dutre, and J. De Schutter, "Peg-on-hole: a model based solution to peg and hole alignment," in *Proceedings of 1995 IEEE International Conference on Robotics and Automation*, vol. 2, 1995, pp. 1919–1924 vol.2.

[2] J. Xu, Z. Hou, W. Wang, B. Xu, K. Zhang, and K. Chen, "Feedback deep deterministic policy gradient with fuzzy reward for robotic multiple peg-in-hole assembly tasks," *IEEE Transactions on Industrial Informatics*, vol. 15, pp. 1658–1667, 2019.

[3] G. Borghesan and J. De Schutter, "Constraint-based specification of hybrid position-impedance-force tasks," 05 2014, pp. 2290–2296.

[4] H. Bruyninckx and J. De Schutter, "Specification of force-controlled actions in the "task frame formalism"-a synthesis," *IEEE Transactions on Robotics and Automation*, vol. 12, no. 4, pp. 581–589, 1996.

[5] E. Aertbeliën and J. De Schutter, "Etasl/etc: A constraint-based task specification language and robot controller using expression graphs," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2014, pp. 1540–1546.

[6] K. L. Moore, *Iterative learning control for deterministic systems*. Springer, 1993.