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Automated Installation of Inserts in Honeycomb Sandwich Materials

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Abstract

Threaded inserts are a standard connecting element for sandwich components, which are widely used for aircraft interior. Therefore, inserts are installed in large quantities. However, installation is mostly done manually. An automation of the insert installation process yields high potentials for cost savings, increased output and increased productivity. Tight joining tolerances, highly individual components and quality requirements, however, pose challenges for insert placement, component referencing and program generation. In this paper a system for automated installation of potted inserts is presented. An automation concept is developed based on an analysis of the inserts, sandwich components and joining tolerances. For validation the concept is implemented in a demonstrator. Achievable accuracy, the system's robustness, as well as the joining process are examined. Further optimizations are discussed and future steps presented.

Keywords: aircraft interior; honeycomb sandwich materials; process automation; potted insert

1. Introduction

In recent years, global air travel market was growing steadily and relatively unaffected by global crises [1, 2], which resulted in an increasing demand for aircraft interior.

Nomenclature

x_{RB}	x axis in robot coordinates
x_T	x axis in tool coordinates
y_{RB}	y axis in robot coordinates
y_T	y axis in tool coordinates
z_{RB}	z axis in robot coordinates
z_T	z axis in tool coordinates
Δt	time difference
Δx_{RB}	difference in x_{RB}
Δy_{RB}	difference in y_{RB}
Δz_{RB}	difference in z_{RB}

Based on the statistics, this trend is expected to continue in the future. To keep up with increasing demand, automated processes for aircraft interior production where proposed [3]. However, automation yields high potential for cost reduction as well, which is especially needed during crises. Aircraft interior is mostly made from honeycomb sandwich materials due to high stiffness to weight ratio, good overall strength, as well as great flammability properties [4, 5, 6]. However, introduction of concentrated loads is challenging due to comparably low local strength [7]. A standard connecting element for sandwich components are so called inserts [8, 9]. These threaded bushes made of metal or plastic are adhered to sandwich material, to increase local strength and provide standardized connection points [10, 11, 12]. Since the amount of inserts per sandwich component can vary between zero and several hundred, inserts are installed in large quantities. The standardized installation process is mostly done manually [13], which results in relatively low output and high labor costs. Due to these effects, automation of the insert installation process yields high potential for cost savings, increased output and increase of productivity. However, tight joining tolerances, highly individual components [3], as well as strict quality requirements [14] pose challenges for component referencing, insert placement and program generation. In order to overcome these obstacles, this paper presents an automated process for installation of inserts in honeycomb sandwich materials.

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2. State of art

2.1. Potted inserts

Common inserts are so called potted inserts, usually made of metal or polyetherimide with 30% glass fiber (PEI-GF30) and a stainless steel thread. Potted inserts come with an installation cap, which has two holes for adhesive feed and venting. The cap has a sticky film on its bottom surface to keep the insert in place during installation. Since inserts are installed in bores, installation takes place after component machining. The installation process as illustrated in Figure 1 is usually performed manually. First, the insert is placed into its respective hole (Figure 1 a).

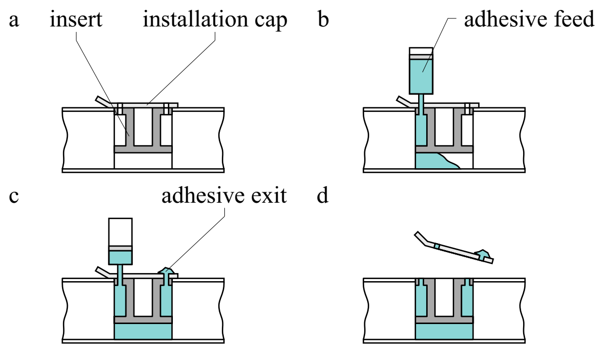

Fig. 1. (a) Insert in hole; (b) Adhesive injection; (c) Exit of adhesive; (d) Cap removal after curing

The installation cap has to be aligned with the panel surface so it sticks to the surface, keeps the insert in position and guarantees flush installation. Next, adhesive is fed through one of the two holes in the cap until it exits the venting hole (Figure 1 b and c). In case of inserts without anti-torsion protection, adhesive may be poured into the bore before the insert is placed and potted to ensure an adequate bonding. 2-component epoxy resin is widely used as adhesive. After curing, remaining adhesive on the surface and the cap are removed (Figure 1 d). Potted inserts as described above are only set in top and bottom surfaces. However, other potted inserts types for different purposes (e.g. high loads) and positions (e.g. component edges) exist [10, 12]. No automated solution for the described, manual installation process is known. However, a few approaches for automated insert installation based on proprietary insert designs exist. One example is an automated machine for installing inserts with an adhesive-filled groove in the bottom surface. However, this process limits design freedom and only allows insert installation in the face sheets. Installation of high strength inserts is not possible. Further more, adaption of the new insert type to existing interior designs creates high costs and may cause certification problems [15, 16].

2.2. Friction inserts

A different type of inserts are friction inserts. The main difference to potted inserts is a thermoplastic coat. For installation, a insert is mounted on a spindle. The insert is pressed against the sandwich panel surface and rotated. Due to friction the thermoplastic coat melts. Meanwhile, force-feed is applied and the insert is driven into the panel. The thermoplastic coat softens/melts and eventually fills honeycomb cells. As soon as the insert is aligned, rotation is stopped and the insert cools down under a constant load [17]. A form-locked and substance-locked connection is created. The installation process of friction inserts is fully automated and allows for high productivity [18]. However, friction inserts can transfer lower loads than potted inserts and the load capacity cannot be adapted to the load case.

2.3. Cast inserts

A completely different type of insert are so called cast inserts. Compared to potted inserts and friction inserts, the insert is not a solid component placed in a sandwich part. Instead, a 2-component adhesive with very short curing time, typically polyurea, is poured into a bore. While curing, a mandrel is driven into the adhesive and forms a hole. At the same time the mandrel stops further adhesive feed. After the adhesive has gained sufficient stability (depending on the adhesive 70-80% after seconds), the mandrel is pulled out and the pouring head is removed. A casted insert remains [19]. This process is already automated, but shares the disadvantages of friction inserts. The transferable loads are comparably low and cannot be adapted to the load case.

2.4. Summary and outline

As shown, a few solutions for automated installation of inserts in sandwich components exist. However, these solutions rely on proprietary insert design and have limitations and drawbacks. Load capacity of these inserts is lower than with standard potted inserts and significantly lower than with high strength types. Additionally, the load capacity of these inserts cannot be adapted to the load case, which limits design freedom and may cause additional component weight. Furthermore, adapting new, proprietary insert types to existing interior design causes high costs, can cause certification problems and reduces the flexibility of the supply chain. In order to keep design freedom and avoid the deficits of new insert designs, automation of the conventional insert installation process is needed. Therefore, the conventional process is analyzed and requirements for an automated process are derived. Afterwards an automation concept is developed. Finally, the key technologies are realized and tested in a demonstration setup and the automation concept is validated.

3. Analysis

In order to derive a concept for process automation, the range of sandwich components, insert types as well as the joining process are analyzed.

3.1. Sandwich components

The geometry of the sandwich components is highly variable while each part is only produced in small quantities. Flat sandwich components are most common, but there is also a comparatively small amount of curved components. Due to possible geometries, end stops can not be used. Component referencing has to be done by a sensor system instead. Bores for inserts can be on top and bottom surfaces, as well as on edges. Possible insert positions and component geometries require a highly flexible handling system with six degrees of freedom. Due to the small lot sizes, automated program generation is required to make the overall process economical. The position tolerance of manufacturing is $\pm 0,1$ mm. All sandwich components are labeled with text and a 2D-code.

3.2. Inserts

10 different inserts have been considered. The general shape is quite similar due to their origin of three adjacent standards [20, 21, 22]. All inserts have filling notches at the upper flange for the adhesive. The distance between the notches is equal to the distance between filling/ventilation holes in the installation cap, but not constant for all types. The caps outer contour however is mostly constant. Due to manufacturing tolerances, concentricity between insert and cap is between 0,2 and 0,4 mm. Inserts are delivered in blisters as seen in Figure 2. Since different inserts can occur, different end effectors for insert placement may be required and therefore a flexible handling system is needed.

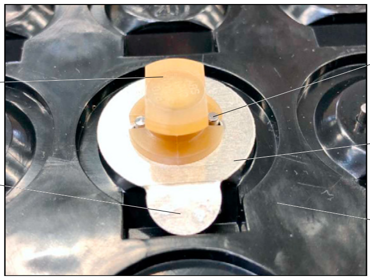

Fig. 2. Insert provision in blisters

3.3. Joining process

Analyzing insert dimensions and their respective bores showed the joining tolerance is $\pm 0,25$ mm at the lower flange. If the insert is not self-centered, the joining tolerance of $\pm 0,05$ mm at the upper flange is crucial. The joining tolerances require a highly repeatable insert gripping, as well as high positioning accuracy within joining tolerance or compensation of occurring tolerances. The insert has to be installed flush with the component surface. The orientation around its longitudinal axis is arbitrary.

4. Concept

In this section a general concept is presented before various components are described in detail.

4.1. General concept

According to the analysis, the system has to be highly flexible and have six degrees of freedom. A suitable and cost-effective handling system is an industrial robot (IRB). However, while having a good repeatability (usually less than $\pm 0,1$ mm) IRBs usually lack positioning accuracy (greater than 1 mm is common [23]) and the joining tolerance is exceeded. The joining process, however, can be seen as a peg-in-hole-problem, where tolerances can be compensated by a correctional movement based on sensor data [24, 25]. Therefore, we propose a two step referencing process. First, the position of the component in the robot's workspace is identified in order to allow component identification and positioning of the gripper in the area of the bore. In this step, a large area has to be covered but comparably low accuracy is acceptable. To compensate tolerances and positioning accuracy, a second, fine referencing step is performed during insert placement. In this step, the position of the bore hole is measured with a second sensor system, which is mounted to the end effector. In this second step high accuracy is needed, however only the bore has to be detected. The general concept is shown in Figure 3. It consists of an IRB with an end effector, a sandwich component and sensor systems for referencing the workpiece and the bore respectively. As periphery a insert pick up holder is included.

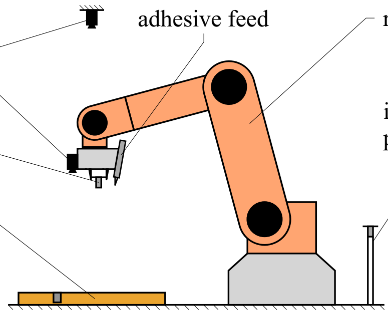

Fig. 3. General concept

4.2. Workpiece identification

As all components are labeled, identification is trivial. The label is processed by an optical system (e.g camera and image processing, laserscan) and refers to a database where information like insert positions, types etc. can be extracted.

4.3. Workpiece referencing

Different approaches for referencing have been discussed, among them referencing with optical sensors and by workpiece shape, bore pattern and by artificial features. Referencing by workpiece contour and bore pattern lack of robustness due to possible symmetries and therefore multiple orientations with similar contours. Additionally, these approaches are relatively complicated to implement for curved components. Therefore, an approach with artificial features is pursued and described in the following. Due to large field of view, low hardware cost and ease of integration of a camera system and image processing are well suited for workpiece referencing. In combination with camera systems, ArUco-Markers are widely used [26]. Such markers can be placed on the component surface and measured with respect to the known component coordinate system, directly after machining. By capturing the marker with a top mounted camera, before insert placement, workpiece origin and insert positions in camera coordinates can be calculated.

4.4. Fine referencing and positioning

After the robot moved roughly to the bore based on workpiece referencing, the bore is used for fine referencing. For detection of the bore, a camera system and image processing, as well as laser scanning where considered. Preliminary tests with a laser line scanner have shown that precise detection of the bore edge with a laser scan is challenging, due to the reflective characteristics of the component surface. However, with camera systems and front illumination by a ring light, the reflection can be utilized to increase contrast between bore and component surface. For this reason, fine referencing by image processing is pursued. During insert placement, fine referencing begins with the camera positioned above the bore perpendicular to the component surface. The camera takes a shot and a circle detection algorithm detects the bore. Based on the position of the bore, a comparably small correctional movement is performed, in order to align the insert with the bore. A suitable approach strategy prevents changes in the rotation direction of the individual robot axes during the correction movement. This results in positioning errors much closer to the robot's repeatability of approximately 0,1 mm.

4.5. Gripping the insert

Gripping the insert can be done either on the insert itself or on the installation cap. Due to cap tolerances, the insert gripping can not be done with sufficient repeatability and joining tolerance would be exceeded. Instead, gripping at the upper flange, in the filling notches, is much more appropriate. Tolerances between insert and cap have no influence and the insert is always centered in the gripper. Also, orientation of the insert is known which is useful for adhesive feed. The gripping concept is illustrated in Figure 4. The inserts are delivered the wrong way round for installation (see Figure 2) and have to be rotated before gripping.

4.6. Joining strategy

The way the insert is gripped influences the joining strategy. As the insert is gripped at the upper flange, the insert can not

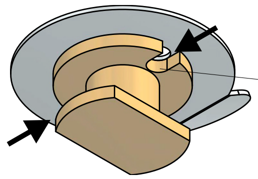

Fig. 4. Gripping the insert

be installed in one move, due to collisions of the gripping fingers with the component surface. Also, preliminary tests have shown that the sticky film on the installation cap causes the insert to be pulled out of the bore while opening the gripper. To prevent this and to ensure that the insert is installed flush, a compression spring between gripper and the installation cap is used. The spring also pushes the insert into the bore when the gripper is opened. Joining can be further assisted with chamfers on the insert, but require an insert design modification.

4.7. Program generation

For an automated placement, a list with all insert types and positions with respect to the component's coordinate system is needed. In this work, a plugin in the CAD software CATIA is used to export these information directly from the CAD model. The information is stored in a CSV-file. The easiest approach for program generation, which is also used in this work, is to place all inserts in the order of appearance in the CSV-file. Further processing, like checking for reachability or collisions, as well as optimizations regarding path generation, can be done. If a mobile insert magazine is used, the IRB would not have to return to insert pick up after each placement. Instead, the next insert position can be approached. For insert placement sequence and path optimizations, approaches regarding the traveling salesman problem can be used.

5. Demonstration

For demonstration and validation a demonstrator was built. All parts regarding accuracy and robustness of the placement process were realized. However, feeding of adhesive and inserts have not been implemented since their subsequent integration is considered unproblematic.

5.1. Setup

The setup is shown in Figure 5. A KUKA KR 6 R900 sixx IRB on an aluminum frame is used. A camera (top camera in the following; type: IDS UI-3250LE-C-HQ, camera lens: Tamron M118FM06) is mounted to the ceiling of the cell and covers the robot's workspace. The transformation between top camera and robot base coordinate system has been calibrated by cross referencing of checkerboard corners with the camera system, as well as a measurement tip mounted to the flange. The end effector consists of a second, identical camera (robot camera in the following), a pneumatic gripper (Schunk KGG 80-30) with

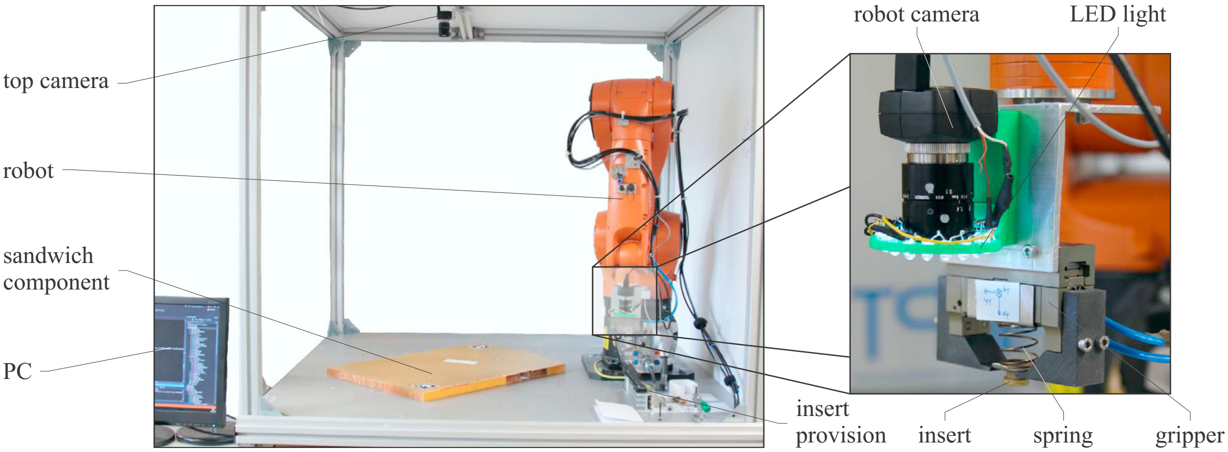

Fig. 5. Demonstration setup

SLS-printed gripping fingers, a compression spring and a LED ring light. The transformation between robot flange, robot camera and the insert in the gripping fingers have been calibrated respectively. The same cross referencing method as for top camera and robot base was used. For insert provision a fixed insert holder has been built. The robot poses for pick up, a home position and a pose for collision free approach have been teached. Robot, gripper, LED ring light and cameras are controlled by a computer. The control software is programmed in C++, using OpenCV for image processing and KUKA Ethernet KRL for robot interaction. A test workpiece was cut from an larger interior component. It has 13 insert positions of three insert types. A CAD plugin generated a CSV-file containing the insert positions and types. Two different ArUco-markers were manually placed on the component surface and their coordinates with respect to component origin were determined. For demonstration the workpiece is fixed with double-sided adhesive tape.

5.2. *Placement process*

The placement process[1] begins with the top camera taking a picture to localize the ArUco-markers on the arbitrary positioned sandwich component, as well as the label for identification. Label localization is necessary as the top camera's resolution is not sufficient for reading the label. In order to read the label, the robot camera is positioned over it. After the workpiece is identified, insert positions and types are gathered from the CSV-file. The ArUco-Markers are localized and the workpiece origin in top camera coordinates is calculated. Origin and insert positions are transformed into robot coordinates and a placement program is generated. Now, the robot moves to insert provision, picks an insert and approaches the respective bore. The robot camera references the bore with a circle detection and a small fine positioning movement is calculated and executed. After fine positioning, the robot places the insert in the bore.

[1] A video of the procedure can be found here: https://youtu.be/O5fL26Lk8cA

5.3. *Testing and optimization*

The general function of the demonstrator was tested and some improvements were made. Therefore, the workpiece was positioned in the cell several times in different positions and orientations. Each time all inserts were placed. The tests made clear that the inserts could be placed very reliably. In some cases, however, the inserts touched the bore edge before sliding into the hole. This indicated that the accuracy requirement was not always met. Manually adjusting the calibration between the robot camera and tool improved the result, but could not completely eliminate the collision. During installation, a sporadically occurring rotation of the insert (according to estimates less then 5 degrees) can be observed. This is probably related to the dimensional accuracy of the gripping fingers. The lugs on the gripping fingers are not directly opposite to each other in the direction of movement of the gripping fingers and therefore cause a moment. Besides an insufficient calibration and too great measurement inaccuracies of the image processing (e.g. due to a low camera resolution), the insufficient positioning accuracy can be caused by low gripping accuracy or correction movement of the robot. For this reason, in the next section the impact of these two error sources is examined.

6. Validation

To validate the proposed concept, extensive tests were carried out on positioning accuracy and robustness of the system.

6.1. *Accuracy*

6.1.1. *Gripping accuracy*

For a reliable placement process a high gripping repeatability is mandatory. To measure gripping accuracy, a laser target is attached to an insert and tracked by a Leica LDT 800 laser-tracker. The insert was manually fed to the gripper and gripped 25 times without robot movement. Each time the insert position was measured. Figure 6 shows the gripped insert with the target. The deviation from mean position in tool coordinates x_T,

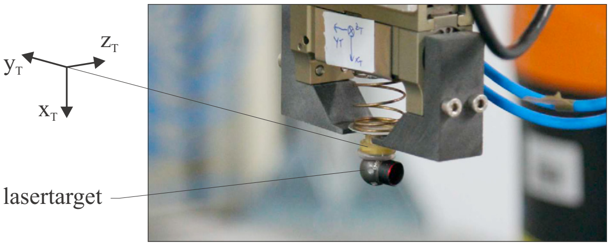

Fig. 6. Lasertarget attached to an insert

y_T and z_T was calculated. Results are shown in Figure 7. Mean

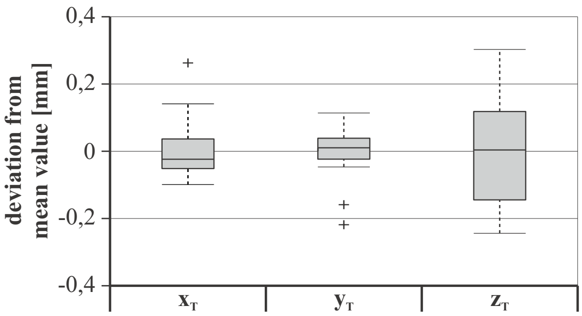

Fig. 7. Deviation from mean value in tool axes

absolute deviation from mean value in y_T is 0,045 mm which indicates a good centering between the gripping fingers. However, in z_T the mean absolute deviation is 0,136 mm and scattering is much bigger. The biggest deviation is 0,303 mm and indicates a gap between the filling notches and the lugs of the gripping fingers. In x_T-direction the mean absolute deviation is 0,063 mm, but a deviation in x_T is less critical for the installation process than deviations in y_T or z_T. The results show that a reliable installation is not guaranteed. In addition, it is expected that the low gripping accuracy strongly affects the calibration between robot and tool as well as between robot camera and tool. An increased repeatability is therefore needed and can be achieved by using CNC-machined gripping fingers with tight tolerances instead of the SLS-printed ones. Another approach is compensating gripping tolerances during fine referencing. This can be done by a different sensor arrangement, which also detects the insert in the gripper. Tracking of insert and bore allows dynamic calculation of remaining distance during fine positioning. This yields potential to further increase accuracy.

6.1.2. *Fine positioning accuracy*

The influence of fine positioning has been examined as well. For this reason, the insert with laser target was gripped and the robot performed movements similar to real correction movements (movement of short distance and only in x_{RB} and y_{RB}, $\Delta z_{RB} = 0$). Table 1 contains the performed movements. For each measurement the deviation between performed and theoretical distance of start and end point has been determined.

Table 1. Traverse movements

	V1	V2	V3	V4	V5	V6	V7	V8
Δx_{RB}	+50	-50	+50	-50	+5	-5	+5	-5
Δy_{RB}	+5	+5	-5	-5	+50	+50	-50	-50

Results are shown in Figure 8. The influence in z_{RB} can be neglected. Mean absolute deviation of all measurements is 0,0534 mm. A scattering between the measurements, especially be-

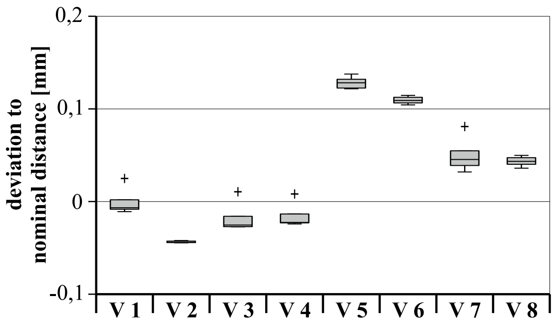

Fig. 8. Deviations to nominal distances

tween the first four and last four measurements, can be seen. This indicates the influences of the individual robot axes, which are involved in the movement to varying degrees depending on the measurement. It is nevertheless evident that errors due to the short traverse path have less influence meeting the joining accuracy requirement than gripping the insert.

6.2. *Analysis of joining*

During testing it became clear that the final insertion process runs mostly as planned. However, it was repeatedly observed that the insert was installed correctly, although the insert had contact with the bore edge, which indicates that theoretical accuracy requirements where not met. To examine the final installation and to find out why the insert was still successfully placed, high speed video recordings were made. In the following both compliance and non-compliance to required accuracy are discussed. Figure 9 shows the process when the accuracy requirement is fulfilled. The insert is positioned in the bore without contact (Figure 9 a). During gripper opening however, the insert moves inside the bore within the joining tolerance and collides with the bore edges (Figure 9 b and c). It is expected, that the movement is caused by the installation cap sticking to the gripping fingers. The spring pushes the released insert into the bore (Figure 9 d) and aligns it to the surface (Figure 9 e). The installation with contact is shown in Figure 10. When the insert makes contact with the component surface, it tilts slightly in the gripper into direction of the bore (Figure 10 a). As soon as the gripper opens, the insert slides along the bore edge in the direction of the bore and tilts back (Figure 10 b). Despite

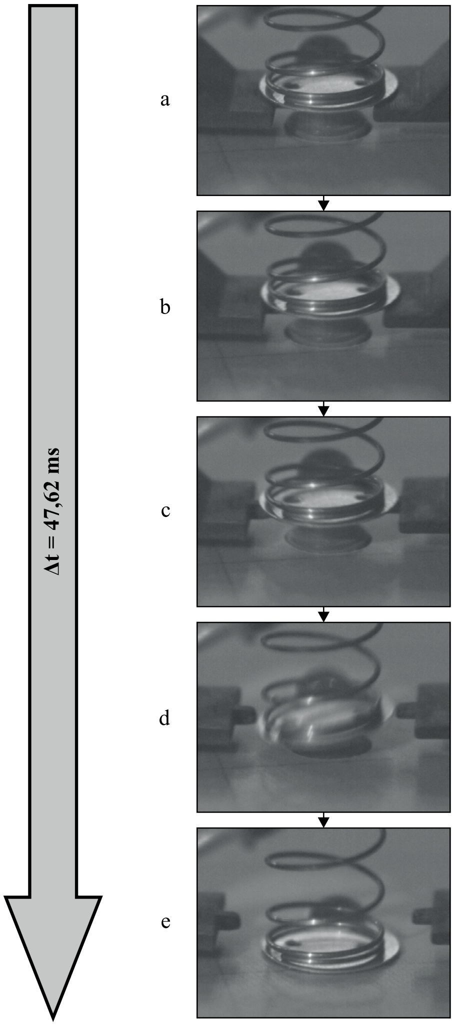

Fig. 9. High speed recording when compliance with accuracy

chamferless edges the insert centers itself (Figure 10 c). When the lower flange of the insert is fully inserted in the bore, the remaining installation (Figure 10 d-f) is similar as in Figure 9.

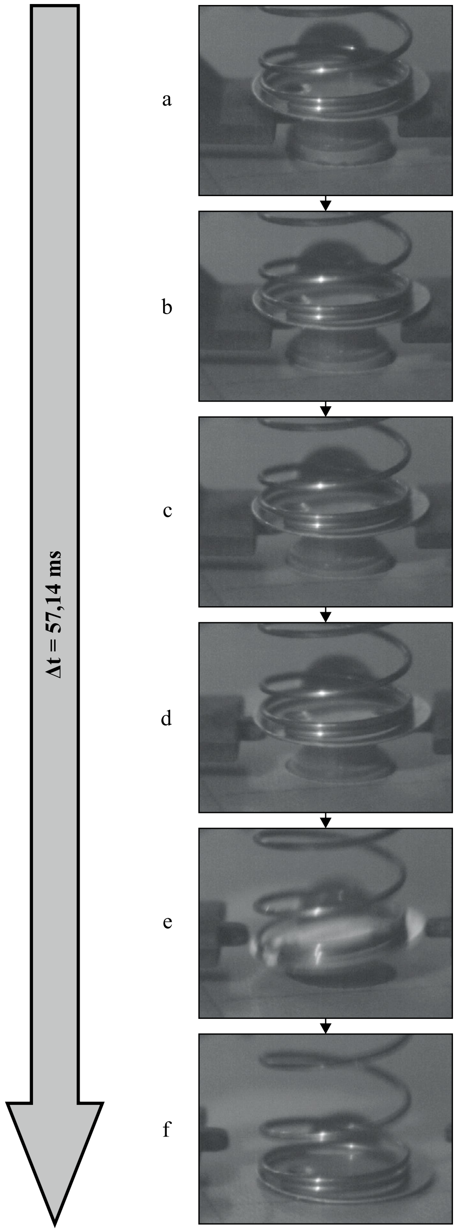

Fig. 10. High speed recording when non-compliance with accuracy

6.3. Robustness

Tests were carried to evaluate the system's robustness.

6.3.1. Deviations of artificial features

To examine the influence of deviating marker positions (e.g. if placed manually after machining), the markers have been moved about ±1 cm, rotated and swapped. Position deviations cause deviations in the calculated workpiece origin, the insert positions in top camera coordinates, and therefore false robot coordinates. The robot moves slightly deviated over a bore. Joining can still be successful when fine referencing tracks the bore. However, if the bore is out of the illuminated area the circle detection does not succeed. Rotation has no effect at all, since only the marker position is used. Swapping the features can not be compensated as each marker has a specific position with respect to workpiece origin. Using more markers or additional marker properties can improve robustness.

6.3.2. Deviations of insert data

To simulate machining tolerances, deviations between the CSV-file data and the actual component have been examined.

The insert positions have been modified in a range the bore is still in the robot camera's view. Deviations yield false coordinates for robot approach. However, as with marker position deviations, small errors up to ±1 cm can be compensated by fine referencing. Larger deviations cause the bore to be outside the illuminated area and the circle detection algorithm fails. A bigger ring light would therefore improve the robustness. However, large deviations enable mix-ups of bores while the algorithm still believes to fit the correct bore.

7. Conclusion and outlook

In this paper a system for automated placement of potted inserts was presented. An analysis of inserts, sandwich components and joining tolerances was carried out and requirements were derived. Tight joining tolerances and the highly individual components are major challenges. These were overcome by a two step referencing process based on image processing, universal insert gripping and automated path generation. The concepts were implemented for testing and validation. It was proven that an automated installation of inserts with the proposed concept is possible. Test have also shown a certain robustness to errors. However, the achieved overall accuracy does not always fulfill the theoretical accuracy requirement. A low gripping repeatability was identified as major influence. An analysis with high speed recordings was carried to understand why the installation is still successful, though the positioning tolerance does not meet the joining tolerance. Future work is required to integrate the concept into series production. Outlined improvements should be implemented and the system should be adapted to curved components and inserts in component edges. To further validate the process, adhesive feed and insert feed could be integrated into the demonstrator. Finally, a production sized automation cell including workpiece storage, feed, clamping and turning needs to be developed and built.

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