WHAT IS THE BEST WAY TO INCREASE EFFICIENCY IN PRECISION ASSEMBLY?

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Abstract: Assembly of high precision products is often done manually. The main reasons are the complexity of automation and the production volumes that often remain small to medium. Watches, medical devices and sensors are some examples of products requiring high precision assembly: often expensive products with high margins. It is interesting to notice that achieving higher assembly yield allows for relative quick pay-back of equipment. This is also the reason why western European countries remain competitive in this field. In this paper, the important points to remember when selecting a solution to efficiently assist operators in their assembly tasks are highlighted. Good assistance should lead to higher yields, higher throughputs and better quality. One should take into account assembly processes and their difficulties, as well as production volume and economic profitability.

Key words: micro-assembly; precision assembly; man-machine cooperation; semi-automatic assembly

1. INTRODUCTION

Precision assembly is often done manually due to difficult processes, high equipment cost and short product life cycle. But manually assembly results in low yields and thus high assembly cost, which drives to find better solutions. The issue is to provide efficient assistance to assembly operators with automatic or semi-automatic devices: some examples are high precision axis with manual actuation like the Tresky cell's, semi-automatic assembly cells, telemanipulation with haptic devices (Ferreira 2003), intuitive programming, and vision enhancing.

It is a priori difficult to decide how to assist the operator, and to choose the part of the assembly process to automate. This decision shouldn't rely on some kind of dogmatic principle, but on a thorough analysis and on long and short term economic considerations.

2. HISTORY AND MACRO ASSEMBLY

In the past, all assembly operations were entirely manual. Mechanization was introduced to achieve lower cycle times, as well as robotics some decades later. Machines achieved simple feeding operations, and simple assembly operations with straight movements where men could easily be replaced. Operators did the more complex operations, such as orienting, adjusting, tuning, and inspecting.

Design for Assembly rules (Boothroyd, 1991) were introduced in the 80thies by classifying assembly processes from the easiest (or fastest) to the most difficult for automatic assembly. Soon people understood that easy for automatic assembly also meant easy for manual assembly. From that point, the design rule for new products was: make them easy to assemble automatically, even if you do it by hand.

The easiest assembly operation is a simple straight insertion along one axis, the preferred one being vertical. It is the well known peg-in-hole situation. Assembly with two or more axis, in hidden positions becomes difficult for machines, but also trying for operators.

A problem occurs in simple insertion when there is a slight misalignment between the insertion position and the component. This is easily corrected by a human operator. He holds the parts between his fingers, touches the receptor, senses the forces transmitted to his fingers and fine tunes the position. Attempts were made to do the same with robots, and a lot of compliant solutions were proposed: active compliance, compliant grippers, etc. Due to the forces that where transmitted to the gripper (or to the robot) when the two parts to assemble met, the axis of the gripper was modified in order to adapt to the real insertion axis.

But in the end, industries retained simpler ways. One of the easiest solutions with a cartesian or a SCARA robot, is to switch off the control of the x and y axis during insertion, so that the robot can simply adapt its x-y position. As long as the z axis of the gripper and the axis of the receptor are well aligned, insertions are then very easy.

The kinematics the human uses is extremely complex. A multitude of "sensors" are used: touch, multidimensional force feed back, very high resolution force sensors, vision. On the other hand, the best results achieved with robots or mechanical devices are based on precise straight movements and precise positioning. These are two features the operator lacks completely. So the insertion of a peg can be achieved either by an operator using intuitive complex sensing and kinematics, either by an apparatus using straight and precise movements. Copying the human with a robot is not the best solution to achieve high yields and short cycle times. It is better combine the strong features of both.

3. PRECISION ASSEMBLY

3.1 What are the constraints in precision assembly?

Today, products become smaller and micro assembly or high precision assembly is the challenge. Microsystems and other fine mechanical systems are often produced in small to medium batches. Full automation is than not the right solution as the investment costs are too high and pay back can not be reached on such small volumes. On the other hand, human operators are clearly not efficient enough in this domain. Operations become very tedious, resulting in fatigue, low yields and thus high costs. Precision components are often expensive, which reveals the importance of maximizing yield by providing the right tools to ease the operator's task.

The best approach is than semi-automatic assembly. An important step is to define which tasks, processes or part of processes should be carried out by the operator, and which by an automatic device.

Therefore it is important to identify the assembly processes that are needed and the corresponding requirements, to identify the operator and the machine's strong and weak points, and than to allocate the operations accordingly.

3.2 Strong and weak points

Machines and operators don't function the same way. In order to combine the strong points of both (and to avoid the weak points) it is important to identify them with precision. They are described in the following paragraphs.

The strong points of the human operator are the ability to learn, to react to unforeseen situations, high flexibility in case of product change, multi sensorial detection, a very large sensing (10 mN to 100 N) and actuating range (from 10 μm to several meters, more when walking).

The weak points are the impossibility to stop at a predefined position, no force limitation, no straight movements, subjectivity, and the difficulty to move hands with precision without force feed back.

The strong points of an automated device are repeatability and precision, straight movements, force and position control. The weak points are limited motion range, low flexibility to product changes, no reaction to unknown situations, and the fact that it has to be programmed.

The points we surely want to combine are the precision, straight movements, and repeatability with the ability to learn, to react on unforeseen situations, and the ability to make small and very long displacements

3.3 Most frequent micro-assembly processes and their specificities

3.3.1 Component placing

In macro assembly, the peg in hole situation (or simply insertion) is relatively generic of most assemblies. In precision assembly, "peg in hole" also occurs. The difficulties are then:

- To identify the peg and the hole, their exact position, and sometimes to define the hole axis!
- To grip the peg
- To align the peg axis with the hole axis
- To insert the peg in the hole while limiting the constraints on the components
- To control the position.

But most assemblies are of another kind: mainly plane on plane with visual references on both parts (for example die bonding). This is due to the fact that most components are 2 dimensional, manufactured with silicon technologies. Assembly references are often not visible during assembly (for example flip chip, or the reference hidden by a drop of glue).

3.3.2 Specificities of placing

The main difference compared to assembly in the macro-world is that parts can not be positioned on a mechanical reference. Tolerances on parts are either less precise than the precision required, or of the same order, some μm. The functional dimensions and characteristics of the parts have to be identified and measured. The positioning is done by placing or aligning one functional element relatively to another.

3.3.3 Attachment an other processes

The most frequent attachment processes are: press-fitting, glue application, wire bonding and laser welding. A further major process is control and inspection: visual, measurement of forces or positions.

3.4 Difficulties for the human operator

In micro assembly, difficulties are of two kinds: sensing and actuating. Most operations require both simultaneously.

3.4.1 Gripping

First of all, the operator wears gloves and has to use tweezers to grip the component. The multi dimensional force feedback he had in macroassembly through direct contact with his fingers lowers tremendously. Forces are transmitted through the tweezers, resulting in a drop down of tactile information. Furthermore, forces are also smaller, making gripping a real delicate task.

3.4.2 Releasing

Releasing of components is especially difficult in the micro-world due to adhesion forces becoming dominant. Although this problem is not related to the operator but a global one, it has to be taken into account.

3.4.3 Force Sensing

Forces are very small making it hazardous to manipulate small and fragile parts. The level of the force that may create damage increases with the size reduction of the component. The weight and the inertia of the parts are so small, that feeling them with tweezers is very difficult. As stated above, force sensing through tools is much less precise than with the bare fingers.

3.4.4 Visual Sensing

Human vision is not sufficient to control tiny details, and work under a microscope is the rule. The operator only sees a fraction of the component at a time, the depth of field being limited. Training is needed to be able to quickly position the interesting part of the component under the microscope.

It becomes particularly risky to identify functional assembly references that often can not be seen with the bare eye, like on chips.

3.4.5 Actuating

Using mechanical references is the natural way to position a part to another: a book on a table, a key in a key-hole, a washer on a screw. In all those cases, we use one of the components to guide the other one, and positioning is achieved using the dimensions of each part. It is really difficult to position two references to one other without making contact, such as a mass between to parts (first accelerometers), a visual reference on a part at a given distance of a hole, or to align a flipped chip on the corresponding solder balls. A major difficulty in microassembly is to align and to make match the assembly references of two components without mechanical references.

3.4.6 Actuating with force control

An other problem is to position a part without exceeding a given force. This is the case for fragile components such as IC pressure sensors, or fragile mechanical parts, like watch needles. The assembly operator places the needle on the shaft and applies a force; when he feels a resistance, he increases the force to reach the right position. This may damage the inside of the watch movement.

3.4.7 Yield

Yield is always an important factor in assembly, and becomes really significant in precision and micro assembly. Yield consequences are of two kinds:

- Bad components or processes conduct to stops in the assembly installation. Throughput is then lower than expected, resulting in production delays and/or slow pay-backs of the installation. A detailed description is given by Oulevey (2006).
- The assembly of a bad component leads to a bad product, resulting in rework and/or the loss of all assembled components. When they are expensive, which is often the case with precision products, very high losses occur.

The main attention when automating or providing tools should be on the reliability of the assembly processes.

4. WHERE DO THE SOLUTIONS LIE? – PROPOSED METHODOLOGY

Operators have to be assisted where precision is needed. Several approaches are proposed, some academic, some industrial. Our objective is to propose a method to define a suited technology for each particular situation, and to provide technologies to enable precision assembly. Three main thoughts guide our approach:

1. To be economically interesting, the cost of the equipment to assist the operator shouldn't exceed the manual assembly cost, and a quick payback of the investment is necessary. This means: high productivity rate, thus few down-time. A thorough cost calculation is necessary to evaluate the total assembly cost of the products to be produced, and to estimate of how much may be invested. Losses due to human mistakes because of very difficult work have to be taken into account in this calculation.
2. To assure precision assembly, we have to guarantee the processes: this means high yield. This can be achieved only by the precise identification of the processes, of the assembly functions needed, and of the functional references on the parts.
3. For each process or operation, we have to consider the best way to fulfill the function: manual or automatic. Automation should be restricted to where it is really needed in order to control costs; full automation only is interesting for big production volumes.

5. CASE STUDIES

Two case studies will illustrate our approach: the development of a flexible semi-automatic assembly cell at the LPM with the collaboration of the firm Sysmelec SA (Koelemeijer 2002, 2003, 2005), and the press-fitting of a watch jewel in a hole.

5.1 Case study 1 – Flexible micro assembly cell

As the investment for a flexible assembly cell is quite high, it is important to achieve a high throughput. Operations have to be allocated either to the robot, either to the operator, according to the requirements. It is important to restrict the man-machine interaction time for a better efficiency. Their speed is different, the operator shoudn't have to wait on the machine, and the machine should'nt have to wait on the operator.

The preferred solution is then :

- To use the operator for programming, and to avoid teleoperation. Programming time for a new product shouldn't exceed 10 minutes.
- To use the operator for feeding. Parts are very small, an operator can easely carry thousands of parts prepared on palets. As batches are small, this is a very cost effective solution, while automatic feeding would be very problematic (Koelemeijer, 1999, 2001).
- To use the robot (a high precision cartesian Sysmelec robot, equipped with a high resolution camera) for precise positionning, with straight and fast movements. Functionnal refrences on the components are identified by image processing. The robot is also equipped with a gripper mounted on a force control device, and a gluing unit. This ensures that the assembly cell can carry out most of pick and place operations that occur in micro-assembly: insertions, alignments, force controlled placing.

This type of collaboration is a good combination of strenghts. The precision is ensured by the robot and the image processing system. The operator hasn't have to manipulate the components during difficult assembly operations. But he uses his skills and know-how for the programming of the assembly sequence, to choose and to parameterize generic operations and to define references.

5.2 Case study 2 - Press-fitting of a jewel in a hole

A jewel is manually positioned in a hole of a watch bar and then inserted with force to a given position. This jewel is the bearing of a shaft in a mechanical watch. Several jewels are inserted in the same watch bar. A tool is needed: either a hand operated press, either an automated press with position and force feedback. The functional requirement of this assembly is that the shaft should have a play of 20 μm. The capability of the hand operated press and the servo-controlled press are different, resulting in different assembly yields. Details can be found in (Bourgeois, 2005). If the resulting play is outside the tolerance range, the watch bar has to be removed, the jewels pressed out, and then reassembled.

The costs with the hand operated press C_m and the numerical controlled press C_n are:

$$C_m = C_{pm} / Y_m + (1 - Y_m) \cdot C_{rwk} \cdot N + c_h \cdot T_{pm} \cdot N$$

$$C_n = C_{pn} / Y_n + (1 - Y_n) \cdot C_{rwk} \cdot N + c_h \cdot T_{pn} \cdot N$$

The break even point is reached for the assembly of N jewels:

$$N = [C_{rwk} \cdot (Y_m - Y_n) - c_h \cdot (T_{pn} - T_{pn})]^{-1} \cdot [C_{pn} / Y_n - C_{pm} / Y_m]$$

The following values are used:

C_{rwk}	=	Cost of rework = 8 €/part
C_{pn}	=	Cost of numerical controlled press = 200'000 €
C_{pm}	=	Cost of manual press = 10'000 €
Y_n	=	Yield of numerical controlled press = 93.7%
Y_m	=	Yield of manual press = 36.7%
c_h	=	Cost of operator = 80 €/hour
T_{pn}	=	Cycle time of numerical controlled press = 15 s
T_{pm}	=	Cycle time of manual press = 10 s

Rework being long (10 minutes) and parts very expensive (high end watches), the servo-controlled press is more interesting as soon as the break even point of 42'000 jewels is reached. As a watch has about 5 to 10 jewels, a production of 4 to 8'000 watches a year allows for a pay back of an expensive servo controlled press in one year.

6. CONCLUSION AND FURTHER WORK

To achieve high precision assembly, operators have to be assisted by some tools or automatic devices. The question of what to automate remains difficult, but always has to respond to economic efficiency. The three following points are important guidelines:

1. To achieve high throughput and a high productivity rate of both machines and operators, tasks should be well separated and collaboration periods limited.
2. Low assembly yield is often what makes precision assembly very expensive. Difficult processes should be automated to achieve better capabilities and higher yields. This quickly results in cost reduction, even when some investment is necessary. This can't be achieved without a very good understanding of the process.
3. Each operation or process should be analyzed in terms of precision, cycle time, range, and capacity, and allocated to the most suited of either the automatic tool, either the operator.

Further work at the LPM-EPFL is done on the identification of micro-assembly processes and their in depth understanding. High process yields can only be achieved through the comprehension of the role of each parameter. We are especially active in laser heating and welding (Seigneur, 2005, 2006), and micro-press fitting (Bourgeois). Another research topic is the use of surface forces for gripping and positioning of small components (Lambert, 2005).

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