COST MODELLING OF MICROASSEMBLY

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Abstract - In the microsystem domain, technical as well as economic factors must be considered simultaneously when developing assembly tools. At the same time, the specificities dictated by the parts to be assembled must be weighed in. Furthermore, not only the cost of the assembly station must be considered; the cost of each individual assembly operation has to be known. In this paper we will show how the type of assembly station chosen influences the individual costs just mentioned. We will also consider the fact that part conformity rates are significantly lower in microsystems when compared to conventional systems. The variation of assembly costs will be analysed by means of three examples. This will allow us to establish what steps of the assembly process need to be optimised in order to make microassembly cost-effective and at the same time define the direction that future research should follow.

Keywords - Cost model, microassembly, microsystem, microassembly station, microfactory, assembly cost, yield, design for microassembly.

1. INTRODUCTION

The electronics (especially SMD components) industry and todays microsystems technology (MST) have been driving the assembly world in the last decade to provide equipment of higher accuracy. The watchmaking industry has been working for ages in the micron range, but has only developed high-dedicated solutions for their mass production range (long-life products, only small evolutions). Though accuracy is still an important issue, there is nowadays a need for more flexible stations [Reinhart, 2000], which tend to be also more cost-effective. This becomes more critical in the MST world, where batches extend from low to middle sized ones [Zühlke, 1997].

Economic factors as well as technical difficulties have to be considered when designing a microassembly station. Assembly costs depend on the kind of installation used. They are an important part of the product cost.

The level of integration of microsystems is high, and the number of components is small. Therefore, the initial estimation of assembly costs tends to be low. They are even often neglected at the design stage. But low component count does not automatically result in low assembly cost. In general, the cost of a simple packaging represents 50% of the product cost, and when assembly is necessary, the assembly and packaging costs make up for 80% and more [Beardmore, 1997]. For microsystems, assembly cost is proportionally higher than for regular sized items. Because of their small size and the required positioning accuracy, and also because of their high integration level and special manufacturing procedures, traditional automation processes are not very suitable for microsystem assembly. In addition, the rate of conformity - or yield - of components produced by microsystem manufacturing processes, is considerably lower than the conformity rate of components produced with traditional 'mini- or macromanufacturing' processes.

In this paper we will show how the microsystem assembly costs divide up, and compare them to the assembly costs of a minisystem. The analysis of the total assembly costs and of the main differences between mini- and microassembly will show why microsystem assembly is often so expensive.

This cost analysis will allow us to determine the specificities that can make microsystem assembly cost-effective, and to indicate in which direction new developments must be sought to design cost-effective assembly stations.

We will use three different examples of assembly stations, and analyse the resulting cost variance. The three stations we will compare are: a traditional

assembly station for miniproducts without any special accuracy specifications, and the two possible alternatives for microsystem assembly: a conventional sized microassembly station and a microfactory.

2. ASSEMBLY COSTS

Assembly costs widely depend on assembly installation cost and targeted production volume. There are also other factors, among which the cost of clean rooms is specific to MST. We won't take it into account in this paper.

Our cost model will consider that assembly can be separated in two sub-operations: component feeding and component assembling [Boothroyd, 1992]. For each component to be assembled, we have a feeding cost and an assembling cost.

The total assembly cost of a product $C_{ass\ pr}$ is:

$$C_{ass\ pr} = \sum_{N_{cp}} \frac{1}{Y_{cp_i}} \cdot \left(C_{f_i} + C_{ass\ cp_i} \right)$$

where

N_{cp} is the number of components of the product.

Y_{cp_i} is the rate of conformity of component i.

C_{f_i} is the feeding cost of component i.

$C_{ass\ cp_i}$ is the assembly cost of component i.

3. MANUAL AND AUTOMATED ASSEMBLY

Automated assembly (e.g. components feeding) is well-known and well developed in normal assembly (centimeter range), where the only force to take into account is gravity. It is tricky in the miniassembly field – millimeter range [Byron, 1999] – because of the greater importance of other forces, and is really difficult in the microassembly field (parts within the micrometer domain), where gravity becomes negligible. At this range, manual feeding is not a solution, as the size of the components is too small.

In miniassembly, the required accuracy level for component feeding and component assembly allows them to be done either manually or automatically.

Micro- and miniassembly operations are similar (mostly pick and place and gluing), but the positioning accuracy level, the complexity, the cost of the equipment, and the component feeding will be different. Traditionally, delicate operations were the task of operators, automation being reserved for the more simple

operations requiring no high precision. The high level of positioning accuracy required by microsystem assembly inverses the situation: the limits of human performance are reached and automation becomes necessary to guarantee technical feasibility. Therefore, all microassembly operations will be automated, even for small production runs.

Component feeding is often quite easy to automate for macro- and miniparts, mostly by using vibratory-bowl feeders. On the other hand, due to the small sizes of the microparts, surface forces become bigger than inertial forces [Benmayor, 2000] [Arai, 1996], and such automated vibratory-feeders become impossible to use. Parts are either fed on wafers if they are produced that way, or are to be prepared on pallets.

In miniassembly, it is possible to compare the cost of manual and automated feeding, and the cost of manual and automated assembly, and to choose the most cost-effective equipment design.

In order to compare mini- and microassembly, we will consider manual part preparing in pallets and automated part assembly. In terms of cycle time, feeding and assembly tasks are carried out simultaneously. But both tasks must be taken into account from the cost point of view.

4. COMPONENT FEEDING COST

Component feeding onto the assembly station is a two-stage process: the distribution on the station and the correct orientation in order to allow the picking by the assembly device. Components are first placed and oriented on the pallets, and then the whole pallet is then introduced into the station. The feeding cost is:

$$C_f = C_{or} + C_{dis}$$

4.1 Cost of orientation of the component

To prepare a tiny component so that it can be grasped and handled by the robot or assembly manipulator, the operator has to pick it up, orient it and place it at the correct spot. We call the time required T_{pal}.

The orientation cost is directly related to the time required, and to the operator hourly rate c_{op}:

$$C_{or} = T_{pal} \cdot c_{op}$$

4.2 Cost of distribution on the workstation

The cost of distributing components to the workstation depends on the number of interventions required – the cost is inversely related to the autonomy of the workstation, and on the time required for each intervention.

Thus the distributing cost C_{dis} is equal to the intervention cost divided by the number of components fed onto the workstation at each intervention. We call the number of components on a pallet N_{pal}. The cost of the intervention is related to the time required T_{int} and to the operator hourly rate c_{op}:
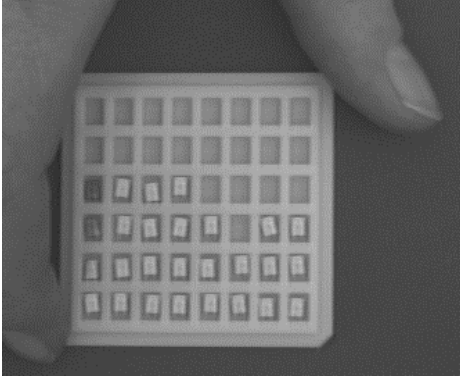
$$C_{dis} = \frac{T_{int} \cdot c_{op}}{N_{pal}}$$

Figure 1 - Pallet for microsystem components

The number of components on the pallet depends on the ratio of the surface available for component feeding S_f to the component surface S_{cp}. The utilisation rate R of the pallet has to be taken into account.

$$N_{pal} = \frac{S_f}{S_{cp}} \cdot R$$

Figure 1 shows that the separation between the places in the pallet is very large compared to the size of the microsystems, resulting in a low utilisation rate.

4.3 Feeding cost

The manual feeding cost of component on pallets is thus:

$$C_f = c_{op} \cdot \left(T_{pal} + T_{int} \cdot \frac{S_{cp}}{S_f} \cdot \frac{1}{R} \right)$$

5. ASSEMBLY COST

5.1 The assembly operation

Component assembly is also a two-stage process: first the positioning of the component at the right position, and then its attachment.

In miniassembly, both operations are often done at the same time. For example, when clipping a component on another, positioning and attaching are done in the same insertion movement: the first part of the movement is positioning, and the second is attaching, or securing the position [Boothroyd, 1992]. In microassembly, attachment is often done by gluing. The component is first brought into the right position, and then glue is applied. The manipulator releases the part when the glue is cured.

The cycle time is the sum of the positioning time and the attachment time:

$$T_c = T_{pos} + T_{att}$$

5.2 Assembly cost

The cost of an assembly operation performed with automated equipment depends on its cost C_{eq}, the depreciation method and the cycle time (in this comparison we will not take into account set-up times, which we will consider to be equal for each case: miniassembly, microassembly, and microfactory).

The equipment must be paid off by the quantity of manufactured items:

$$Q_{produced} = \frac{T_{prod}}{T_c}$$

where T_{prod} is the total production time available to write off the equipment (for example 2 shifts during 3 years).

The cost of an assembly operation is then:

$$C_{ass\ cp} = \frac{C_{eq}}{Q_{produced}}$$

$$= C_{eq} \cdot \frac{T_c}{T_{prod}} = C_{eq} \cdot \frac{T_{pos} + T_{att}}{T_{prod}}$$

5.3 The cycle time

The technological time T_{tech} is the minimum cycle time required to realise one operation, in this case an

assembly operation (pick and place, and attachment). It depends on the assembly technology used.

A technological time of 1 second allows a positioning accuracy of up to 0.1 mm, using manipulators with mechanical stoppers, without separate attachment. When an accuracy higher than 0.05 mm is required, numerical axes are needed, increasing the technological time to 3 seconds.
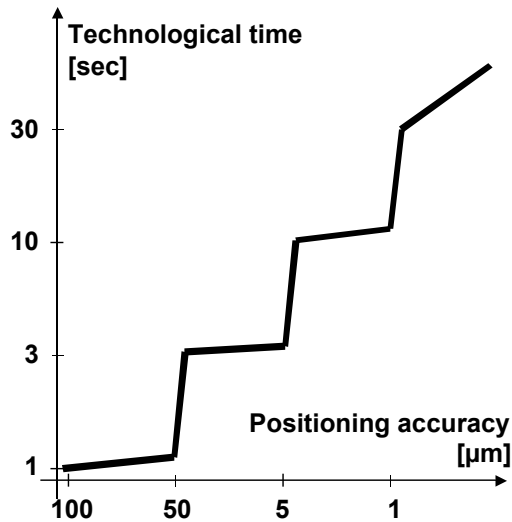
Figure 2 - Technological time in relation to required positioning accuracy

In the case of microsystems, an accuracy of as much as one or two microns is required: the components must first be located, generally with an image processing system, and then precisely positioned by means of the high precision axes. Positioning is relative and final position must be controlled. Attachment is always a separate operation. No insertion or mechanical positioning is possible. Even with potentially shorter distances, the technological time is longer: approximately 3 to 5 seconds for the positioning with a traditionally sized station, and another 5 to 15 seconds for the attachment.

When using a microfactory, the technological time increases to 30 seconds or more. The picking-up of the components by the wide-range coarse manipulator, the orientation and positioning by the high precision small range robot, the separate gluing operation, result in a longer technological time. The positioning accuracy aimed for is less than one micron.

The technological time is not a linear function of the positioning accuracy; it is a sort of stepladder function. Currently, at the Laboratoire de Production Microtechnique, we are working on a more precise determination of this function.

5.4 Assembly cost of a product

The final assembly cost integrates the cost of feeding (orientation and distribution) and the cost assembly:

$$C_{ass\ pr} = \sum_{N_{cp}} \frac{1}{Y_{cp_i}} \cdot \left(C_{f_i} + C_{ass\ cp_i}\right)$$

$$= \sum_{N_{cp}} \frac{c_{op} \cdot \left(T_{pal_i} + T_{int\,i} \cdot \frac{S_{cp_i}}{S_f} \cdot \frac{1}{R}\right) + C_{eq} \cdot \frac{T_{pos_i} + T_{att_i}}{T_{prod}}}{Y_{cp_i}}$$

6. DIFFERENCES BETWEEN MINI- AND MICROASSEMBLY

When components are manually placed in pallets and assembled automatically, the equation above is the same for mini- and microassembly, but the terms become different when the product and the parts become smaller.

6.1 Number of components

Miniproducts have approximately one component per function. The technology used to produce microsystems allows for the integration of several functions in the same component. Even if there is always a package and some connections needed, the number of components tends to be much smaller.

6.2 The rate of conformity or yield

The conformity rate of components manufactured with microsystem processes is considerably lower than that of mini- or macrocomponents. Conformity rates obtained in normal minimanufacturing are almost 100%, faulty components being often less than 10 ppm.

These rates are considerably lower in microstructuration processes used to manufacture on-wafer microsystems. These technologies have been adapted from microelectronics. With well run-in processes and high-volume production such as CMOS, conformity rates or yields of 80% or 90% can be obtained. Among others, the integration of sensors and electronics in the same circuit increases the surface, hence the probability of defective components. In addition, the manufacturing processes used for sensors are often new, and not easily made compatible with those of microelectronics. The production runs are small, which also results in a considerably lower conformity rate. Hence, a yield of 70% can be considered as very good, and yields of 50% are the norm [Wolfenbuttel, 1996].

Preassembly testing of microsystem components is generally impossible. Assembly and packaging must be completed before testing becomes possible! The cost of distribution and assembly of faulty components will affect the cost of producing conforming end products.

The production and assembly cost of a batch of conforming microsystem items will thus be increased by 25 to 50%, which has a devastating effect on their economical success. Especially because of this reason, mastering manufacturing processes is essential for the success of microsystem production on industrial scale.

In a microsystem product there are usually one or two microsystem components, other components being plastic housings, leads, isolation, etc… Therefore, we assume in our numerical application, that there is only one component for which it is difficult to obtain a yield significantly different from 1.

6.3 Orientation

The time required for orientation and positioning of the component on the pallet depends on its size. If about 1 second is enough for an easy-to-orient minicomponent, this task becomes very tedious for small microcomponents. The operator uses tweezers under a microscope, parts stick together and to the tweezers. The time becomes close to 10 or 20 seconds.

On the other hand, if parts are produced on wafers and can stay on the wafers until the assembly operation, there is no need for orientation and T_{pal} is zero.

6.4 Surface and utilisation rate

In miniassembly, the surface available for component feeding is relatively large, but so are the components. Only one pallet at a time can be fed to the station, so interventions of the operator to feed new pallets are frequent. The rate of utilisation of the feeding surface is good: only small separations are necessary between the components.

If microassembly is carried out on a big station, one or more wafers containing a lot of microsystems can be fed to the station. The autonomy is big, and no operator is required for long periods. Furthermore, the rate of utilisation is good if components are on wafers, even if there is some space around the wafers.

If a microfactory is used, the surface for component feeding is small; components must be placed on small pallets, requiring a lot of work. The utilisation rate is poor, as the separation becomes as large as the components themselves.

6.5 Cost of equipment

Minicomponents can be assembled with very simple on-off pick and place units, while microassembly requires precise movements, axis and measuring systems. The equipment cost is at least three times higher.

Possible equipment is described below.

6.6 Attachment and cycle time

In most miniassembly operations, attachment is done while positioning the component. Even if a separate operation is needed, such as gluing or welding, the component can be released: it remains in its position due to gravity and the attachment can be done in masked time.

In microassembly, attachment, most often gluing, is a separate operation. But the component can not be released: it has to be held in position during the curing process. Hence, there are no masked times.

Micropositioning is a bit longer than gross macropositioning. But the attachment time, often zero in macro- or miniassembly, is the biggest part of the microassembly cycle time.

Therefore, there is a stronger need to develop gluing techniques that result in shorter polymerization time than to shorten the positioning cycle time. Alternatives to gluing techniques are also expected.

7. ASSEMBLY EQUIPMENT

The three installations we will compare are a traditional assembly station for miniproducts without any special accuracy specifications, and the two possible alternatives for microsystem assembly: a conventional sized microassembly station and a microfactory.

7.1 Traditional miniassembly station

Traditional miniassembly stations are made of simple mechanisms or actuators with mechanical stops and a chassis. The required floor space is about 2 m². The surface available for the component feeding is 500 x 500 mm. The components are taken in bulk by an operator and arranged on a pallet. The surface utilisation rate of such a pallet is 80%. The cost of the installation is about 60'000 €.

7.2 Conventional sized microassembly stations

At the Laboratoire de Production Microtechnique of the Ecole Polytechnique Fédérale de Lausanne, we have developed a flexible microassembly station. It is based on a high-precision robot from Sysmelec SA (axis resolution is 0.5 μm), with a zoom and autofocus equipped image processing system. The required floor space is also approximately 2 m². The station is equipped with a picking device, which allows the picking of microsystem components directly from four 8" wafers. To feed in new components, we only need to load a new wafer on the station, while keeping the components with the same orientation. The utilisation rate of the wafer surface reaches 90%, and with the space around the wafers, the utilisation rate is 50%. The cost of the installation is approximately 200'000 €.
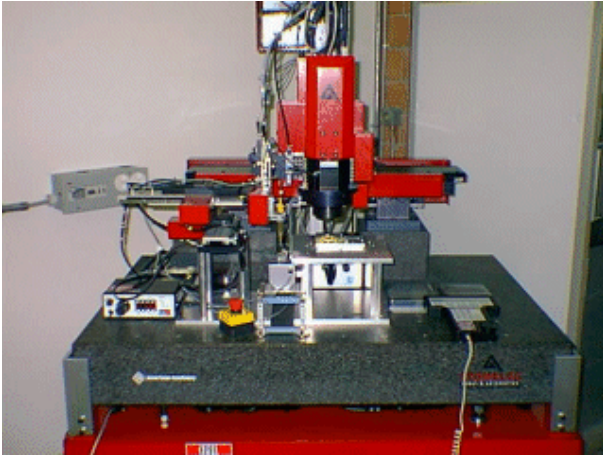
Figure 3 - Flexible microassembly station of the Laboratoire de Production Microtechnique of the EPFL

7.3 The microfactory

The microfactory consists of a clean box with a pallet entrance and an exit slot. Within the box are a wide-range manipulator, a high precision narrow-range robot, and an image processing or measurement system. The component feeding surface is approximately 100 x 100 mm. An operator prepares the components on small pallets. The utilisation rate of the feeding surface for very small components is approximately 40%.

Today, no microfactory is commercially available, but many are under development in different laboratories, one of them at the Institut de Production et Robotique of the EPFL. We estimate the industrial manufacturing cost at 150'000 €.

	Mini assembly station	Big size micro assembly station	Microfactory
N_{cp}	20	4	4
Y	1	0.7	0.7
c_{op} [€]	40	40	40
T_{pal} [s]	1	0	15
T_i [s]	180	180	180
S_{cp} [mm^2]	400	4	4
S_f [mm^2]	250'000	250'000	10'000
R	0,8	0,5	0,4
C_{eq} [€]	60'000	200'000	150'000
T_{pos} [s]	1	5	10
T_{att} [s]	0	10	20
T_{prod} [s]	2 shifts, 1 year: 14'000'000		

Table 1 - Figures used

8. NUMERICAL APPLICATION

Lets compare the assembly and feeding cost on an example. We have considered the following characteristics of the products to be assembled:

The size of the minicomponent is 20x20mm, that of the microsystem component is 2x2mm. The microsystem product counts 4 components, their yield is 70%, the miniproduct 20 components with a yield of 100%.

We have taken an hourly rate of 40 € for an operator (Swiss rates) and a 1-year 2-shifts depreciation of the installation. An operator needs 3 minutes to feed a pallet or a wafer.

The figures used are listed in table 1.

The resulting costs are listed in table 2.

	Miniproduct	Microsystem

9. ANALYSIS OF THE RESULTS

9.1 Analysis

Six main points result from the analysis of the data:

1 - The distribution costs $C_{dis\,i}$ are lower for microsystems than for minicomponents. They can be neglected in the case of the conventional sized microassembly station.

2 - The orientation cost is zero if the microcomponents can be kept and fed on wafers, as in the case of the conventional sized microassembly station. They may become very important if they have to be prepared by an operator.

3 - The cost of the assembly operation is much higher for a microsystem than for a minicomponent.

4 - Feeding costs are higher than assembly costs for the miniproduct: feeding should be automated.

Feeding costs are near to zero for microsystems on wafers: there is no need for automation.

5 - In this example, the microsystem assembly on the microfactory is twice the cost of the microsystem assembled on the big size microassembly station.

6 - Component yield is a decisive factor of microsystem cost.

	Costs [€]	Mini product	Micro system	
		Mini assembly station	Big size micro assembly station	microfactory
Cost per component	C_{or}	0,011	0	0,167
	C_{dis}	0,004	0,00006	0,002
	C_f	0,015	0,00006	0,169
	$C_{ass\ cp}$	0,004	0,214	0,321
Product cost	$C_{ass\ pr}$	0,388	1,225	2,450

Table 2 - Breakdown of product assembly costs

10. DESIGN RULES DRAWN FROM THIS ANALYSIS

Our previous analysis demonstrates the importance of the economic factor on the choice and realisation of assembly workstations. The right choice determines the commercial success or failure of the product. The design rules that derive from this analysis are the following:

10.1 Component feeding

- There is no need to invest in the automation of component feeding for microsystem manufacturing. In view of the weight and size of the components, it will be cheaper to have an operator bringing the components to the workstation in a container, a task which is not labour intensive. The whole process is considerably cheaper than component transfer in traditional assembly operations. If components are manufactured on wafers, orientation and palleting can be avoided, thus simplifying the feeding even more.

- The components must be kept in batches or on wafers; the orientation cost in these cases will be zero, and utilisation of the workstation surface is

optimised.

- The workstation surface must be compatible with the size of the wafers.

10.2 Mastering the manufacturing processes

The conformity rate of microsystem components is much lower than that of minicomponents. This results in a significant cost increase. We have seen the result on the unit cost of the products when the defective components cannot be detected prior to assembly, which is often the case. Even if they are detected prior to assembly, the cost of rejected components weights on the price of the end product.

The microsystem component is not only the most expensive, but also its manufacturing processes are more complex and delicate. The manufacturing of on-wafer components consists of many steps; an error in one of these steps can cause the whole batch to be faulty. A high yield must be preferred to a reduction in component size.

10.3 Cycle time

The technological time of the assembly operation has an important impact on the cost. The high positioning accuracy required does not only result in expensive equipment, but even more so in a long technological time. The accuracy required for the assembly equipment depends very much on component specifications and product design. At the product development stage, these factors must be considered, and high-precision positioning must be avoided.

11. CONCLUSION

In this paper, we have shown an often ignored aspect of microsystem and microassembly: a cost model should be used when designing or choosing an assembly equipment in order to reduce production and assembly costs. Especially design of microfactories should be based on a thorough cost analysis.

Cost models will further be improved, taking into account component manufacturing cost, set-ups, component transfer from one station to another, and clean-room costs.

Cost models taking into account component manufacturing costs as well as assembly costs will lead to new design for assembly rules.

12. REFERENCES

[Arai, 1996] F. Arai, D. Andou, T. Fukuda ; "Adhesion forces reduction for micro manipulation based on micro physics"; Proceedings of the IEEE Micro Electro Mechanical Systems, pp. 354-359, 1996.

[Beardmore, 1997] G. Beardmore; "Packaging for microengineered devices - Lessons from the real world"; Assembly and connections in Microsystems, IEEE colloquium 26 February 1997.

[Benmayor, 2000] L. Benmayor; "Dimensional analysis and similitude in microsystem design and assembly"; Thèse no 2232, EPFL-DMT-IPM, Lausanne, 2000.

[Boothroyd, 1992], G. Boothroyd; "Assembly automation and product design"; Marcel Dekker, Inc., New York, 1992.

[Byron 99] T. Byron Carlsson ; „When "light assembly" is shrinking: Mini Assembly – precision-assembly of very small parts"; Proceedings of the Scandinavian Symposium on Robotics 1999, October 13-15, Finland.

[Koelemeijer et al., 1999] S. Koelemeijer, L. Benmayor, J.-M. Uehlinger, J. Jacot; "Cost Effective Micro-System Assembly Automation"; Proceedings of the IEEE Emerging Technologies and Factory Automation 1999.

[Koelemeijer, 2001] S. Koelemeijer ; "Méthodologie pour la conception de microsystèmes et de leur équipement d'assemblage" ; Thèse no 2343, EPFL-DMT-IPM, 2001.

[Koelemeijer et al., 2002] S. Koelemeijer, B. Moll, F. Bourgeois, C. Wulliens, J. Jacot; "Small lot size microsystem assembly: The Flexible Micro-Assembly Cell"; International Symposium on Robotics, Stockholm, 2002. To be published.

[Reinhart, 2000] G. Reinhart, D. Jacob ; „Positioning Strategies and Sensor Integration in Tools for Assembly MOEMS"; SPIE 2000.

[Wolfenbuttel, 1996] R. F. Wolfenbuttel; "Silicon Sensors and Circuits, On-chip compatibillty"; Chapman&Hall, London, 1996.

[Zühlke, 1997] D. Zühlke, R. Fischer, J. Hankes; "Stepwise into Micro-Assembly"; Proceedings of the 8th International Conference on Advanced Robotics, ICAR'97, Jul 7-9 1997, Monterey, CA, USA.