

AGILE ASSEMBLY ARCHITECTURE: A PLATFORM TECHNOLOGY FOR MICROASSEMBLY

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Abstract

It is proposed that fundamental changes will be required for automated assembly of precision micro-scale products. We suggest that the time has come to develop a scalable platform technology for microassembly and describe initial steps taken in this direction.

WHAT IS A "PLATFORM TECHNOLOGY"?

Technologies that are so pervasive that they serve as springboards for other technologies and regarded as essential for progress in multiple fields are often referred to as "platform technologies." A platform technology has several characteristics; among them are:

- a common substrate upon which to build,
- a uniform set of services upon which to draw,
- a set of abstractions insulating the user from implementation details,
- standard methods, philosophy, and semantics usable by a broad community, and
- a system architecture comprising modularity, extensibility, and scalability supporting rapid design and efficient implementation.

Precedents in the world of software are computer operating systems. Programmers used to be concerned with the computer hardware directly, spending a great deal of time and effort dealing with registers, memory allocation, and hundreds of atomic operations. Writing a complex "bug-free" computer program was a Herculean effort. Modern operating systems are true platform technologies which are substrates for realizing a wide variety of important applications. They provide an abstraction to the underlying hardware, insulating the user from obscure details; a common and consistent environment for user programs, enabling portability; and transparent allocation and management of hardware resources.

Another precedent can be found in Very Large Scale Integrated (VLSI) circuit design methodology. In the early days, chip designers layed out individual transistors, passive components, and wiring from "scratch." Very dense, efficient, and fast designs were possible, however they took years to create and were extremely difficult to debug. In the 1970s, Mead and Conway [1] observed that "*ICs are so complex and dense that human designers cannot deal with individual devices, instead, they must be handled at a higher level of integrated system architecture.*" They decided on a hierarchical, modular approach that combined replicated functional blocks to form larger subsystems. Using this methodology, designers no longer worked at

the lowest level, instead they merely combined pre-defined and pre-debugged circuit modules in new ways to create the needed functionality. The results were VLSI circuit designs that were neither optimized in speed nor in silicon area, but could be very rapidly designed, and through the MOSIS foundry service, fabricated in weeks. Nowadays, all circuit design is done using these principles.

One can think of many other kinds of platform technologies serving as foundations for diverse applications.

HOW MICROSYSTEMS ARE ASSEMBLED TODAY

Most small, complex products are assembled manually. When there are very high volumes, very small parts, high precision required, or extreme cleanliness needed, robot assembly lines or robot work cells are used. There remain significant issues concerning robot precision, high integration costs, and lengthy deployment times. In some cases these problems can be avoided with micro-products based on MEMS.

MEMS have the extraordinarily useful property that mechanical and electronic functions can be integrated on the same chip. Moreover, the mechanical structures emerge from the batch fabrication process in fully assembled and operational form. In fact, the avoidance of costly and tedious serial assembly steps is one of MEMS' most remarkable aspects. Micromechanical systems of impressive complexity can be made without assembly of any kind [2]. That said, there is a growing recognition that more complex and more useful microsystems comprised of different materials such as Si, GaAs, metals [*e.g.*, formed by LIGA (Lithographie Galvanoformung Abformungsglass)], and plastics will require some form of assembly [2]. Without assembly, MEMS will be forever limited in the impact it can have. Figure 1 illustrates the tremendously difficult problem of correctly and automatically joining together disparate components and materials (perhaps from different vendors around the world) to form a working microassembly. Whatever automation methods are employed, they must be precise, economical, and deployable in finite time.

In recognition of these issues, a number of parallel and sequential methods have been devised for MEMS assembly, including wafer bonding, flip up and folding of planar structures, fluidic self-assembly, and precision robotic assembly [2]. Few of the methods use automation to an appreciable degree.

Wafer-level assembly and packaging: Several wafer bonding techniques have been developed for batch assembly of MEMS components. These include eutectic

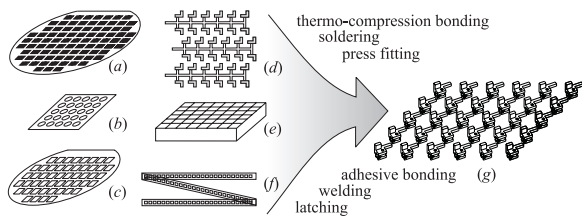


Fig. 1. Hybrid Microassembly (Example): (a) CMOS device wafer, (b) LIGA parts, (c) MEMS device wafer, (d) precision molded plastic parts, (e) micro-EDM metal parts in trays, (f) ribbon of micro-stamped metal parts, (g) array of assembled products whose parts are fastened together by various means (after [2]).

bonding between Si and Au-covered Si, Si fusion (atomic) bonding, low temperature glass bonding, and Si-to-Si anodic bonding, among others. After bonding two or more wafers together, the assembly is diced to form multiple assembled MEMS devices, commonly used for packaging MEMS accelerometers and pressure sensors. Batch assembly and packaging by wafer bonding will continue to be an important method for MEMS device assembly.

“Self-assembly” of quasi-3D structures by flip up from the plane: As early as 1992, it became possible to create hinge structures in MEMS permitting planar structures to be fabricated, released, and then folded up out of the plane by hand under a microscope to form lockable quasi-3D structures [3]. Recently, there has been a great deal of interest in “powered” or “assisted” flip-up assembly to produce quasi-3D structures. For example, the surface tension of solder melting in a reflow process can be used to raise up planar structures from the wafer and lock them in place [4]. The flip-up self-assembly approaches to MEMS assembly are extremely important and rapid progress is being made.

Fluidic self-assembly: Whereas the flip-up self-assembly techniques are largely limited to quasi-3D silicon-based structures, related techniques using surface tension for planar alignment has demonstrated the capability of assembling discrete micro parts of different materials to binding sites on a substrate with high efficiency and high accuracy. For example, GaAs diodes have been assembled on Si wafers [5], and cylindrical displays have been created [6]. Fluidic self-assembly results to date have been impressive and appear to be most suitable for creating assemblies with large arrays of identical parts.

Sequential assembly using robotics: Robotic assembly of macro-scale products dates back to the late 1970’s. Many issues of “design for assembly,” assembly planning, part transfer and feeding, part grasping and details of part-assembly interaction forces have been intensively studied. In the past decade, attention has focused on two important areas: assembly automation that *i*) can be rapidly deployed, with important economic benefits; and that *ii*) can deal effectively with very small parts and precise dimensional features.

With few exceptions, most of the reported work in robotic microassembly has dealt with precision and parts-handling aspects and has taken place in Europe and to a lesser degree in Asia. Sysmelec, in Switzerland, produces

several robotic assembly workstations for MEMS and Microoptoelectromechanical systems (MOEMS) [7]. Assemblies of four layers of microlenses and eight micromachined chips have been produced automatically at CSEM SA (Centre Suisse d’Electronique et de Microtechnique), Microsystems Manufacturing [8]. A flexible microrobot-based microassembly work cell was developed in Germany [9]. In the U.S., work has progressed at Sandia National Laboratories to produce automated microassembly systems [10]. Zyvex has produced small semi-automated robotic systems for microscopic and nanoscopic assembly [11]. Impressive precision microassembly results have been obtained through robotic approaches.

WHY A MICROASSEMBLY PLATFORM TECHNOLOGY IS NEEDED

Despite excellent efforts, there is currently no viable platform for microassembly. Almost everything has to be done by hand, or else by cobbling together an eclectic collection of microscopes, precision stages, and micromanipulators. There is no way to integrate promising parallel or sequential assembly techniques into an automated system without a huge and costly effort, notwithstanding some “point” solutions such as fiber pigtailling.

There are significant drawbacks associated with the assembly methods previously described that offer a real set of opportunities for architectural and system-level advances. For the foreseeable future, micro-scale devices will require packaging into macroscopic “products” to be useful. Moreover, these products are likely to be customized in many different ways and have relatively volatile lifetimes. These considerations point to the need for highly flexible and rapidly deployable *information-intensive* production systems.

Fundamentally, the novel batch assembly technologies listed above suffer from a lack of scalability in three separate directions *i*) product size, *ii*) product heterogeneity, and *iii*) process variety. These dimensions of scalability are critical aspects of delivering assembly technologies capable of effectively bringing complex microstructures from the laboratory setting to the real world. The ability to reliably manipulate and assemble components of vastly different scales allows seamless integration of micro-devices into macroscopic products, making them readily available in a familiar form factor. The ability to integrate components having drastically different material properties enables the effective and efficient integration of function-specific components—*e.g.*, CMOS electronics coupled to MEMS sensors monitoring LIGA mechanisms—as well as the integration of non-MEMS micro-components such as photonics. Finally the ability to incorporate a broad range of processing functions directly into the assembly environment facilitates integration of function-specific and heterogeneous material bonding technologies.

Future hybrid microsystems will greatly benefit from the fusion of heterogeneous technologies. For example, an autonomous wristwatch-sized total chemical analysis system might integrate digital electronics instantiated in

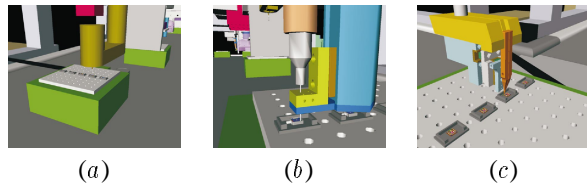


Fig. 2. Virtual factory views of small microphone assembly processes from the AAA Interface Tool: (a) manipulator agent placing micropart on a product held by courier agent, (b) dispensing agent, (c) microwelding (gap welding) agent.

CMOS, micromechanical structures made from polysilicon, microfluidics formed from plastics, optical interconnects routed in glass fibers and laser light emitted by III-V semiconductor diodes. To succeed in the marketplace, these systems must meet performance goals at low cost and thus be made from known good components using best-of-breed technology. Microsystem-based products are driven by a wide variety of market segments with huge numbers of small to medium volume applications. This desire for many different products combining multiple technologies drives the opportunity for highly flexible production systems that can be rapidly reconfigured to meet these demands.

No coherent microassembly methodology exists today for achieving these levels of integration. Advances in the specific batch assembly processes listed above are impressive and are expected to continue. As a result, micro-components in select areas will gradually increase in sophistication. However, these batch methods currently have inherent material, process and geometric restrictions that inhibit their range of applicability. Wafer bonded assemblies are essentially 2.5D; flip-up self-assembled microstructures are constrained to specific 3D structures and imperfect yields; fluidic self-assembly has future challenges of generating general 3D assemblies with suitable yield. Precision robotic systems have the potential to assemble complex hybrid products from heterogeneous micro-components but they are limited by high equipment complexity and cost, lengthy deployment times, and more fundamentally by their serial one-by-one nature which restricts throughput for many applications.

AGILE ASSEMBLY ARCHITECTURE

At Carnegie Mellon University, we have been developing a flexible architecture for precision assembly over the past several years. Unlike other microassembly approaches, whether wafer-level assembly, self assembly, or serial robotic assembly under a microscope, we visualize a highly modular robotic pipelined approach with a much higher level of *scalability*. This scalability is manifest in four different ways: *i*) the ability to assemble products from MEMS chip size up to products whose size is 100 mm or more, *ii*) the ability to integrate diverse fastening technologies and non-MEMS microscale parts, *iii*) the ability to introduce parallel assembly steps to increase throughput, and *iv*) the ability to assemble complex products requiring an arbitrarily large number of process steps. Achieving this will require solving funda-

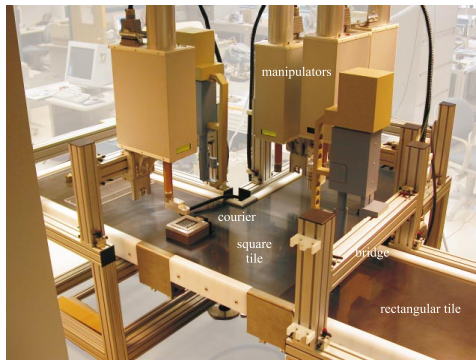


Fig. 3. Photograph of a section of our laboratory minifactory (under development).

mental problems associated with composable distributed computational/physical systems.

We have begun to tackle these issues with a framework and technology for rapid design, programming, and deployment of precision automated assembly systems, called “Agile Assembly Architecture,” (AAA), first discussed in [12]. AAA has two components: *i*) a distributed system of tightly integrated mechanical/computational agents (collection of highly modular and intelligent robots, feeders, and fastening equipment), and *ii*) a unified Interface Tool that allows a user to select and order agents over the Internet and to assemble, program, and monitor them both in a simulated (virtual) factory environment and in the real factory. To instantiate these ideas, we have been developing a small, modular assembly system called “minifactory” in our laboratory over the past several years.*

Using our Interface Tool, we have created several virtual factories for assembling small transducers and optoelectronic products. For example, Fig. 2 shows several virtual agents operating in a 29-agent virtual minifactory which assembles small microphone devices. The virtual minifactory was rapidly configured using the AAA Interface Tool. Whereas the assembly operations depicted in the figure are small but still macroscopic, we project that the architecture will be suitable for MEMS-scale operations with integration of appropriate sensing, gripping, and manipulation techniques.

Figure 3 shows part of the modular minifactory system under development in our laboratory. Active components include *courier agents* responsible for transporting products through the factory and participating in assembly and fastening operations, and *manipulator agents* for picking and placing parts. The agents, acting cooperatively, perform 4-DOF assembly operations in an order of magnitude less space and with two orders of magnitude more precision than current state-of-the-art industrial assembly systems. Courier agents move about on an ensemble of platen tiles forming the factory floor, and are based on novel closed-loop planar motors [13] that can move at 1.5 m/s with a position resolution of $0.2 \mu\text{m}$ (1σ). The manipulator agents have two degrees of freedom (DOF)

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<http://www.cs.cmu.edu/~msl>.

for precise vertical (z) motion and rotary (θ) motion [14]. Many other kinds of agents are possible (*cf.* Fig 2). Agents are designed to be highly generic and therefore widely applicable across broad spectrums of product and process types, so only small items, *e.g.*, part-specific end effectors need to be customized.

Agents are physically and computationally modular, self-describing, and self-representing [15]. Control is distributed during factory execution, and there are built-in mechanisms for synchronizing and registering virtual and real minifactories [16]. The collection of robotic agents in a minifactory is supported by a service infrastructure comprised of modular base units, platen tiles, and bridges. The system is designed from the outset to enable rapid deployment.

In our first-generation minifactory (now retired) we demonstrated cooperative visual servoing between manipulator agents and courier agents and vision-guided parts placement [17]. We also demonstrated cooperative force servoing between a manipulator agent and courier agent at several-mN force levels [18].

For the past several years our effort has focused on completion of the second-generation minifactory shown in Fig. 3. The new minifactory incorporates numerous enhancements over the prototype but is not yet fully operational. All of our work on the project to date has been of a fundamental and generic nature which has served us well. At this stage of development, we are beginning to explore relationships with industry to select strategic areas of application to real product microassembly.

DISCUSSION

We have argued that a platform technology will be necessary (or at least highly desirable) for developing future automated microassembly systems. Like all platform technologies, there must first be an overwhelming need to set the stage for their introduction. We are perhaps not quite at that point yet, but we see it coming in the near future.

Agile Assembly Architecture and minifactory serve as our initial foray into automated hybrid microassembly. As the work proceeds, there is no doubt that some of its concepts will need to be augmented, modified, and perhaps eliminated. A principal attribute is that of *scalability* in product sizes, kinds of fastening processes, parallel processing, and in number of assembly process steps.

Figure 4 schematically illustrates the kind of hybrid microassembly that we believe can someday be performed in minifactory. An automation system based on a microassembly technology platform that could reliably and quickly produce this example product in quantity would serve to illustrate the capability to assemble three-dimensional microproducts from heterogeneous materials.

Acknowledgements

The authors thank the more than 30 persons who have so far contributed to AAA and minifactory. This work was supported in part by NSF grants CDA9503992, DMI9523156, and DMI9527190.

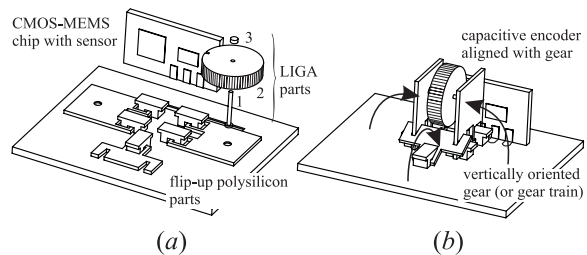


Fig. 4. Exemplary Hybrid Microassembly Test Vehicle: (a) collection of polysilicon MEMS, CMOS-MEMS, and LIGA parts to be assembled, (b) final configuration of the assembly.

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