PROCEEDINGS OF SCIENCE

Industrialization of Silicon Detector Module Production

Alan Honma
CERN
PH Dept., Geneva 1211, Switzerland
E-mail: alan.honma@cern.ch

The large-scale silicon detector projects for upgrades (Super-LHC) or new experiments (linear colliders) may benefit from a higher level of industrialization of the detector production. This paper will focus primarily on the possibilities of industrialization of module production. A review of the module production in existing detectors including a detailed look at an example of in-house industrialization (the CMS robotic module assembly system) will be made. The prospects for using industrialization for future projects are discussed.

19th International Workshop on Vertex Detectors - VERTEX 2010
Loch Lomond, Scotland, UK
June 06 – 11 2010

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1. Introduction

This paper examines the possibilities of industrialization in silicon detector module production, where module is defined as the active silicon sensor, the local front-end read-out electronics and the support structure that holds these elements together. In this paper, three levels of industrialization will be considered: manual production (no industrialization), in-house automation, and outsourcing to industry. Historically, most high energy physics (HEP) silicon detectors have relied on manual production with some sub-assemblies outsourced to industry. With very large numbers of modules needed, in-house automation becomes a cost-effective alternative. A recent example of in-house automation, the CMS robotic module assembly system, will be described and some guidelines for when such automation would be beneficial will be presented. The prospects for in-house automation for future projects will be examined followed by a discussion of some general issues concerning large-scale module production.

2. Silicon detector module production

2.1 Silicon detectors in high energy physics

The continuing reduction in cost per unit area of silicon detectors has allowed the usage of silicon for more of the tracking volume of experiments. Nearly all HEP experiments use silicon detectors in one form or another. The range of silicon detectors includes pixel, strip, and drift types for tracking. Pad read-out silicon detectors are used for calorimetry and electromagnetic shower localization. The total surface area of these silicon detectors has now exceeded $200m^2$ for the CMS silicon strip tracker, which required the use of more than 30,000 sensors. These numbers are a strong motivation for moving toward a high level of industrialization.

2.2 Working definition of a module

We will consider a "module" as the most obvious basic detection building block consisting of the silicon sensor(s), its local front-end electronics and the mechanical structure holding these parts together. A typical example is shown in Figure 1 which shows an endcap silicon strip detector module from the ATLAS experiment at the LHC. There are many other modular elements one could consider, such as the larger scale structures holding groups of these modules (known as staves, ladders, or wheels) but these are not considered because the focus is on modular units to be produced in large numbers which are most likely to require industrialization of their production. The module concept considered here is primarily for silicon strip detectors although most of the discussion also applies to other silicon detector modules (pixels, pads, etc).

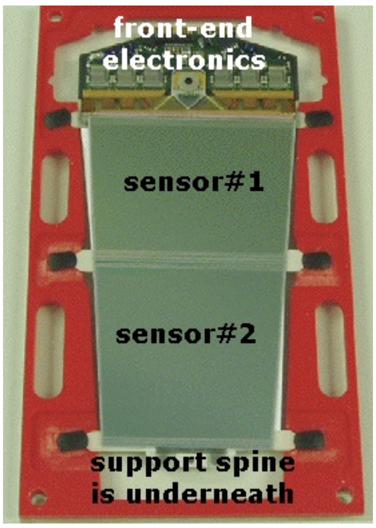

Figure 1: An ATLAS endcap silicon strip module

2.3 The process of module production

Module production usually consists of the following steps:

1. Procurement, reception, inspection, and testing of components
2. Assembly of components onto module support structure usually involving gluing followed by metrology
3. Connection (usually wire bonding) of sensor channels to fan-out circuits (if needed) and then to the readout electronics located on the front-end hybrid circuit boards
4. Testing of completed modules (mechanical, electrical, electronic, burn-in, long-term, and environmental)

Each of these steps can involve large amounts of manpower, equipment, and logistics. In addition, many module components (i.e. the front-end hybrid PCB or the module mechanical support) are sub-assemblies that require the same production steps as the modules.

3. Industrialization of module production

Three types or levels of industrialization of module production are considered: manual production, in-house automation and outsourcing to industry. In reality a mixture of these three types of industrialization is normally used for large projects but the distinction of types is useful since they are very different in their requirements for planning, manpower, resources and quality assurance. The main interest in industrializaton of module production is the usage of large-scale in-house automation, since this is something fairly new but with large potential benefits. Nevertheless all three types will be discussed since they all will remain important to any module production.

3.1 Manual production

Manual production basically implies no industrialization. This has been the standard method employed since the first (small-scale) silicon detectors were built by hand in a workshop by a small group of people. For cost reasons and the need for dealing with many non-standard components, nearly all the module production was done by hand in the laboratory of the institute building the detector. Standard components were usually obtained directly from industry and some specialized versions of standard components (such as the front-end hybrid PCBs) were sometimes outsourced to industry. However, the bulk of the production steps outlined in section 2.3 were handled in-house with minimal automation. The manual production method requires a high level of engineering expertise and support facilities to be found in-house. It also relies heavily on the competence of the people involved in the highly critical steps, e.g. the precision placement of the sensor on the support structure or the interconnect work (wire bonding). The nature of silicon detectors for HEP experiments is always to be at the limit of the possible, i.e. using the minimal material to obtain the maximum track position resolution and number of points. As such, one is rarely in a situation of being able to use off-the-shelf components to build the detector modules. Manual production remains the mainstay because there are no exisitng industrial automated machines to assemble the module

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components. Certainly in the case of small- and medium-scale detectors with highly non-standard components and designs, manual production of modules will likely remain the norm.

3.2 In-house automation

In-house automation is the usage of automated machines or tooling in the module production. It is clear that this has already existed for many steps or parts of the steps in module production as defined in section 2.3. Possibilities for automation in the component procurement, interconnections and testing steps (points 1, 3, and 4 from section 2.3) will be discussed in section 4. However, the critical step 2 which is the assembly of the basic module components (sensor and read-out electronics to support structure) has not been attempted using in-house automation until very recently with the CMS silicon strip tracker. In section 5, this project will be examined in detail in order to assess its potential for future detectors.

3.3 Outsourcing to industry

The third type of industrialization to be considered is the most literal interpretation, having the work done in industry. This has already been the case for most of the standard components in a module (such as IC chips, PCBs, connectors) but is less utilized for the more complex or high-precision assembly steps. Clearly, in an ideal world where one has infinite funds, adequate time and extremely competent and willing technological partners in industry, one would outsource the entire module production (as well as the complete detector construction)! Although there are some competent and willing industrial partners, the funding and time are usually far from adequate and thus outsourcing of complex assemblies will be a rare event. However, for the very large-scale projects of interest, outsourcing of component manufacture and relatively standard assembly jobs must take on a larger and larger role since in-house resources are typically not designed for this scale of production. Thus finding and working with competent industrial partners is of prime importance as is the often neglected understanding of the critical role of quality assurance in achieving a satisfactory result. A discussion of these issues will be presented in section 7.2.

4. Possibilities for automation in module production steps

Some examples of where automation can be applied to the component procurement, interconnections and testing steps (points 1, 3, and 4 from section 2.3) include:

1. Automatic probe stations with cassette wafer loaders are capable of handling and probing sensors without the risk of “operator error”. As the testing of sensors and chips can often be time consuming, automatic systems are capable of working 24 hours a day resulting in a high throughput.
2. Advanced wire bonding machines can be obtained with large working areas allowing rapid bonding of large size modules. These machines are highly programmable and equipped with high resolution microscope cameras and pattern recognition systems so that all reference marks and bond pads can be recognized automatically. A well designed module can have hundreds of connections made in minutes with little or no intervention from the operator.

3. For post-assembly metrology, highly automated coordinate measurement machines (CMM) exist with large work areas allowing for checking and high precision measuring of component placement on a large number of modules.
4. The need for burn-in and/or long-term electrical and electronic tests is essential for assuring high yield and reliability. The very large number of modules to be tested for the long time periods required by such tests is a challenge which can be met with clever multi-module test set-ups. In many cases for the LHC experiments, these multi-module test set-ups were simply the larger detector structures, e.g. the “stave” (ATLAS) or “rod” (CMS) containing 6 or more modules on the same structure which could be fully tested using the real on-detector read-out electronics. In other cases, special set-ups with fanned-out power and control systems were used. Although not mechanically automated, these are examples of electronic automation of the testing.
5. As many silicon detectors will be subject to high radiation levels during their lifetime, this often implies low temperature operation (down to -30°C) to minimize the bulk damage and to reduce the leakage currents. Therefore the modules will be subject to environments with varying humidity and temperature differences as large as 70°C. To ensure that all parts can withstand these conditions, large volume rapid cycling climatic chambers exist for screening, destructive tests and accelerated life tests. Such tests assure the reliability of components and of assembled objects for their often harsh working environment.

All the above examples require significant financial investments in equipment. For very large-scale detectors, this investment may be more cost-effective than to have the same work done in industry. A cost analysis for a given project can show when some of these tasks could be brought in-house. Often the equipment will continue to be useful for future projects. The advantages to in-house automation are the immediate turn-around (very important for time critical tasks), full local quality control, reduced handling, and low unit cost (once the initial investment is made). Negative aspects to keep in mind are maintenance costs and the necessity for in-house expertise which sometimes requires a long learning curve.

5. Example of in-house automation: The CMS tracker module assembly robot

The motivations for attempting the first large scale highly automated mechanical module assembly for the CMS silicon tracker were many:

- 15,148 modules required (17,000 with losses and spares)
- Tight schedule (1 year for preparation, 2 years for production)
- Budget not sufficient for outsourcing
- Manpower not sufficient for manual assembly
- Prototype assembly robot showed feasibility of concept both for precision and throughput

A completely manual assembly program was evaluated based on the available manpower and budget in the collaboration and the resulting timescale was more than 4 years. The evaluation of the robotic system showed that it could be achieved within the 3 year timescale.

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5.1 Basic description of the CMS tracker assembly robot

The CMS robot was based around a standard industrial product from a vendor specializing in high precision, high speed positioning stages. Some key features of the robot system were:

- Large work area (50cm x50cm) gantry robot with magnetic air bearing X-Y movement and stepping motor Z-ϕ movement.
- Gantry = overhead (crane-like) suspended working head. Chosen on purpose so table does not move (no vibrations or shocks to module).
- Trays with pre-placed components are put on gantry table. Module components held in place with vacuum during assembly and glue curing.
- Permanent rack of vacuum pick-up tools and gluing syringes located at back of work area.
- Working head carries microscope camera and vacuum-based tool holder. Serves dual function of metrology and pick/place/dispense.
- Software control of 4 axis motion, vacuum and air pressure valves. Pattern recognition used to find and measure positions of components and check final placement accuracy.

The purchased robot contained the 4 axis positioning mechanics, the drive interface and computer control card and software. However, all the pick-up tools, glue dispensing system, component trays, assembly trays, microscope camera, other I/O devices, pattern recognition software and the robotic movement programs had to be developed in-house for this project. The fully equipped robot is shown in figure 2 and is described in technical detail in [1].

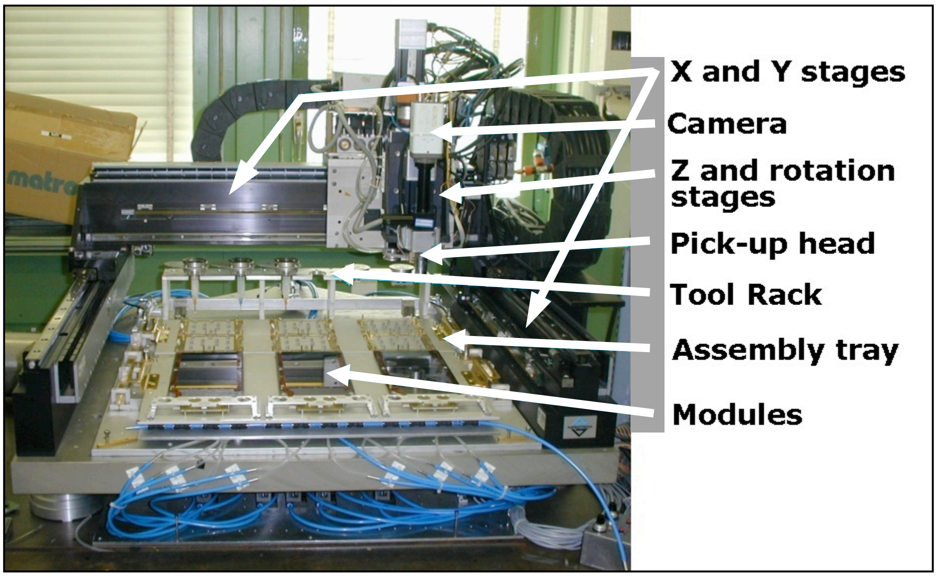

Figure 2: The CMS silicon strip module assembly robot

5.2 Project development and execution

The prototype robotic system or "proof of principle" was built at CERN, but the module assembly was done at 6 other collaborating institutes. The 6 assembly centers purchased identical robots and tooling was built for all centers following or improving upon the CERN design. The CERN robot was reconfigured to do all hybrid + pitch adapter sub-assemblies (17000 using one robot). The time scale for development to reach the "proof of principle" was about 1.5 years. It took about an additional year to adapt and perfect the tooling and software to move into a production mode. Once the final tooling and procedures were in place for full production, the expected assembly rate (15-20 modules per day per robot) was reached allowing the full production to be completed in just under two years. The failure rate (from assembly only) was very low (<1%).

Conception of the structural components and overall module design was based on knowledge that assembly would be done by robot. This meant keeping all parts flat and with correct thicknesses. It also meant trying to keep things as simple as possible (single-sided sensors, minimal numbers of individual components and types of material). Because of the large variety of module types (15) required by the CMS tracker design, this implied many different component and module trays as well as different types of pick-up tools. Strong engineering and machining support groups at each assembly centre were essential for achieving good results.

5.3 Other robotic assembly systems

A review of the module production of all the LHC experiments as well as several large recent non-LHC HEP experiments did not find more cases of extensive use of robots nor a high level of automation for the module production. Some of the larger silicon detector projects are given below with the number of modules in parentheses and their method of production:

- ALICE silicon strip (1978), silicon drift (260) and pixel (120) detectors all used in-house manual assembly.
- ATLAS silicon strip detector (2112 barrel, 1976 endcap) used a small robot for sensor positioning, otherwise the strip detector and pixel (1456 barrel, 288 endcap) detector used mostly in-house manual assembly and some outsourced assembly (to two Japanese firms that produced somewhat less than 20% of strip detector modules)[2].
- CMS silicon pad preshower (4288) and pixel (768 barrel, 672 endcap) detectors both used in-house manual assembly.
- LHCb VELO (42) and silicon strip (464) detectors both used in-house manual assembly.
- FERMI-LAT (ex-GLAST) silicon tracker (2304) detector used in-house manual assembly.

It is apparent that the numbers of modules shown above are much smaller than the 15,148 needed for the CMS case and that the production of several thousands of modules is still quite possible for in-house manual assembly, at least for these very large collaborations.

However, one very interesting robotic system was used in ATLAS, not for module assembly but for the mounting of modules onto the larger support structure. This robot did metrology, pick and place of modules and even inserted and tightened the screws that held the module on the shell structure of the ATLAS SCT barrel. Thus the module handling mechanism was quite sophisticated and given the large size of the barrel, this required a high precision stage of unusual length. This robot was built and refined by groups from KEK, University of Tsukuba and Oxford University [3].

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6. Prospects for automated module production in future HEP silicon detectors

6.1 Comparison of manual and automated (robotic) module assembly

When does it becomes advantageous to move from manual to in-house automation of module production? To help answer this question, we will look at a fictional project and compare a manual versus robotic assembly based closely on the CMS tracker model. First, we will consider the following detector definition, the financial, schedule, manpower and other resource parameters and assume we are at the end of the R&D phase in the module design:

- 20000 modules needed with similar mechanical design
- Must finish module production 3 years from now
- Budget for module production (excluding component procurement) is 2MCHF (million Swiss Francs) which can be spent on manpower, equipment, and outsourcing.
- Four participating institutes can offer laboratory space and mechanical workshop access. Manpower for design, supervision, organization and testing is provided by those institutes. Manpower available from the institutes for the routine production tasks is 8 people.

Given these boundary conditions, an estimation of a manual production will assume that one year is needed for prototyping and tooling set-up for production. Four parallel production facilities would be created at a cost of 0.25MCHF per site. Production costs (consumables, infrastructure, transport, logistics) are estimated at 0.2MCHF. Module throughput of 5 modules per day per site is assumed. The personnel needed per site for production tasks is estimated as 4, so 8 people must be hired for the 2 years at a cost of 0.8MCHF. This production system would produce 20 modules per day. In the two years available, assuming 200 working days per year, 8000 modules could be produced. It order to reach the goal of 20000 modules, one could run 2.5 shifts which would require more hired personnel (32 in total). Production costs would have to increase and an estimate of the cost would be about 4.6MCHF or 2.3 times the allocated budget.

A robotic assembly system would add 0.25MCHF per machine to the facilities cost. Assume three machines are used. The budget for facilities would be 1.5MCHF. Production costs are about the same, 0.2MCHF. More time is needed to develop the robot for the production, 1.5 years is assumed. We will assume the personnel needed per site for production tasks is 4 although much of the manpower is replaced by the robot. Four additional persons are needed at a cost of 0.2MCHF per year. The throughput of one machine is 25 modules per day so for the 3 sites, 75 modules/day or 15000 per year. The 20000 modules would be produced in 1.33 years, thus leaving a small contingency in the schedule. The total budget comes out to be 2MCHF assuming personnel costs for 1.5 years. So, if the estimated manpower needs and throughputs of a real project were close to the above example, it clearly shows that a robotic assembly is both cost-effective and could save on time as well for a project of this size.

However, if one dropped the number of modules to 8000, then the manual production can do the job with this budget and timescale, albeit with no contingency. It is true that the robotic assembly would be able to do 8000 modules in even less time and for less total cost (using 2 machines, it would take 2.3 years instead of 3 and cost 1.2MCHF instead of 2MCHF) but there

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would be the same overhead in development work and time which is estimated at 4-6 people (physicists, engineers, programmers, technicians) who spend the 1.5 years acquiring and building the associated hardware and then refining the system. It may not seem worthwhile to take the risk of investing both money and time in a complicated new system when the old tried and true method will work. However, the examples above give an indication at what point a robotic assembly system begins to be an interesting alternative. To give an over simplistic answer: below 5000 modules it is probably not a cost-effective solution, above 5000 modules it is probably worth investigating robotic assembly in more detail.

6.2 Candidate projects for robotic module assembly

Which future silicon detector upgrades (for Super-LHC) and other new projects are good candidates for automated module assembly? A survey as of mid-2010 gave the following results:

- ALICE upgrade: In the most aggressive case, they could have both outer silicon detectors replaced, an upgrade of 2000+ modules.
- ATLAS upgrade: In the most aggressive case (replace straw tubes), they could have a similar size to CMS, an upgrade of 20000 modules.
- CMS upgrade: Probably a replacement of existing volume with modified geometry, an upgrade of around 20000 modules.
- LHCb upgrade: In the most aggressive case, an upgrade of less than 1000 modules.
- International Linear Collider: SiD (ver.2) silicon tracker has 10978 modules.
- Space detectors: No knowledge of any planned with large amounts of silicon.

The above numbers show that the most likely candidates for an automated module assembly are ATLAS, CMS and SiD. However, ATLAS may subdivide the detector upgrade into separate parts (endcap vs. barrel) or in several stages that may result in numbers that make manual assembly still advantageous. CMS will likely make the upgrade at one time and will likely follow a uniform module concept (all modules types have identical or very similar technological choices for the mechanical structure, e.g. single-sided silicon sensors connected to a glass pitch adapter which is connected to read-out chips on a polyimide PCB, all glued to a carbon fibre frame) which is essential for an automated assembly. Since CMS pioneered robotic assembly, it is highly likely that they will choose it again. The SiD experiment is still very early in the R&D phase but if they choose a similar module design for both barrel and endcap, then they would be a strong candidate for an automated assembly.

Note that automated assembly should not be ruled out simply because the number of modules is not 5000 or more. If high precision, reproducibility or yields are very important criteria, then automated assembly may be desirable in spite of the cost and large overheads. Each project should do a detailed analysis to judge the pros and cons of this approach.

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7. Issues concerning large scale module production

7.1 Search for new robotic technologies for module assembly

A literature and product search for new robotic technologies that might be applicable to silicon detector module production was performed but no interesting discoveries were made. Much of the recent emphasis on robotics centres on humanoid robots and robots capable of elaborate object recognition and handling. These are still mostly in the R&D stage, the few available as consumer or industrial products had little to offer. The module production application requires high accuracy and very high levels of flexibility since the types of object needed to be handled are diverse in size, shape and composition and the manipulations are delicate and complex. The conclusion of the survey was that the standard cartesian positioning robot was still the best choice since it is well adapted to work with very planar objects. It may be that robotic arms could be used for this type of assembly but a substantial development effort would be needed to reach the point of “proof of principle”.

7.2 The role of quality assurance in module production

In manual production, with most of the critical steps under local supervision, quality assurance (QA) is still important but the task is simplified by the fact that the processes are controlled in-house. For in-house automation, QA becomes much more essential because many critical steps are handled by machines often with little or no human supervision. The quality assurance planning must begin very early in the case of in-house automation. The constraints imposed by a robotic assembly system (flatness, stiffness, reference marks, areas for vacuum pick-up, etc) often require that the components and the module design follow guidelines that are not needed for a manual assembly. This, in turn will have implications on the overall process so the quality assurance plan should be adapted to assure the quality of the entire process such that the quality of the final product meets the requirements. In addition, because of the large numbers of components and modules, it may not be possible to test every piece at all critical steps. In that case, sampling should be applied with the appropriate sample sizes. Other tests may be needed to verify the quality of processes which would otherwise be checked by human observation in a manual assembly. The entire production process should be considered as if it was being performed in industry, since for in-house automation, one is effectively performing an industrial process. Therefore the same quality assurance protocols should be applied as for a company that respects a high level of QA.

For outsourcing, because one is handing over the entire fabrication or assembly process to a company, the QA plan should be of the highest priority. Many HEP project managers (often physicists) are not familiar with how QA is handled in industry. If one does not require a specified level of QA, there is no guarantee that a company will apply any QA standards. An ISO9000 or 9001 label only means that the company has been certified to be able to apply certain standards. It is the customer who must require that those standards be met. A basic guideline for outsourcing of non-standard components or assembly work is to write a highly detailed technical specification document which includes all the required final specifications and how they should be tested as well as the quality assurance planning to be imposed on the fabrication or assembly process. This can include intermediate tests and documentation of the results. In many projects, not applying such a QA plan resulted in receiving non-compliant products which then required months to years of further analysis, additional production runs and even changing companies before achieving a satisfactory result. Many excellent QA guidelines have been established in other fields requiring high quality, especially in the aerospace sector.

8. Conclusions

For future HEP silicon detector module production, it is clear that a mix of manual assembly, in-house automation and industrial outsourcing will be used. In the case of very large numbers of modules (>5000) or where high precision and reproducibility is essential, robotic assembly systems such as the one used by the CMS tracker could be a cost-effective alternative to traditional manual assembly. The future large projects will require that more emphasis be placed on in-house automation and outsourcing. This trend increases the need for quality assurance of the highest industrial standards as found in the space, aviation and medical fields.

References

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