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Robotic mounting of ATLAS barrel SCT modules

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Abstract

The 2112 silicon detector modules of the barrel part of the ATLAS SemiConductor Tracker (SCT) have been mounted on their carbon fibre support structure. Module insertion, placement and fixing were performed by robotic assembly tooling. We report on our experience with this assembly method. Part of the mounting sequence involves a partial survey of elements of the support structure which is needed to align the modules properly during insertion. An analysis of these data is used to estimate the positional accuracy of the robots.

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Keywords: ATLAS; SCT; Barrel; Mounting; Assembly; Robotic; LHC

1. Introduction

The barrel section of the ATLAS SemiConductor Tracker (SCT) consists of four concentric carbon fibre cylinders (labelled B3 to B6 from the innermost to the outermost) with outer diameters of 568, 710, 854 and 996 mm [1]. The outer surface of each of the cylinders is hermetically tiled with silicon detector modules [2,3]. The tiling was designed so that modules have a small overlap with all adjacent modules (Fig. 1). The gaps between modules in the overlap regions are very small (approximately 1.6 mm), making insertion of individual modules difficult.

Modules are laid out in rows of 12. The number of rows for B3, B4, B5 and B6 are 32, 40, 48 and 56, respectively. In total, 2112 modules were mounted to complete the barrel SCT. Modules are mounted almost parallel to the local surface of the support cylinders, at a small angle and with every second module at a slightly larger radius to accommodate the overlaps. The tilt angles accommodate overlaps between adjacent rows and are 11° for the two inner cylinders and 11.25° for the two outer cylinders. Modules at smaller radius are referred to as lower modules, and those at larger radius are called upper modules.

The precision mechanical connection between the support barrels and the silicon detector modules is achieved by carbon fibre brackets (Fig. 2). Each of the modules is supported on two points located on one bracket and a third point on the bracket in the next row. At the two first points there are precision bushes (inner diameter specified as 1.8 mm H7, i.e. 1.800–1.809 mm) where the module is positioned by a precision washer (outer diameter 1.8 mm

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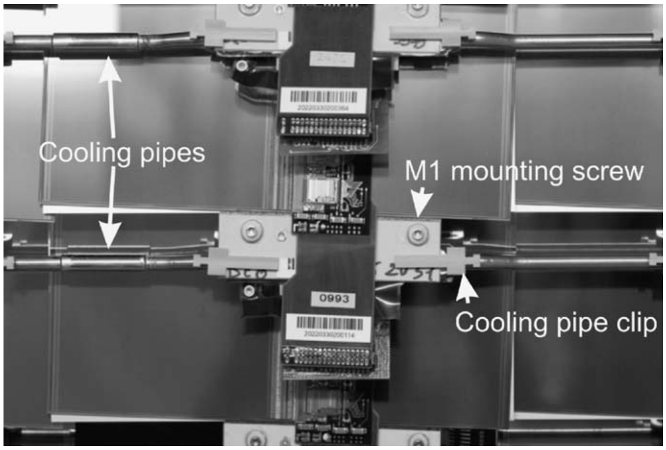

Fig. 1. Modules mounted on a barrel. The modules shown in the centre are upper modules, and the modules to the left and right are lower modules. Rows are horizontal across the picture. Note the overlaps at the ends of the modules. Unprotected wirebonds are located along the hybrid boards on both sides of the module

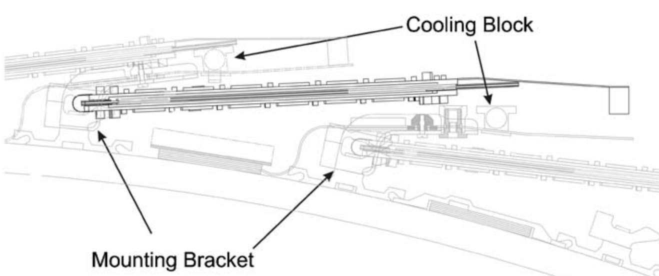

Fig. 2. Cross-section of insertion of module (dark) into barrel. Existing parts of the barrel (brackets, services and mounted modules) are in a lighter grey. The module is shown after insertion into the spring clamp at the left edge and before contacting the cooling block.

f6, i.e. 1.794–1.788 mm) and secured by an M1 screw with an M1.6 screw head, constraining three degrees of freedom on one and two degrees of freedom on the other point. The third mounting point is a simple sprung clamp constraining out-of-plane movement.

The part of the module which makes mechanical contact is the encapsulated thermal pyrolitic graphite (TPG) baseboard [4] with beryllium oxide (BeO) facings, with precision glued aluminium washers at the two screw locations. The holes in the washers provide accurate module location and the BeO facing is also used as the mechanical handling point during the assembly. The carbon fibre cylinder also supports the services: electrical power cables (referred to as low mass tapes, LMTs), optical control and data fibres with the electro-optical converters, and cooling pipes. All the services are segmented in rows or multiples of rows on the barrel.

The electrical connections are made through one Samtec SFMC-120-L3-S-D connector (2×18 pins, 1.27 mm pitch).

Thermal contact between the modules and the cooling pipes is made through cooling blocks soldered around the cupro-nickel (CuNi) pipe. A $60 \times 8\,\mathrm{mm}^2$ section of the BeO facing overlaps with the cooling block. The 100 μm-thick gap between the two is filled with thermally conductive grease (Dow Corning 340). While the gap thickness is defined by the relative position of module and cooling loop their contact is secured by two clips per module.

Before mounting the modules, all brackets and services, LMTs, fibres [5] and cooling pipes had been installed.[1] As the cooling pipes are suspended from the modules, dummy modules are in place at this stage of the assembly.

All the services leave very small clearances (around 1 mm) for the insertion of modules (Fig. 2). In addition the insertion path required to avoid clashes was not simple. These were the main reasons for the choice of robotic assembly. For the size and schedule of the barrel SCT project distributed assembly on different sites was not necessary and it was sufficient to build and operate two assembly stations with one robot each at Oxford University. Each robot was used to assemble two cylinders. The first cylinder to be assembled was B3, followed by B6, B5 and B4, where during assembly of the latter three both assembly stations were used in parallel. B3 and B5 were assembled using one robot, and the B4 and B6 with the other. The robots were used to assist in mounting as well as in removal, in cases where there was a problem with the detector module.

2. Robots

The robots used in the assembly were originally designed and fabricated at KEK by the groups of KEK and University of Tsukuba [6] and extensively adapted and commissioned at Oxford University, where the mounting of SCT modules onto the barrel cylinders took place. During the assembly the functions of the robot were to: (1) pick up a module from a custom module box; (2) transport the module to the location on the cylinder along a safe path; (3) align the module to the fixing holes of the bracket on the cylinder; (4) position the module on the fixing points; and (5) tighten the screws with torque-limited motorized screw drivers. Similar procedures, in reverse order, were performed when removal of a module was required.

Another sequence was a recovery procedure. In the case that the module insertion had to be stopped at any arbitrary point during the process, the module could be returned to its box by exactly reversing its approach path.

The modules were placed in the custom-built module boxes [2] at the module assembly sites. The boxes were then used to protect the modules during transportation, storage and pre-assembly tests, and also worked as an interface for the robot during the assembly. For this, each box was positioned at a pre-defined position in the robot from where the module was picked up by the robot so that manual handling of the modules was never required.

[1]Services were attached to the cylinders at Rutherford Appleton Laboratory, UK.

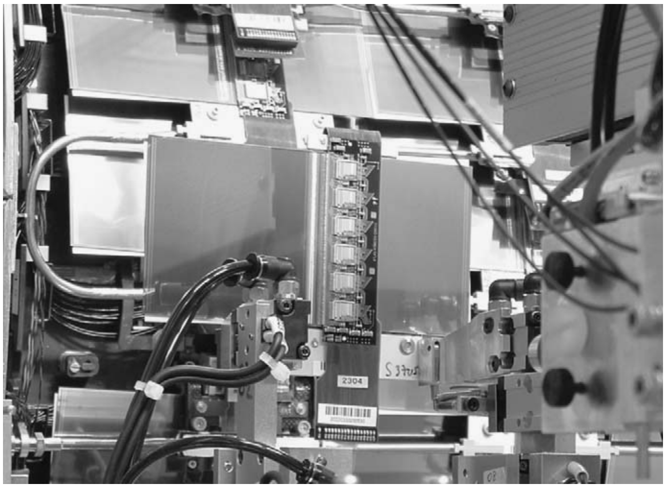

Fig. 3. Module held by robot jaws, ready for insertion into last position on B3.

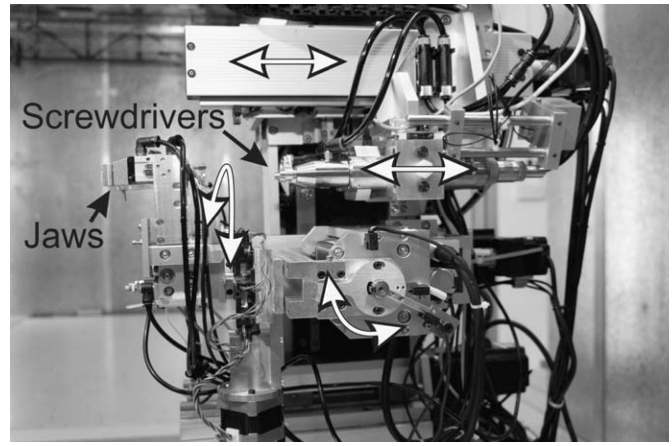

Fig. 4. Side view of robot. White arrows indicate travel of selected motion stages.

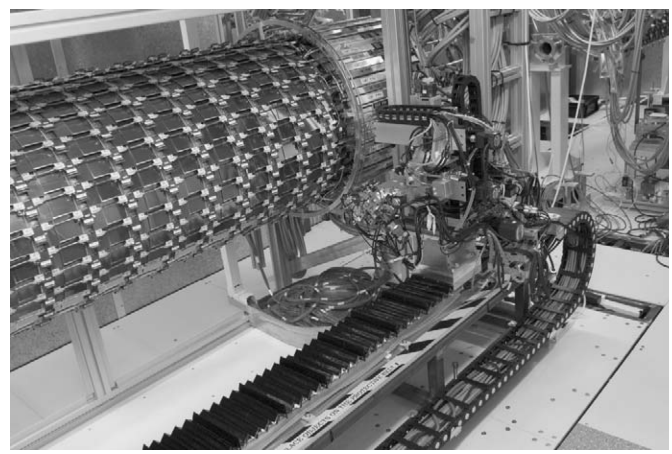

Fig. 5. Robot in assembly position in front of B3. Note the long parallel stage at the bottom of the picture (covered by accordion-type protective cover).

Originally, alignment of the modules with the mounting brackets was achieved visually. The operator viewed both the module fixing holes and the bracket holes with video cameras in the robots and aligned them with manual steering. This was demanding on the visual abilities and concentration of the operator in order to maintain the required precision reliably. Given the large number of modules in the SCT, an automated method was developed to survey the mounting positions on the barrels and each module as picked up by the robot. The mounting position was surveyed by inserting a precision pin in the fixing holes in the bracket and by measuring the location of this pin with two crossing lasers attached to the robot. The module holes were surveyed after pick up with another laser beam, which detected the passage of light through the mounting hole as the module was moved across. This method of alignment did not demand excessive operator concentration and was almost fail-safe.

The safe path was defined for each barrel before the assembly based on construction drawings, relying on the requirement that all objects stay within their nominal envelopes. The operator watched the insertion to ensure that there was no unexpected interference.

The robot held the modules in a set of air-driven jaws, which gripped the BeO facing of the cooling tab of the module from two sides next to the mounting screw holes (Fig. 3). These jaws had plain steel surfaces. The pistons provided about 17 N per jaw. On one robot the jaws were opened by the pistons and closed by a spring exerting a force of 4.4 N, thus maintaining grip even in the case of loss of air pressure. On the other robot the jaws were closed by the air pressure and held open by the spring, yielding a grip force of 12.6 N. In this case the fail-safe feature was provided by a back-up nitrogen bottle. The closed gap thickness of the jaws was set to 830 μm, with the baseboards being 930 ± 70 μm (mechanical tolerance).

The symmetry of the barrels invites assembly in rows. The robot therefore had one long (1.5 m) stage in parallel with the barrel, which allowed access to all 12 positions along one row as well as the module pick-up position, and several smaller stages, which controlled the position and orientation of the robot jaws (Fig. 4). These latter stages were used for the insertion of the module. All stages were open-loop controlled and driven by electrical stepper motors with 500 steps/revolution. The step size along the stages was 10μm. Access to the other rows was possible through rotation of the barrel.

In addition to the jaws the robot was equipped with a set of two air-driven screwdrivers, which inserted the mounting screws together with the precision location washers with a force of 4.9 N and tightened them to a torque of 4 Ncm. It also had fixtures for the different alignment and survey laser sensors.

The cylinders were mounted on a spindle which was supported at each end on a pedestal (Fig. 5). The cylinders could be fully rotated around the axis using a hand crank. An indexing ring on the barrel support spindle allowed the position at each row to be mechanically locked. The precision of this angle was moderate (~1 mm) as the exact location in this direction was calibrated during the assembly of each row by the survey.

The cylinders were enclosed by an aluminium profile frame, which protected the cylinder during the assembly and supported assembly infrastructure. This frame was also used as the skeleton for the innermost protective box during transport of the cylinders to and from Oxford.

3. Safety measures

The power and weight of the robot far exceeded the strength of any component in the assembly (modules, carbon fibre barrels, cooling loops, etc.), so special precautions were taken to avoid catastrophic failures.

Electrical back-up power was supplied by an uninterruptible power supply (UPS) and the compressed air supply was guaranteed by a back-up nitrogen bottle.

When the robot jaws were in a position close to the barrel, where a sideways movement of the jaws or the module would create significant damage operation of the long axial stage was disabled by hardware.

The screwdrivers had a cut-out switch, which limited the force with which the screws with their location washers were inserted to 6.9 N.

A generous number of emergency stop switches were distributed throughout the assembly area and on the robot.

4. Robot commissioning

Most of the commissioning was done on a prototype resembling a 1/8 sector in azimuthal angle of B3 with full length in the axial direction. The sector had a reasonably realistic set of services attached. The final insertion trajectory was tuned for each barrel using a small accurate model section of each cylinder.

Once the hardware and software was in a stable state the final parameter tuning to the as-built geometry of a particular barrel was done using the actual cylinders. Before mounting modules the correct behaviour was verified with dummy modules with realistic envelopes on known critical positions, in particular the positions at the ends of the barrel.

5. Robot alignment

The first step in the set-up of a robot was the parallel alignment of the robot with the barrel and the setting of the azimuthal angle of the barrel. For this the robot support table had adjustable mounts on both ends, the position of which could be fine-tuned with the help of set screws and indicators. The correct parallel alignment was verified using mechanical dummy modules mounted on the brackets. A reflective laser sensor head on the robot scanned the module surface, measuring the distance from the sensor to the surface. The robot support position was then adjusted until parallel alignment was achieved. The typical orientation difference between the robot and the barrel coordinate systems was within 20 μm perpendicular to the barrel axis over the length of the barrel (~1.6 m). The φ angle of the barrel was adjusted to be within 0.05° with respect to the robot coordinate system.

6. Mounting procedures

The assembly of modules on the barrels was usually done in groups of six, either upper or lower modules of one row. The first step was a survey of the mounting points on the barrel. For this precision pins were inserted in the fully constraining mounting bushing at each module location. The protruding ends of the precision pins were located with a crossed beam laser sensor and their position recorded in a database. After this, the survey pins were removed and a grease layer was applied on each cooling block by the operator. The modules were then attached to the surveyed locations.

Modules were delivered and stored individually in precision boxes. During assembly, the lid of the box and module holding clamps were removed. The box was moved to the pick-up position, where the module was picked up with the robot.

The exact location of the module after pick-up with respect to the robot coordinate system was obtained from a laser beam, which scanned the position of the module mounting holes.

Once the coordinates were known the insertion took place and the mounting screws, together with the positioning washers, were inserted in the mounting holes and tightened by the robot. The robot retracted and the procedure was repeated until the group of six modules was mounted. To complete mounting of a group of modules the operator manually attached the cooling loop clips and mated the module connector with the service connector on the barrel.

Up to 24 modules per assembly station were mounted this way in an 8-hour shift.

7. Dismounting modules

In a small number of cases (40 modules) it was necessary to remove a module after initial functionality checks on the barrel. After removal of cooling loop clips and de-mating of the electrical connector a survey of the module on the barrel was performed, as during insertion except that the precision pins were adapted to work with modules in place. The module was gripped in the mounted position by the robot jaws and the mounting screws removed. Because of its strong adhesion it was necessary to break the grease joint by inserting a small wedge by hand. After removal the module holes were surveyed to ascertain the exact gripping location, and the module was then returned into its box. Before mounting a new module in this position the remaining grease was removed by hand. For the removal of lower modules it was necessary to remove first the two neighbouring upper modules.

8. Yield and observed problems

The robotic assembly of the ATLAS barrel SCT was highly successful. Including replacements, over 2180 modules were mounted on the barrels. Forty modules had to be removed and replaced for various reasons, most of which were not associated with the assembly process.

Only four modules were damaged during assembly. Two were operator errors; one was due to a design flaw which was subsequently corrected; and the baseboard of the fourth was damaged when the grease joint was split during removal made necessary by an unrelated cause.

The most prominent problem during the assembly was with the bush tolerances. These tolerances are tight to ensure accurate location of modules, but on 33 modules the robot screwdrivers cut out due to torque limits and the screws had to be tightened by hand. Examination of the washers and bushes involved showed that the overly tight fit was caused by burrs on the bushings.

At an advanced point in the assembly one stage in one robot started to seize causing a loss of steps in its motor. This was traced to improper selection of materials in the sliding joint. The problem, which was the only one associated with the robots during assembly, was rectified with lubricant to avoid schedule slippage.

The small clearances made the setting of the parameters defining the insertion path critical and on a few occasions these had to be adapted slightly after problems during the insertion. Mostly these involved the jaws touching cooling pipes, which were not well constrained in space, and where the jaws failed to clear the cooling block due to insufficient clearance programmed for the approach. These re-evaluations of the parameters were done with dummy modules.

9. Repeatability and absolute precision

The accuracy required on the module insertion path to guarantee clearance was about 100 μm. This was also the precision required for alignment of module and bracket holes, where the clearances were smaller but a chamfer on the washer provided guidance. These were not absolute precisions, but the relative accuracy with which the position of the brackets and the modules were measured and the module was moved along its insertion path. This precision only had to be maintained during the time between the survey and the insertion, which typically was less than an hour.

During commissioning the positioning repeatability of the robot was measured to be better than 10 μm by repeatedly driving the robot from its home position to the same programmed location.

The positioning accuracy was also estimated using the survey data recorded during the assembly, although it was necessary to account for large systematic shifts between measurements separated by long time intervals (and in some circumstances even between measurements taken closer in time). Such shifts may make upper and lower modules look displaced with respect to each other in the data. These differences are larger in some directions, particularly azimuthally where positioning was given by the indexing ring which had modest precision.

After removing known systematic problems, the z position information was compared to the nominal positions in the construction drawings. From the measured position of individual brackets the distance between neighbouring brackets was derived and compared to the nominal distance. As an example the difference between nominal and measured distances in z for B4, is shown in Fig. 6. The spread in the resulting distributions are caused by the build precision of the support structure and the robot positioning accuracy (although not all the movement stages in the robot contribute in this measurement). The precision of the barrel support structure was specified to ± 20 μm for the radial position of the pads, to which the brackets were attached, and the holes used for this junction were required to be within a cylinder of 40 μm diameter on the barrel surface. With such lightweight and relatively flexible structures, these tolerances were considered to be at the limit of what could be achieved and the actual tolerances were most likely slightly larger. The brackets were not systematically measured, but the forms to laminate and to machine them were made on CNC machines with a precision of about 50 μm.

There is a systematic effect along the length of the barrel, which is likely to be a result of the positioning accuracy of the robot (limited by the open-loop controlled stages and/or the linearity of the long stage), rather than of the barrel, as similar behaviour can be found in the other cylinder assembled using the same robot (Fig. 7). Using mean positions for each bracket for a correction for each robot a standard deviation of 87 μm is obtained for the distribution of the difference for all module positions (Fig. 8). Assuming no correlation this translates to a 62 μm spread

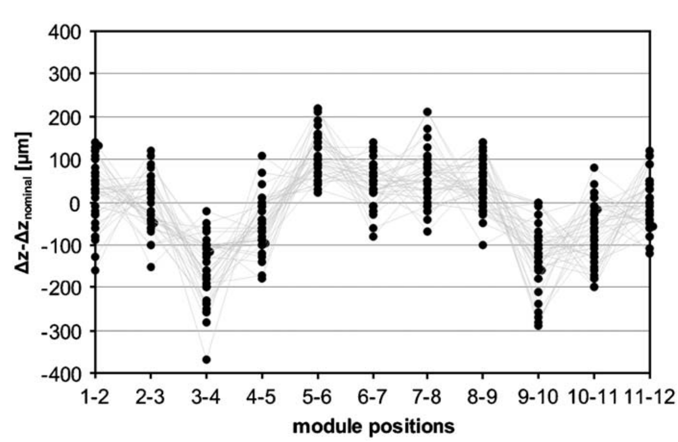

Fig. 6. Difference between measured axial (z) distance between neighbouring modules within a row and nominal distance for B4. The different data points and lines correspond to the 40 rows of modules on this barrel.

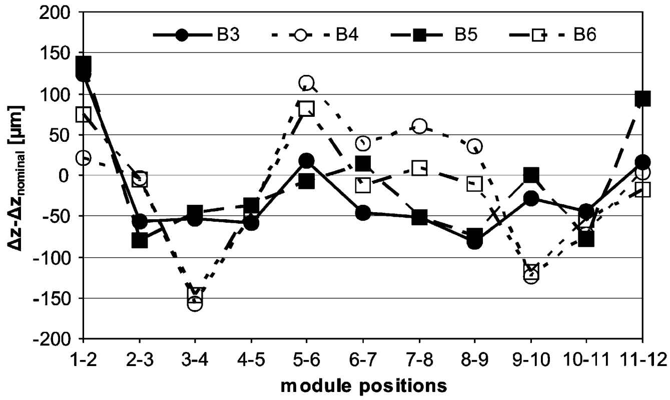

Fig. 7. Distribution of difference between measured axial (z) distance between neighbouring modules within a row and nominal distance averaged for each barrel. B3 and B5 were assembled using the same robot, whereas for B4 and B6 the other robot was used.

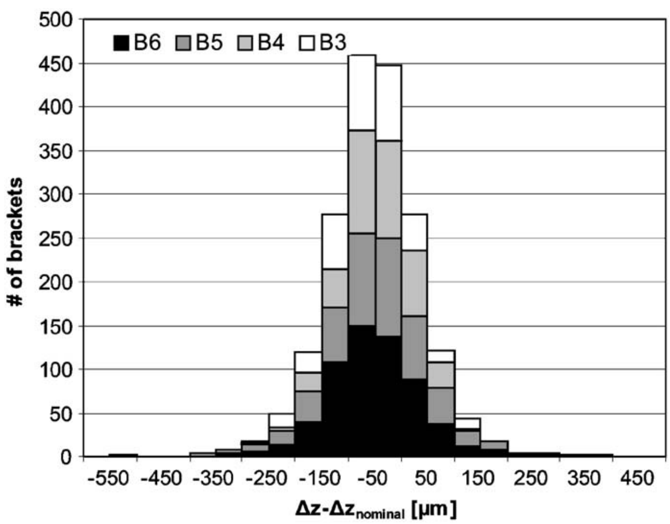

Fig. 8. Distribution of difference between measured axial (z) distance between neighbouring modules within a row and nominal distance after correction for robot-related systematic effects.

in the difference between the measured and nominal location of a bracket position along the row. As discussed above the actual build precision is not well known, but assuming a value of 50 μm yields a robot measurement precision of about 40 μm.

If it had been needed the described systematic effects in absolute position measurement could easily have been overcome by the use of closed-loop controlled stages or the addition of a precision measurement system for absolute distances (e.g. interferometer).

10. Other observations

Generally, robotic assembly is greatly facilitated by simple, uniform design of the objects to be handled, with mechanically well-defined handling points. This was well achieved for the insertion and fixing of the modules on the SCT barrels. These criteria were met less well with the design of the cooling interface and the electrical connection, where attempts to automate assembly were abandoned as the size of the project or access and precision considerations did not mandate it. For a larger or more distributed assembly project issues of simplicity of assembly should be considered at the system design stage to allow for extensive use of robots in the assembly.

11. Summary

A total of 2112 SCT silicon modules have been mounted on four support cylinders using robots. The excellent success rate in attaching modules demonstrates that robotic assembly is a good choice for a tight geometry like the ATLAS barrel SCT.

An automated survey method was selected to reduce the scope for operator error. No emphasis was placed on absolute precision measurement. However, an analysis of the survey data taken during assembly shows that excellent precision can be obtained.

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