The Compact Muon Solenoid Experiment
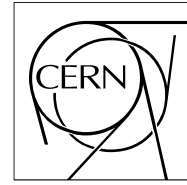
CMS Note

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Assembly of the Inner Tracker Silicon Microstrip Modules

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Abstract

This note describes the organization of the mechanical assembly of the nearly 4000 silicon microstrip modules that were constructed in Italy for the Inner Tracker of the CMS experiment. The customization and the calibration of the robotic system adopted by the CMS Tracker community, starting from a general pilot project realized at CERN, is described. The step-by-step assembly procedure is illustrated in detail. Finally, the results for the mechanical precision of all assembled modules are reported.

1 Introduction

This note describes the assembly of the 3922 silicon microstrip modules for the inner part of the CMS Tracker, which has been performed in Italy at two assembly centres located in Bari and Perugia.

The Tracker consists [1] of silicon pixel and silicon microstrip devices. Figure 1 shows a cross-section of one quarter of the silicon strip Tracker .The central region is covered by the Tracker Inner Barrel (TIB) which consists of four cylindrical layers with strings of three thin modules mounted inside and outside the layer half-shells.

The Tracker Outer Barrel (TOB) is constructed of six cylindrical layers. The basic substructure of the TOB is a rod: a carbon fibre (CF) support frame that carries either three double-sided or three single-sided thick modules on each side.

The TIB and TOB are complemented in the forward and backward regions by the Tracker Inner Disks (TID), composed out of three disks per side with three rings of modules per disk and the Tracker End-Caps (TEC), composed of nine CF disks.

The basic substructure of the TEC is a petal, a wedge shaped CF support plate which carries up to 28 modules arranged in up to seven radial rings. On each disk eight front and eight back petals (which are of slightly different geometry and carry different numbers of modules) are mounted.

The entire Tracker contains approximately 16000 modules. The modules that are closer to the beam line (TIB, TID and first four rings of TEC) are made with 320 μm thick sensors, while the outermost rings of the end-caps and the TOB are equipped with thicker sensors (500 μm).

The construction of such a large system (about 200 m^2) based on silicon technology has never been attempted be-
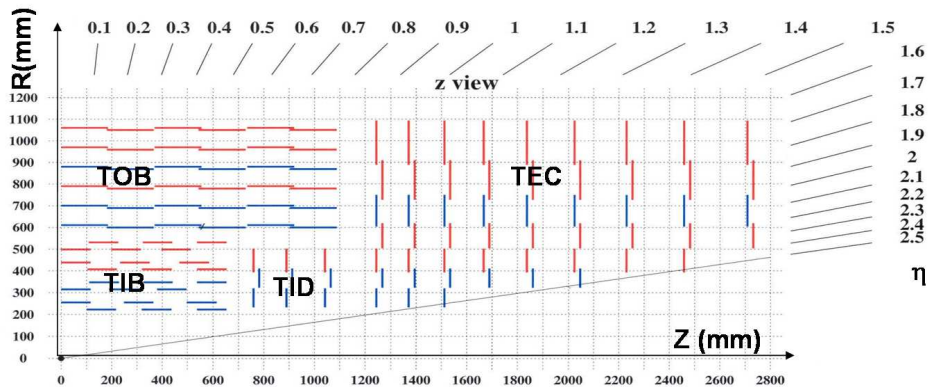

Figure 1: Tracker Layout

fore. Since the silicon modules have been assembled and tested in different laboratories, much effort has been put to guarantee good quality, uniformity and stability in time for the module production. At the same time, extensive use of heavily automatized systems has been made for sensor characterization, module assembly and testing.

In Figure 2 the components of a single sided silicon module are shown. The hybrid electronics circuit and the PA are assembled together on a ceramic substrate and the APV channels are wire bonded to the PA tracks before delivery to the module production centres.

Sensors and front end hybrids are glued to the frames by high precision gantry robots. The components are aligned using digital cameras that measure the position of optical fiducial marks.

All silicon strip sensors are of the single sided type. Double-sided detectors are built by gluing two independent single sided modules (r-ϕ and stereo) back-to-back with a dedicated jiig. To obtain a coarser but adequate resolution on the longitudinal coordinate the stereo module has the sensor tilted 5.7 deg with respect to the r-ϕ sensor. The sensor and electronics of the stereo modules are identical to those of the r-ϕ modules, the only difference being in the support mechanics and pitch adapters.

Seven institutes located in Bari, Brussels, Fermilab, Lyon, Perugia and Santa Barbara (UCSB), shared the responsibility for the automated module assembly for the whole CMS Tracker. The assembly rate was about 20 modules per day per gantry robot with a positioning precision of approximately 10 μm (RMS) achieved. In addition, in Vienna a small number of modules were manually assembled achieving better precision but with a build rate of 1-2 modules per day.

The robotic assembly approach was adopted by CMS in the process of building a very large number of modules across multiple sites.

The construction of a silicon module can be subdivided into different steps, that have been performed in different laboratories: sensor quality assurance, robotic module assembly, bonding and testing. In the following sections,

the robotic assembly is described.

Some characteristics of the modules are summarized in Section 2. An overview of the hardware of the assembly centre is given in Section 3. The assembly centre qualification procedures are described in Section 4 and the general assembly procedures in Section 5. The module assembly quality control is treated in Section 6 and the timeline of the module assembly is described in Section 7. Some remarks and conclusions are given in Section 8.

2   Inner Tracker modules

Table 1: Relevant parameters of TIB/ TID modules.

Module type	Pitch(μm)	Sensor tilt angle(deg)	Active area(cm^2)	Modules assembled at Bari	Modules assembled at Perugia
TIB Layer 1-2 r-ϕ	80	0	35	426	413
TIB Layer 1-2 stereo- left	80	5.7	35	212	208
TIB Layer 1-2 stereo- right	80	- 5.7	35	202	218
TIB Layer 3-4 r-ϕ	120	0	35	671	633
TID Ring 1 r-ϕ	81–119	0	85	40	120
TID Ring 1 stereo- left	81–119	5.7	85	52	28
TID Ring 1 stereo- right	81–119	- 5.7	85	57	25
TID Ring 2 r-ϕ	113–143	0	88	42	123
TID Ring 2 stereo- left	113–143	5.7	88	55	31
TID Ring 2 stereo- right	113–143	- 5.7	88	58	29
TID Ring 3 r-ϕ	123–158	0	79	130	150

Due to the geometry of the Inner Tracker and the need to have double-sided detectors in the innermost layers, the assembly had to deal with ten different module geometries. Three geometries, namely r-ϕ, stereo left and stereo right, are used in the Inner Barrel, whereas seven different geometries are needed for the Inner Disks. In Table 1 a set of relevant parameters about the type of TIB/ TID modules is reported.

Figure 3 shows one example of the modules of layers 1 and 2 of the Inner Barrel. Here the modules are placed
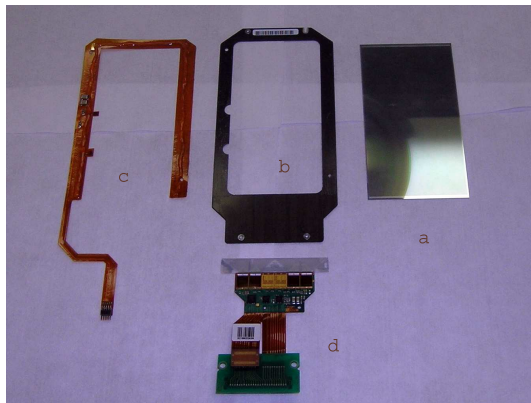

Figure 2: TIB/TID single sided module components: (a) silicon sensor, (b) carbon fiber support frame, (c) the HV bias circuit on a Kapton insulator layer, pitch adapter (PA) and (d) front-end hybrid

Figure 3: TIB modules in their module carrier. On the right side, a r-ϕ module and on the left side, a stereo right module are shown.

in carriers, which are used for shipping them to the bonding and testing centres.

The Inner Disks are composed of three rings, each one mounting three module types, except Ring 3 which has only one type of module, namely r-ϕ. In Figure 4 a picture is shown of all the Inner Disks' module types after assembly.
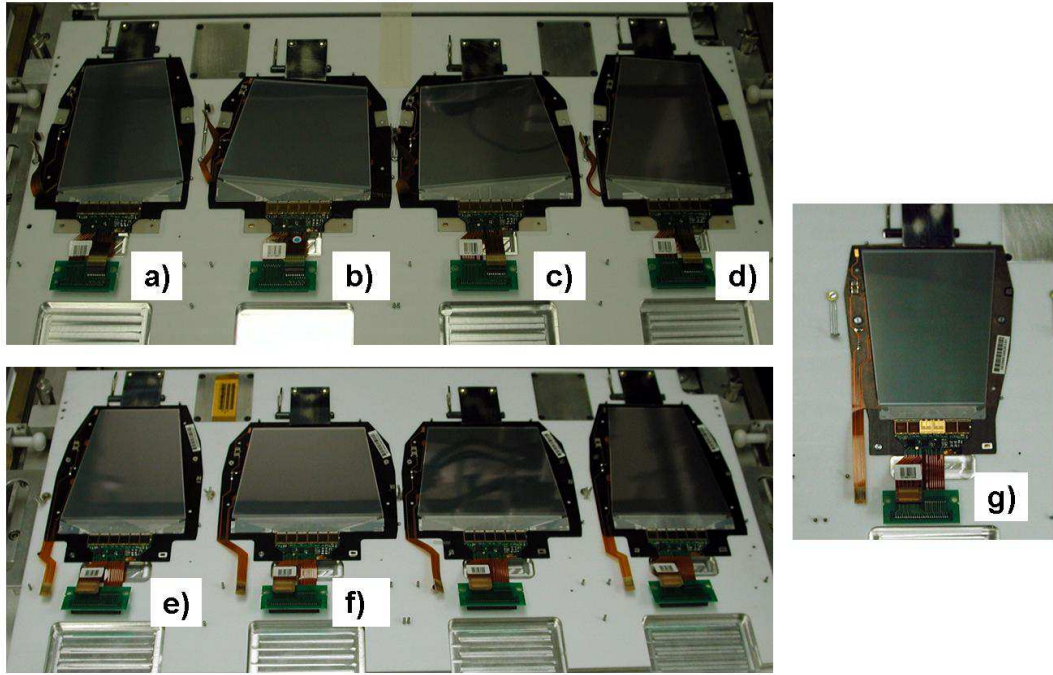
Figure 4: TID modules on the Gantry assembly plate: a) Ring 1 stereo-left, b) Ring 2 stereo-right , c) Ring 2 stereo-left, d) Ring 1 stereo-right, e) Ring 1 r-ϕ, f) Ring 2 r-ϕ and g) Ring 3.

3   Assembly robot hardware setup

3.1   Overview of the Aerotech AGS1000 system "Gantry"

The Gantry system was originally conceived and developed by the CMS Tracker group at CERN [3][4]. The system has been documented by a UCSB group [5] that worked on the assembly of both TOB and TEC modules. The phases of the assembly task are essentially five: 1) procurement of module components, 2) preparation of the robot for assembly, 3) module assembly, 4) module survey after assembly and 5) shipping of modules to the bonding centres.

The basic element of the assembly setup is an Aerotech AGS 10000 gantry positioning system [6], which provides a 50 cm x 50 cm static working area, four separate coordinate (X, Y, Z, and ϕ rotation) positioning motors, and control hardware and software. Figure 5 shows the bare configuration. The Aerotech system is PC controlled

Figure 5: out-of-the-box Aerotech AGS 10000 system

and uses a software interface program (MMI), which allows users to run user-defined programs on a standard PC. The component sensor supply platform, assembly platform and pick-up tools were designed at CERN and use a vacuum to hold the pieces that will be assembled. A glue dispensing system was designed which uses air pressure to provide automatic application of glue. The vacuum and air pressure valves are interfaced through a custom designed logic circuit which is under the control of the robotic positioning machine. In Figure 6, the final version of the setup of the gantry style positioning machine, commonly referred to as a "gantry", with all the tools needed

to assemble the Inner Tracker modules, is shown.

The robot, located in a class 1000 clean room, was placed on an anti-vibration table and, for safety reasons, enclosed in a transparent plastic structure with a window on the front. On the rack, a commercial PC and the control electronics were placed. The X axis linear motors were located on the left and right sides of the platform. The Y
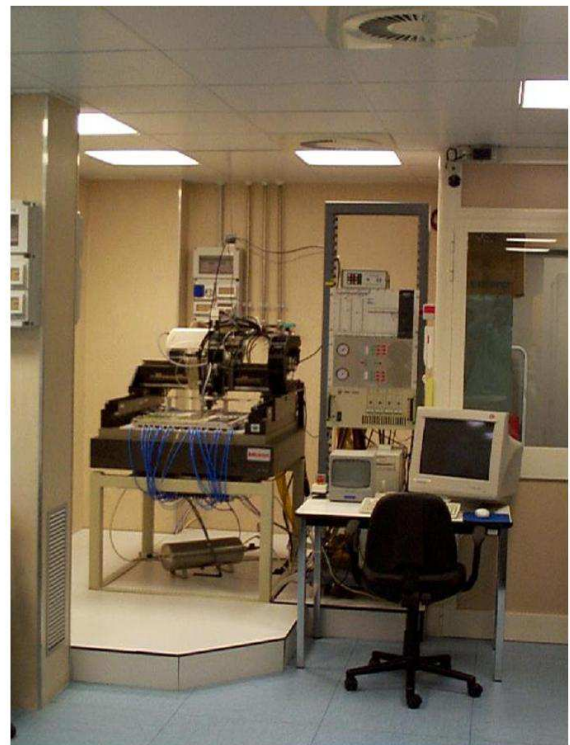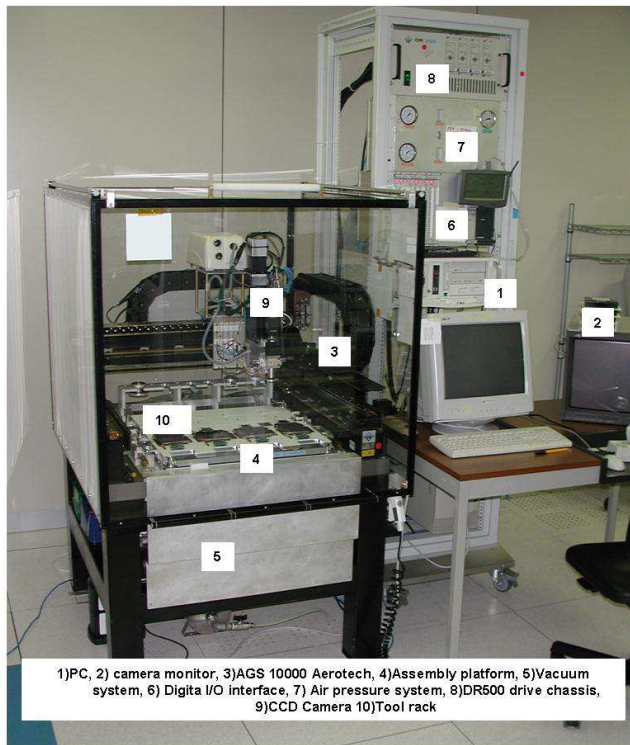

1)PC, 2) camera monitor, 3)AGS 10000 Aerotech, 4)Assembly platform, 5)Vacuum system, 6) Digita I/O interface, 7) Air pressure system, 8)DR500 drive chassis, 9)CCD Camera 10)Tool rack

Figure 6: Assembly robot "Gantry" (Bari center on the left side, Perugia center on the right side)

axis drive was a single linear motor located on the cross-beam near the back. The Z axis drive was equipped with a ϕ motor and a CCD camera to locate fiducial marks on the individual detector components. A UPS (uninterruptible power supply) unit was used for both the PC and Aerotech equipment so that power glitches could not affect the operation of the machine and the power cuts were managed in the best way possible. The PC, monitor, drive chassis (DR500), I/O electronics, vacuum pump, glue dispenser, and optical equipment were also plugged into the UPS.

During the commissioning of the setup, two noteworthy modifications were studied in order to increase the rotation ϕ axis accuracy. The first was a custom gear box inserted as shown on the right side of Figure 7. The gear box (a picture is shown on the left side of the same Figure) was designed to be located between the axis of the ϕ motor and the head support tool in order to give a rotation reduction with a ratio 50:1, thus increasing the precision of the original motor. After the first prototype was realized and successfully commissioned in Perugia, a set of commercial gearing components (Harmonic Drive, CSD series), shown in the top right side of the same figure, was used to realize the final gear boxes in the Bari mechanical workshop, which were then mounted on the two Italian Gantries. A schematic drawing of the gear box is shown in the same figure on the right bottom side. Another modification consisted of custom made contact switches which were mounted inside the head support tool and enabled the robot to pick up the tools used to move the sensors and hybrids, as well as the syringes used to dispense glue onto the frames. The " touch" feature of the gantry was implemented using two commercial microswitches with sensitivities of 1 and 2 Newton, respectively, in order to give two different signals the first related to a normal touch-down and the second in response to a fault situation that immediately caused the robot to stop. The two micro-switches were assembled as shown in Figure 8.

With this particular setup, up to four silicon modules could be assembled during a run. The placement accuracy of the sensors on the target carbon fibre frame was better than 10 μm. The automated module assembly procedure took approximately 30 minutes per set of four modules.
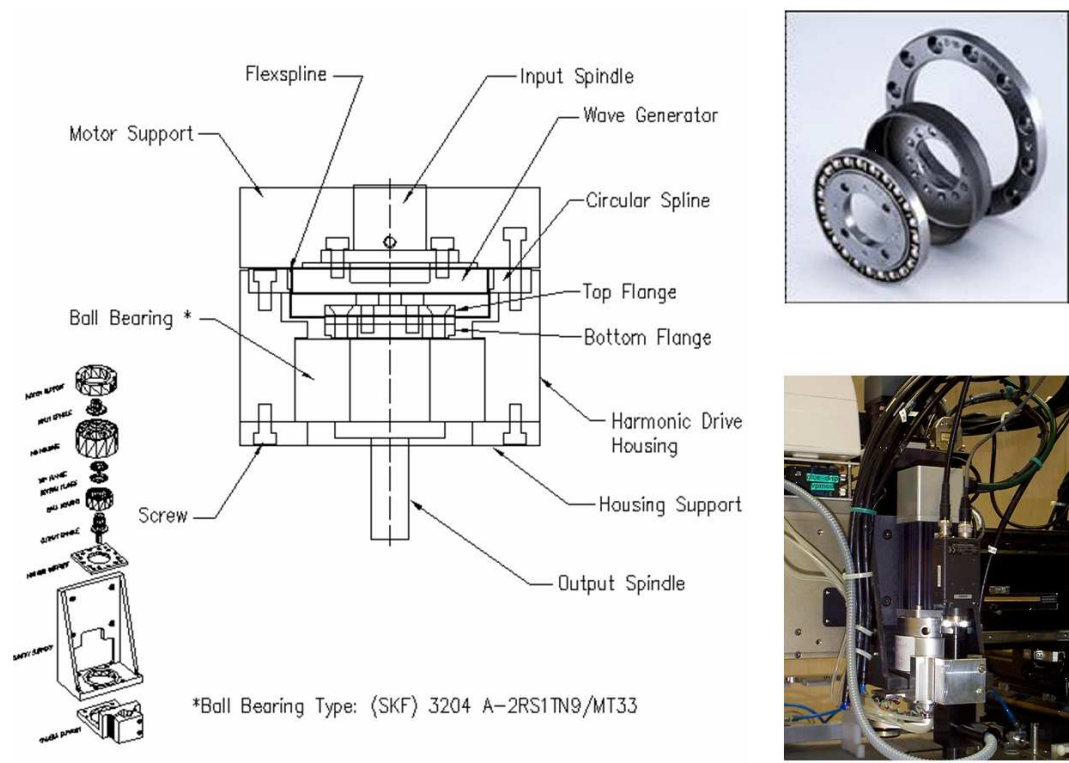
Figure 7: Support head with harmonic drive and their components

Figure 8: Micro contact micro-switches

3.2 Assembly plates for the different modules

The gantry setup used in all the CMS module assembly centres was slightly different from the CERN pilot project, which was originally designed for TOB module assembly. The differences concern in particular those parts related to the specific geometries of the modules needed to populate each sub-detector.

The main difference was in the assembly platforms, which were custom built for each module geometry or group of similar geometries. In addition, the locations of the vacuum chucks mounted in the base plate were modified with respect to the original pilot project, so that one single base plate would accommodate different module geometries. In Figure 9 a picture of this base platform, fabricated in the Bari mechanical workshop for all the assembly centres of the CMS Tracker collaboration, is shown. The base platform was designed to house all the different assembly platforms needed to assemble modules of ten different geometries. It should be noted that it was possible to use a single base plate, with its vacuum chucks in fixed positions, regardless of the particular type of module to be assembled, because the position of each chuck in the modified design was carefully chosen so as to be compatible with all the needed assembly platforms. Each assembly platform, shown in Figures 10 and 11, featured a common bottom side made out of a 25 mm thick aluminium slab and an upper part composed of a 15 mm thick Teflon plate. The entrance vacuum valves were located on the bottom side and perfectly overlapped with the vacuum chucks of the base plate. From these valves, a network of narrow channels drilled through the aluminium bottom side of each assembly platform conveyed the vacuum to grids of holes in the Teflon layer. Each grid occupied an area corresponding to the different modules of a specific geometry (or group of similar geometries). Further example of assembly platform with TIB modules after assembly is shown in Figure 14.

   A dedicated platform ("supply plate") was designed to use the vacuum to hold the sensors steady before their placement into the module being assembled (see Figure 12). On this platform, in addition to the vacuum holes,
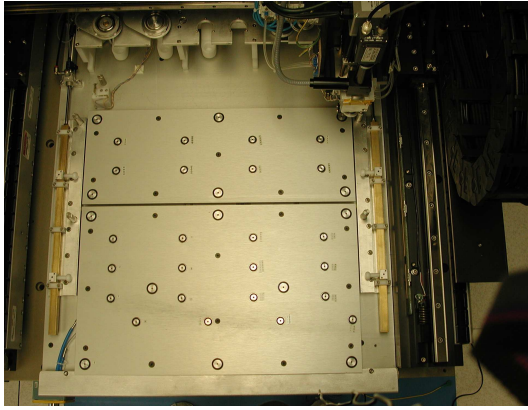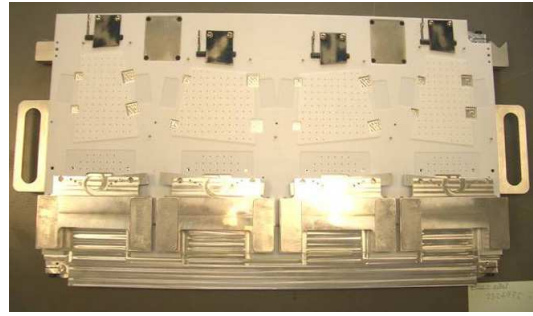
Figure 9: Base Platform with vacuum chucks

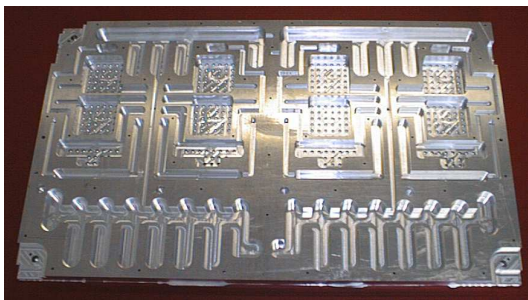Figure 10: Upper side of an assembly plate
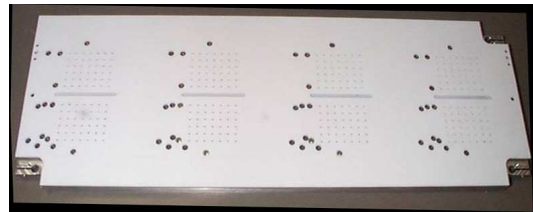

Figure 11: Inner structure of an assembly plate

Figure 12: Supply plate

there was a set of larger holes in which positioning pins were inserted as part of a process to correct the rotation angle of the sensors as much as possible prior to their transfer to the assembly plate. Figure 13 shows the sensors fixed under the vacuum on the supply platform, the frames placed on the assembly platform and the hybrids under their pickup tool (described below), ready for the assembly of four TIB modules.

The entire set of supply and assembly platforms used to build all the TIB/TID module types were designed and produced in Perugia for both Italian gantry centres.

3.3 Vacuum system

In order to supply a vacuum to the vacuum chucks mounted on the assembly and supply platforms, a set of air pressure-driven Festo electro-valves [7] were fixed on a dedicated aluminium plate (see Figure 15). This was done in Catania and was common to all the Tracker gantry centres.

Together with the valves, a closed cylinder acted as a vacuum backup in case of vacuum failure near the valves. In addition, a bigger vacuum backup steel cylinder was connected at the input of the gantry vacuum line to prevent general long-term vacuum losses. The air-pressure valves were also mounted on the same platform in order to supply air-pressure to the pistons for the movement of the tool rack and the assembly plates' blocking bars (see also Figure 9).

3.4 Pickup tools

Two different tools were designed and realized in order to pick up sensors of the two different basic shapes: a rectangular tool for the TIB modules and a circular tool to fit the wedge-shaped TID sensors (see Figures 17 and 18). The two tools were modified with respect to the original design, especially for the larger dimensions of the pickup surface fabricated with a more elastic material (Teflon).
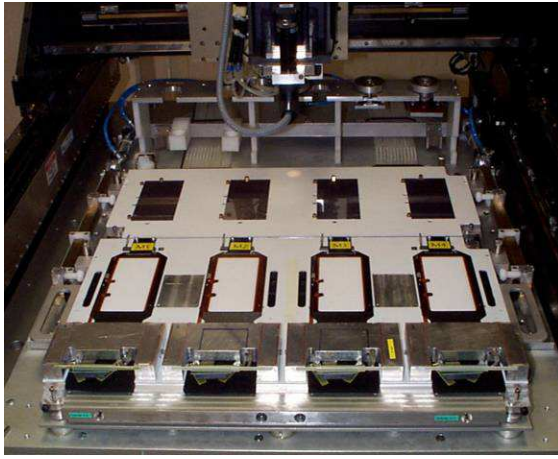
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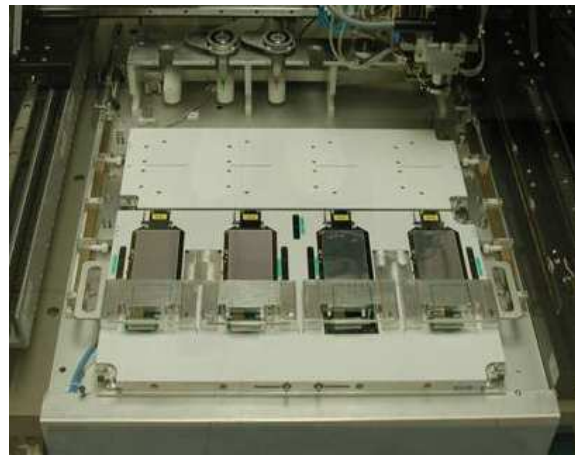Figure 13: Parts of modules on the platforms before assembly

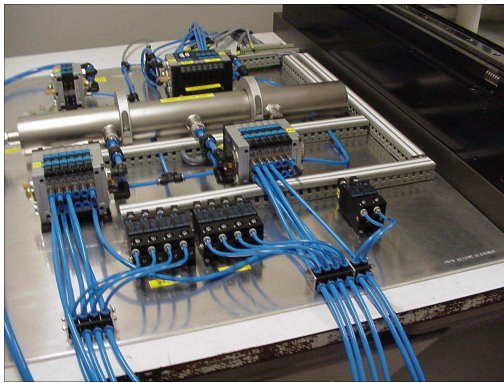Figure 14: Modules on the platforms after assembly
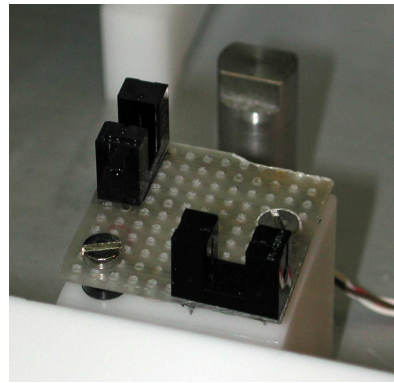

Figure 15: Vacuum distribution plate

Figure 16: Perpendicularity control of the syringe

A more involved tool (hybrid "bridge") was designed and produced in the Perugia mechanical workshop in order to more safely manipulate the electronic hybrid designed for the TIB sensor readout. Because of the overall dimensions of TIB modules which are smaller than TOB and TEC modules, the available free area was very small while the layout of the hybrid is quite dense, as can be seen in Figure 19, so the only way to touch the hybrid was by using little vacuum cups mounted on the bridge to act on the pitch adapter surface.

During the preparation of the gantry assembly platform, each hybrid was first fixed with a vacuum under its own bridge using a dedicated fixing plate connected to a special vacuum line (see Figure 20 on top side).

The operator then moved the bridge from the fixing plate by hand, placing it with the hybrid attached to it in the desired location on the assembly platform. The vacuum "stored" in the bridge body was sufficient to hold the hybrid for several seconds during its movement. After that, each bridge remained fixed with the vacuum supplied by the vacuum chucks connected to the assembly platform (see again Figure 13) and waiting for the assembly operations. Then, the entire body of the bridge acted as a vacuum reservoir able to temporarily supply a vacuum to the vacuum cups in order to hold the hybrid securely while the bridge was in turn held with a vacuum by a hybrid-bridge pickup tool, shown in Figure 21, during the robot movements of the assembly run.

A specific tool was designed and produced to pick up the syringe used to dispense glue (Figure 22). Similar to the other pickup tools, it was stored on the tool rack before the assembly, picked up by the robot with a dedicated vacuum line and instrumented with an air pressure line coming from the glue box (Figure. 23). This box contained a programmable valve to gate the air pressure with a programmable value of pressure depending on the type of glue to be used and also provided a vacuum from a Venturi effect, here used to avoid the loss of glue droplets after dispensing. The setting of the value of the air-pressure was done with three channels of the gantry I/O box directly
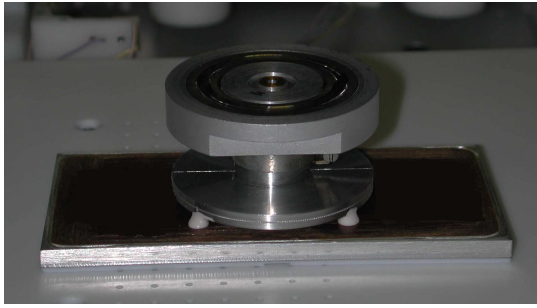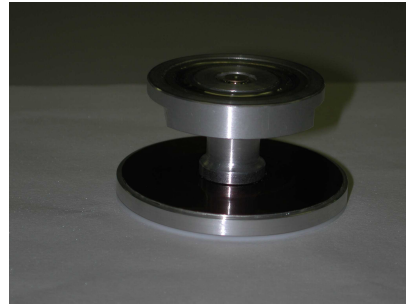
Figure 17: Pickup tool for rectangular sensors

Figure 18: Pickup tool for wedge shaped sensors

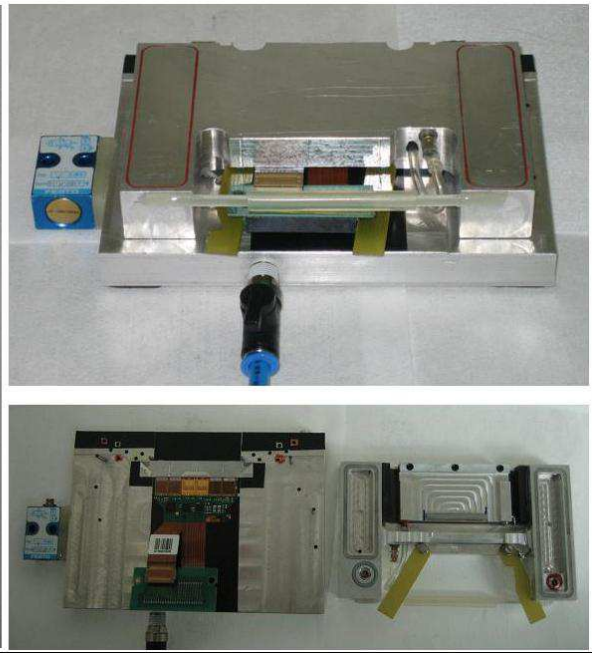Figure 19: Hybrid for TIB r-ϕ module

Figure 20: Hybrid tools and the positioning plate

programmed from the PC.

In order to control the perpendicularity of the needle axis with respect to the gantry working plane, a custom tool was designed and realized in Bari, using two optical switches (see Figure 16) that gave a signal when the syringe needle passed through. In such a way it was easy to identify the coordinates of the needle tip and then verify the position of the syringe axis computed in the Gantry space coordinates.

With this control the precision of the glue dispensing path was better than 0.5 mm on X and Y gantry coordinates.

3.5 Glue curing station

After a full assembly run, the assembly platform, using two-way valves, was connected to a dedicated vacuum line, removed from the gantry and placed on a curing station for the overnight glue curing.

The curing station is shown in Figure 24, ready to support 4 assembly platforms and equipped with 4 vacuostats for visual control of the vacuum status of each assembly platform during the glue curing.

Figure 21: Hybrid bridge pickup tool
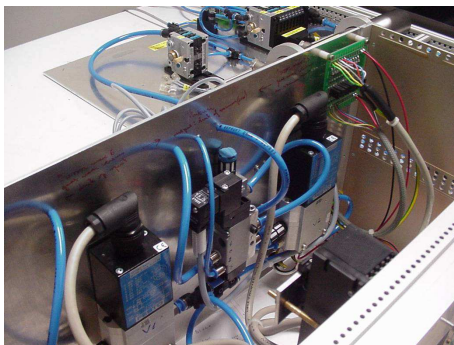

Figure 22: Syringe pickup tool

Figure 23: Inside the glue box

Figure 24: Glue curing station

3.6 Pattern recognition system

In order to both speed up the assembly job and maintain a consistently high placement precision, the identification and placement of the components and carbon fibre frames was done by using video images from the CCD camera (Figure 25).

The digitized images were sent to a pattern recognition code, done by the IMAQ Vision system for Labview [10], running on the PC and interacting with the Aerotech interface program. For this reason all the operations involved in the pickup and placement of the module components used the pattern recognition to evaluate the coordinate of the centre of the fiducial marks (see Figure 26). Fiducial marks were located on each module component to be assembled and used in the proper way by the assembly MMI code.

3.7 Gantry absolute calibration

To achieve the required module quality assurance accuracy goal of $10\mu m$, it was important to have the X and Y gantry axes well calibrated. This absolute accuracy could only be achieved by means of a software correction of the positioning machine by a 2D calibration of the X and Y axes.

A direct measurement of the absolute accuracy for a limited number of locations in X and Y using a laser interferometer was done by Aerotech at the factory and was provided with the machine, but in this context a full working
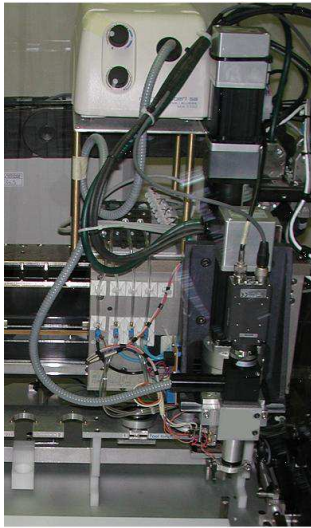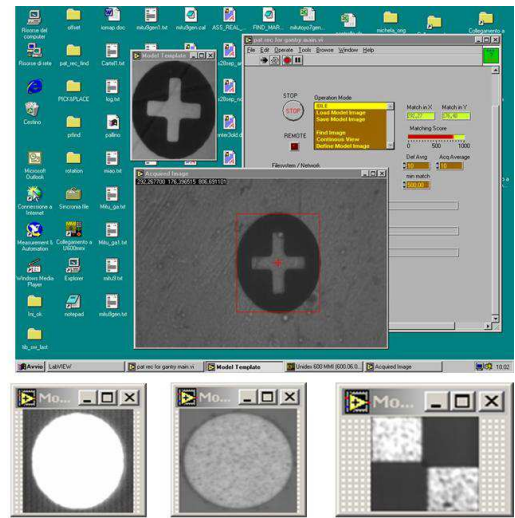
Figure 25: CCD camera with light system

Figure 26: (top) Visualization of the Pattern Recognition code, (bottom) Three different types of fiducial marks are shown: in the centre the sensor fiducial mark, at left and right, two different fiducial marks of the hybrid pitch adapter.

area of the robot was used and very large 2D corrections were discovered, especially at the ends of the Y axis travel. Furthermore the calibration could deteriorate due to several factors such as differences in the support of the base plate, temperature and changes in the machine cabling and loading with tools. For this reason adjustment of the calibration was performed periodically and also whenever an important modification of the setup occurred.

This was done using a dedicated "Mitutoyo" measuring machine (CMM) with the precision of 1 or 2 μm, available in both Italian assembly centres, using the following procedure.

The measurement was done using a borosilicate low thermal expansion coefficient square plate, 50 cm by 50 cm, with a thickness of 5 mm, realized by the Catania collaborators. On the plate, a photo mask film composed of 25 x 25 fiducial crosses spaced 20 mm each (see top of Figure 26) was glued with Araldite NY103/ 991. The thermal conductive properties of the borosilicate glass (CTE = 32.5 x 10^{-7} cm / cm / ^{o}C) were compatible with the needed precision, considering the linear dimensions of the plate (50 cm) and a variation of the temperature in the clean room which did not exceed 2 ^{o}C.

As a first step, the coordinates of the fiducial crosses on the glass calibration plate were measured with the CMM

Figure 27: Calibration plate under Mitutoyo CMM machine

Figure 28: Calibration plate on a Gantry

(see Figure 27) after a mechanical alignment of the plate and recorded on a file. The same crosses were measured with the gantry (see Figure 28) with no calibration file after a mechanical alignment of the plate. Following the Aerotech instructions, a 2D calibration file was made, combining the information from the two groups of coordinates. This calibration file was then downloaded by the gantry MMI software and the plate was measured once more.

In Figure 29, the differences $(X_{CMM} - X_{Gantry})$ and $(Y_{CMM} - Y_{Gantry})$ vs X_{Gantry} and Y_{Gantry} are shown, before and after the calibration correction. These results show that the gantry was rather imprecise without the
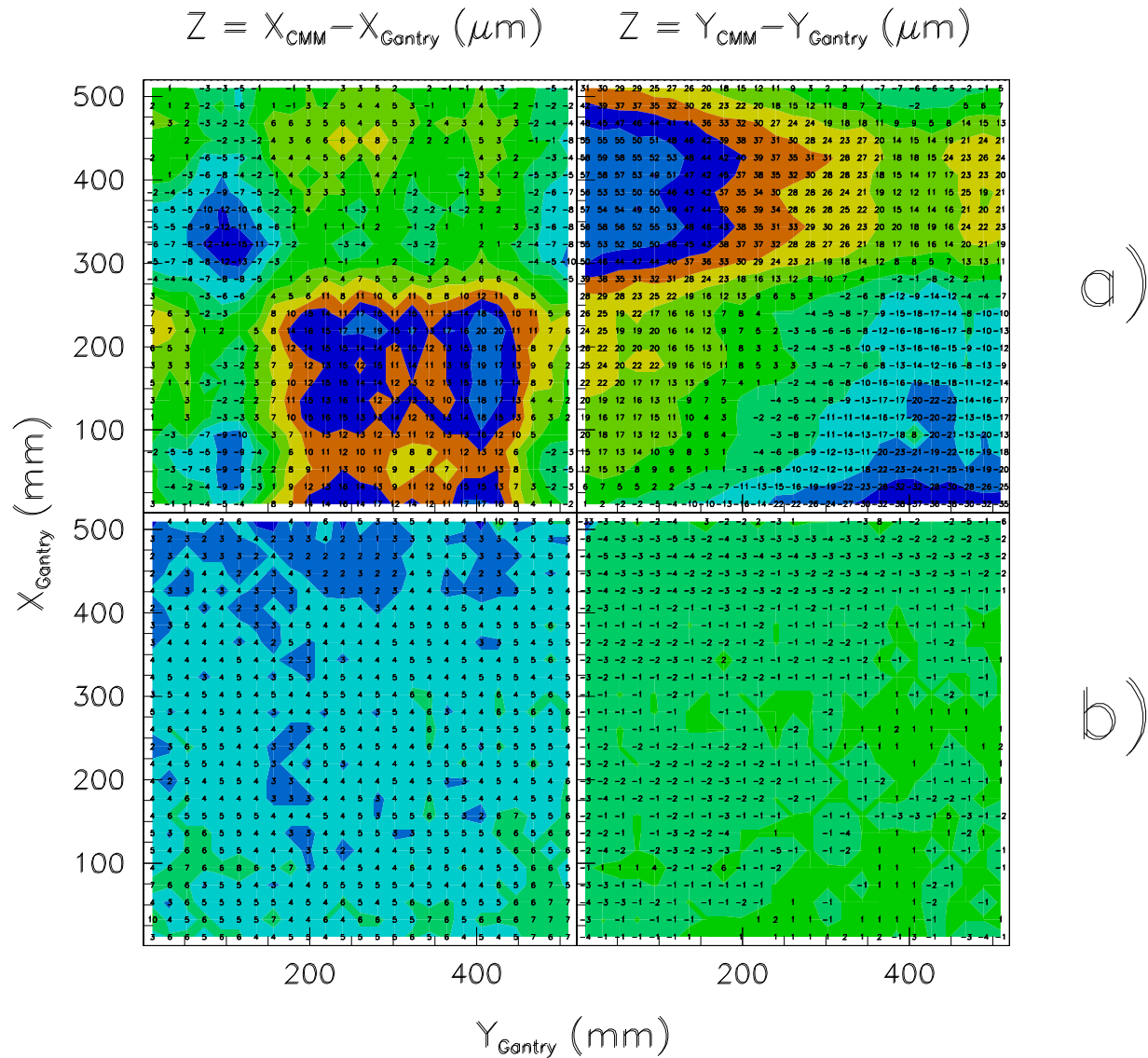

Figure 29: Bari gantry calibration map: a) before correction, b) after correction.

calibration correction, especially along the Y axis, where differences of 50 μm were found. After the corrections, differences smaller than 5-6 μm have been measured on both gantry axes at both production sites.

4   Gantry centre qualification procedures

A set of procedures was devised to perform an initial qualification of the gantry setup in each assembly centre, which consisted of some assembly rules to follow in order to produce modules with the same quality.

In the following sections, all the basic tests which were used to certify the gantry precision in the measurement of the fiducial mark coordinates are described and summarized in Table 2.

4.1 Manual positioning repeatability

This is a very simple first test that certified the error on the repeatability of a manual measurement of the coordinates of the same sensor fiducial marks with the joystick, repeated several times. The test started by holding a silicon sensor with the vacuum, then moving the camera away randomly from the silicon marker (e.g. 50-100 μm away) and measuring the position of the silicon marker with the joystick. After collecting the distribution of X and Y of the silicon marker, the width of the distribution was recorded.

4.2 Pattern recognition (PR) precision

In the production phase, in order to increase the precision and speed up the assembly job, the use of a pattern recognition system (PR) was needed to measure the fiducial mark coordinates.
When all the PR setup and calibration steps were completed, some very simple tests were devoted to certify the PR performance.
A first test certified the repeatability error of the measurement of the coordinates of the sensor fiducial marks with the PR. During this test the camera was placed 100 times in a fixed position with respect to the silicon marker (e.g. 50-100 μm away), and the PR routine was called to find the center of the fiducial mark. The distributions of the coordinates of X and Y (Gantry Coordinate System) were plotted, evaluating their widths. A second test certified the repeatability of the PR measurement, changing the starting point around the position of the target. This was done by placing the camera at the corners of a grid centred on a silicon fiducial mark 100 times (e.g. 100 μm x 100 μm in steps of 10 μm) and finding the centre of the model with PR. Then the distributions of X and Y of the found image (MMI coordinates) were plotted and their widths evaluated.

4.3 Pick-and-Place precision

During this test, a sensor was picked up and placed down 100 times and the distribution of the differences in the fiducial marks coordinates from one step to the next one were plotted, evaluating their mean values and widths.

Table 2: Precisions for Center qualification.

TEST	Bari Gantry		Perugia Gantry	
	$\sigma_X(\mu$m$)$	$\sigma_Y(\mu$m$)$	$\sigma_X(\mu$m$)$	$\sigma_Y(\mu$m$)$
MANUAL POSITION REPEATABILITY	0.9	1.1	0.5	0.9
PR INTRINSIC REPEATABILITY	0.05	0.06	0.5	0.5
PR GLOBAL REPEATABILITY	1.2	1.6	0.5	0.5
PICK AND PLACE	1.04	1.28	1.2	1.4
CORRECTION FOR ROTATIONS	SINUSOIDAL SMALL	BEHAVIOUR CORRECTIONS	SINUSOIDAL SMALL	BEHAVIOUR CORRECTIONS

4.4 Corrections on the rotations

During this test, a sensor was picked up, rotated and placed several times in order to certify the whole gantry rotation operation errors. To perform this test, the suggestions of the Lyon group that strongly contributed to the uncovering of the θ motor anomaly were followed.
A sensor was fixed with a vacuum on the gantry assembly plate, and the coordinates of two fiducial marks, A and B, were measured to define the initial angle θ_{init} with respect to the Y axis. Then the pick-up tool was moved to the center of the sensor and lifted and a (small) θ_{rot} rotation was performed before replacing it on the plate. Finally, the new coordinates of A and B were measured to obtain the θ_{final} final. The corresponding error on the rotation was:

$$\delta\theta_{rot} = \theta_{final} - (\theta_{init} + \theta_{rot})$$

This procedure was repeated several times, starting from the actual position of the sensor, with different θ_{rot} ranging from -5 to 5 mdeg and at the end a correlation plot $\delta\theta_{rot}$ vs θ_{rot} was collected. After the measurements the following correlation was found :
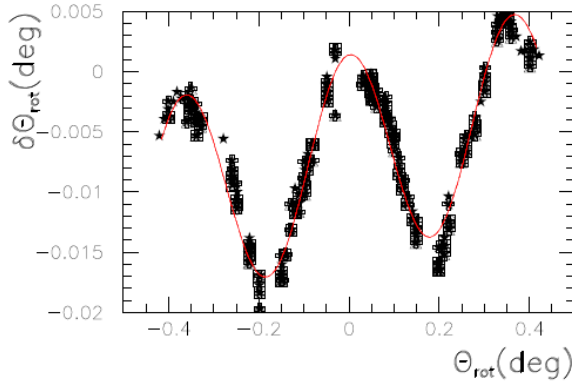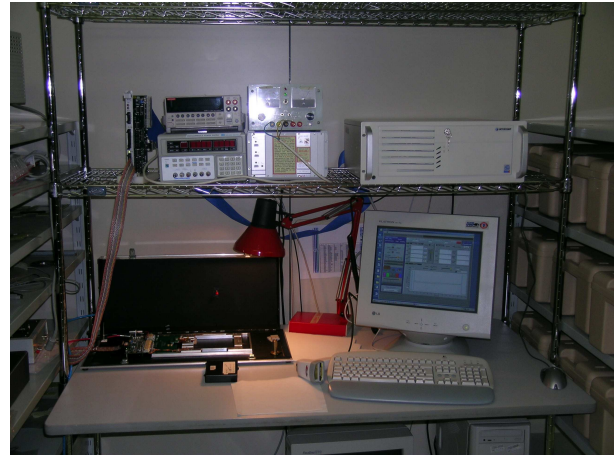
Figure 30: Correction on rotation

Figure 31: Hybrid fast test

$f(\theta_{rot})$ = a + b θ_{rot} + c cos (θ_{rot}) (See Figure 30).

Thus the effective θ_{rot}^{eff} rotation required for the desired θ_{rot} rotation, was:

$\theta_{rot}^{eff} = \theta_{rot}$ - $f(\theta_{rot})$

The observed sinusoidal behaviour was strongly suppressed after the insertion of the custom gear box mentioned in section 3.1; measurements performed following the method here described gave $\delta\theta_{rot}$ values which did not exceed 3 mdeg.

5 Gantry centre assembly procedures

In the present section, the complete set of procedures followed during the module assembly in the TIB/TID Gantry centres, to ensure uniform procedures and assembly quality, is described.

5.1 Reception and registration

The first operation consisted of receiving the boxes containing the components (frames, hybrids, sensors) and scanning their barcodes to register the reception of the components in the construction database.

5.2 Handling rules for components

Carbon fibre frames were, if possible, picked up only by the edges using gloves for handling. The hybrids were touched only on cable or ceramic edges if possible, using gloves for handling and anti electrostatic discharge (ESD) wrist straps and exercising extreme care in order to avoid damaging components or wire bonds and touching the pitch adapter edges and corners. The sensors were almost always manipulated at their edges by ESD vacuum tools with soft suction cups. In rare cases they were handled wearing gloves. The storing occurred in sealed containers except when inspecting or preparing sensors for assembly.

5.3 Storage rules

All components (frames, hybrids and sensors) were stored in the clean room (class 1000) in a dry (RH less than 50%) environment with a constant temperature of about 23 ^oC; furthermore, hybrids and sensors were kept inside ESD safe dedicated boxes.

5.4 Visual inspection of components

During this inspection, a check for damage of frame structure, inserts, components, cable and connectors was done, together with a check of the cleanliness of surfaces to be glued (cleaned with isopropanol only if surface contamination was suspected) and a check for proper flatness and correct glue contact on the kapton.

The hybrids were inspected for cable, connector, ceramic and pitch adapter damage. If any damage was found, a further inspection under a stereo microscope was done. The surfaces to be glued and the pitch adapter, if a lack of cleanliness was apparent and surface contamination was suspected, were cleaned with isopropanol alcohol.

The sensors were inspected under a microscope and cleaned with isopropanol alcohol if necessary. The sensors with observed damage were set aside and not used for assembly and a note was put into the database to that effect.

5.5 Pre-assembly hybrid fast test

After reception and an optical inspection, an automated fast test using the ARC system [12] (see Figure 31), which checked the basic functionality of all the ICs on the hybrid (APV, DCU, MUX, and PLL), was done and the results were stored in a local file.

After the fast test, a series of more detailed tests were performed to study the behaviour of the pedestals, noise, common mode and pulse shape of the APVs composing the hybrid, operating in deconvolution mode or peak mode, both with the inverter on and off. After assembly, the same tests were performed for each of the first 100 assembled modules.

As the results indicated that assembly by the gantry did not cause large modifications of the hybrid performance, after the first 100 modules, the tests were done on a sample basis that is on one assembled module out of nine, which was the contents of one transport box.

The incoming hybrids were classified in this way:

Grade A if the hybrid had less than 1% bad channels
Grade B if the hybrid had between 1% and 2% bad channels
Faulty if the hybrid had more than 2% bad channels

If the results differed from the similar test performed prior to shipping the hybrid to the assembly center, thus indicating possible damage, the hybrid was visually inspected. Bad hybrids were set aside for return to the hybrid bonding and testing centre for repair.

5.6 Operator actions during assembly

5.6.1 Preparation of the assembly plates

The first operation consisted of mounting an empty assembly plate and supply plate on the gantry base plate and inspecting them, cleaning as necessary the critical surfaces on those plates (vacuum chuck surfaces) with iso-propanol. Then the sensors were fixed on the supply plate by the operator, who manually manoeuvred a dedicated tool (see Figure 32) until the sensor butted against the positioning pins mentioned at the end of section 3.2. The operator then verified the association of the sensor ID and module position.

The frames were fixed on the assembly platform, taking care not to damage the positioning pins. The operator verified the association of the frame ID with the module position. The hybrid pickup bridges were placed above each hybrid using the positioning plate and the hybrids were installed on the assembly platform as described in section 3.4, taking extreme care in handling the hybrid because there were already wire bonds between the hybrid and the PA and also because the PA was very fragile.

A piece of tape was placed on the assembly plate to be used during the glue test before the glue dispensing.

5.6.2 Glue mixing and syringe filling

During the module assembly, the Dow Corning 3140 silicone glue [8] was used to fix the sensor on the kapton already glued to the carbon fibre frame whereas the General Electric RTV12 two-component epoxy glue was used to fix the hybrid. The choice of the two glues was made with respect to radiation hardness and elasticity, in order to prevent damage of the sensor due to mechanical stress of the module during its operation. The RTV12 glue was a two-component silicon glue, made of a RTV12A base compound and a RTV12C curing agent [9]. The glue was mixed on a flat glass vessel and put on a precision scale (1 mg) to measure the weight of the two components. Two pipettes, 0.2 cc and 2 cc, respectively, were used to get the required quantity of the components from their
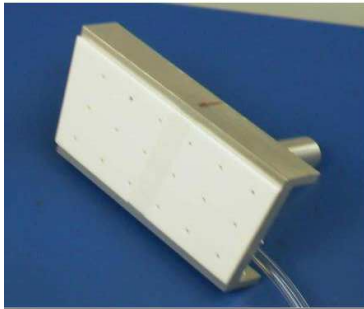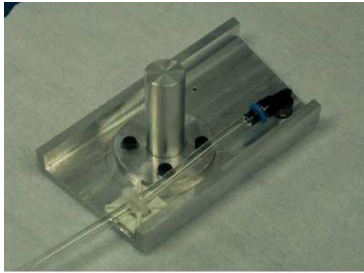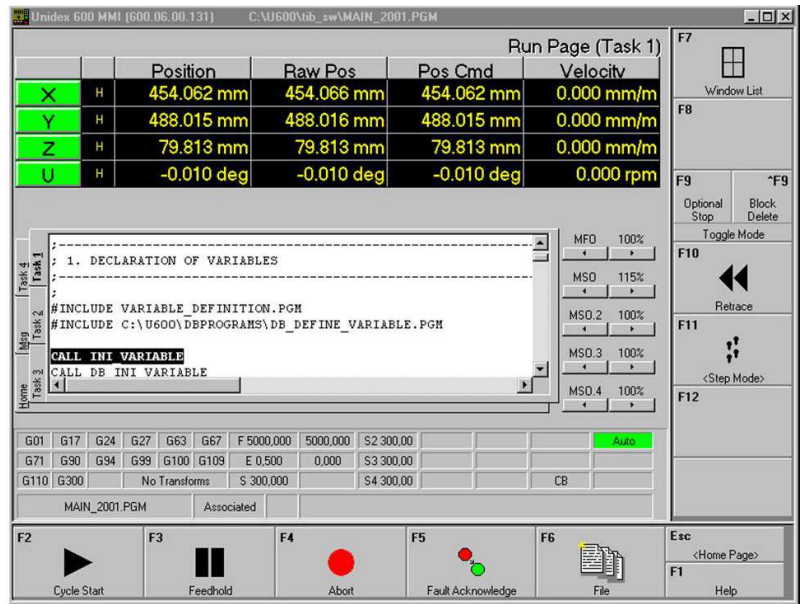
Figure 32: Sensor tool   Figure 33: MMI user interface panel

larger containers. Approximately 3 grams of RTV12 glue was needed to glue four hybrids (one full assembly plate job). The RTV12A base compound was mixed with the RTV12C curing agent in a 20:1 ratio. The two components were mixed very slowly with a small flat tool, in order to avoid air bubbles in the mixture. Due to the low viscosity, the RTV glue line tended to be too thin (few tens of microns); this could be corrected by the addition of a filler, as a mechanical spacer between the surfaces. Suitable filler was a very low percentage (1%) of non-abrasive glass bubbles 3M Scotchlite type K37 [11] which was graded to have a maximum of 85 microns of particle size. The glass bubbles were then added and mixed together with the RTV12 glue, using a mask to avoid inhalation. A vessel containing the mixture was then put in a dryer for 5 minutes under a vacuum where the air bubbles introduced during the mixing flushed out rapidly. A syringe was filled with the mixture to about half of its capacity. To remove the air again after filling, the syringe was put in the dryer for an additional 5 minutes. After removing the air, the mixture remained usable for about one hour, which was long enough to cover the full assembly time for one assembly plate. After all these mixing operations, the syringe was put into the syringe tool and placed on the tool rack, ready to be used. A quantity of DC 3140 glue was drawn directly from the tube to fill a syringe to about 4 cc, then put in the syringe tool and placed on the tool rack.

5.6.3 Equipment initialization

First of all the PC was switched on together with the DR500 drive chassis of the gantry machine and the I/O box. Then the emergency stop micro-switches were tested manually, and the camera light and the line generator were switched on. Afterwards the gantry module assembly program was started using the MMI user interface (see Figure 33) . The vacuum valves were reset and the number of modules was entered by the operator. The program opened the vacuum valves for sensors, frames and hybrids of the modules to be assembled.

5.6.4 Assembly platform position check

Using the joystick to move the camera, the operator found the marker position on the assembly platform. If the coordinates of the fiducial marks were as expected (within 5 μm), then the nominal position of frame pins with respect to the assembly platform, previously measured, were used. Otherwise, the pin positions were measured and the centre was computed by using 3 points of a circle.

5.6.5 Sensors and hybrids position check

Using the pattern recognition code, the marker positions on sensors were found and the rotation angle with respect to the carbon fibre frame was computed. Then the coordinates of the center of the sensors were computed by the

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MMI code. The marker positions on the hybrids were found in the same way as the sensors and their rotation angle with respect to the carbon fiber frame was then computed. With these acquired data, the pickup position of the hybrids was then evaluated. At this time, the sensor syringe tool with the glue was put on the tool rack.

5.6.6 Glue dispensing on Kapton of the frame

The robot picked up the silicon syringe tool from the tool rack and tested the perpendicularity of the syringe needle with the dedicated tool already described in section 3.4. Before dispensing the glue, a test was performed by the robot, consisting of going to a coloured adhesive tape attached to the assembly platform and dispensing glue in a line with the appropriate speed according to the glue type. This operation repeated automatically until operator acknowledgement. Then the glue was dispensed on the carbon fibre frame and on the thermistor pad following the pattern shown in Figures 34 and 35.

5.6.7 Sensors pick up and placement

After dispensing the glue, the robot picked up the sensor tool and moved to the evaluated sensor centre. Then it stepped down with a step of 100 microns until the contact switch gave a signal. Next the vacuum line was opened on the tool head to pick up the sensor and closed on the supply platform where the sensor was fixed. After that, the robot raised the sensor at a certain height, rotated it according to the previously computed angle and moved it to the sensor center position on the assembly plate where the frame was fixed. Finally the sensor was lowered in small steps until the micro-switch activated.

An alternative way, used primarily in the Bari centre before the installation of the harmonic drive that enhanced the precision of the rotations, mentioned in section 3.1 , was the pre-alignment of the sensor on the supply platform, before moving it to the assembly platform. To do that, the sensor was picked up, rotated and placed many times automatically, until the angle computed after the measure of the coordinates of the fiducial marks with respect the Y axis in the module reference frame was less than 3 mdeg. Experience showed that multiple rotations of very small angles were affected by an error smaller than that associated with a single rotation by a larger angle.

The results obtained with this method were comparable with those obtained using the custom gear box (mentioned above), but the assembly time was longer.

In the case of the stereo modules, to avoid the initial large rotation of 100 mrad, the sensors were initially fixed on the supply plate with an angle as close as possible to the desired value, with respect to the Y axis in the module reference frame.

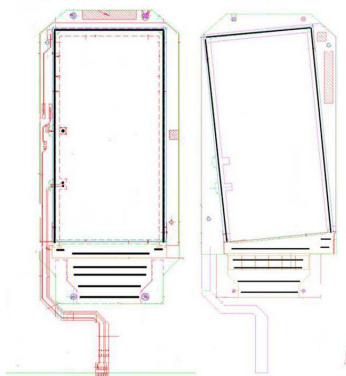### 5.6.8 Glue dispensing and hybrid movement

Figure 34: Glue pattern for TIB modules

Figure 35: Glue pattern for TID modules

Before moving the hybrids, the coordinates of the two sensor fiducial marks nearest to the electronic side of the module where the placement of the hybrid was planned were measured with the pattern recognition routine and the parameters of the line were computed. The same procedure was used for the coordinates of the fiducial marks of the hybrid pitch adapter placed on the assembly plate. Then the angle between the two lines was computed by the program, in order to align the edge of the hybrid pitch adapter to the edge of the sensor. This ensured that the bonding pads of the sensor and the hybrid pitch adapter would be well aligned, thus facilitating the future bonding

operation.

After that, the RTV12 hybrid syringe glue was put on the tool rack and a glue test was performed as in the previous steps, but using a different coloured tape. Then the robot picked up the hybrid syringe tool and dispensed the glue on the frames. Finally the hybrids under their bridges (see section 3.3) were picked up and placed on the correct position following the same steps as used for the sensors.

5.7 Post-assembly procedures

5.7.1 Glue curing

At the end of all the assembly steps, the completed assembly platform had its vacuum switched to the external source and was put in the curing station as mentioned in section 3.5. After an overnight curing, the glue samples on the coloured tape were examined to test for proper curing. The glue joints on the module were examined both prior to removal of the modules from the platform (checking the top side) and after removal (checking the bottom side) and the correct thickness of sensor gluing was checked visually.

5.7.2 After curing module survey

After the end of the glue curing operations, the assembly plate was again placed under the assembly robot and held with a vacuum while the after-curing MMI program was run by the operator. During this run, the barcodes of the modules were scanned and the frame pin positions of all modules were measured by the pattern recognition system, thus allowing the survey of the sensor and hybrid marker positions after curing. These were written in the database and in text files on a local disk. On a sample basis, a plate was surveyed on a CMM machine to check the consistency of the acquired position data.

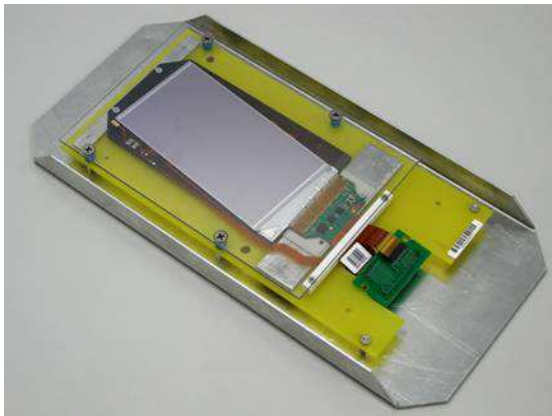### 5.7.3 Final operations and transportation

Figure 36: Module carrier

Figure 37: Transportation box

The assembled, cured and surveyed modules were removed from the assembly plate. A delicate operation was the placement of each single assembled module in a dedicated module carrier as shown in Figure 36.

Modules were mounted on NEMA G10 carrier plates for ease and safety of handling. Furthermore, this carrier, on which the module was secured by holding bars and screws, was sandwiched between an aluminium cradle on the bottom and a Plexiglas lid on the top, for transport and storing. The frames and the hybrids cables were fixed in the carrier using special screws and a Plexiglas cover lid was used to prevent any damage to the module during its manipulation.

Spacers (blue screw sheaths) ensured proper clearance between the lid and module parts. Similarly safe clearance was insured by pillars between the carrier and the aluminium cradle. Sufficient free space between both the aluminium cradle or Plexiglas cover lid and the module carrier and upward-folded sides of the aluminium cradle ensured that the modules were physically isolated during transport and ordinary handling.

A fast test of the hybrids similar to that already mentioned during pre-assembly operations was performed on a sample basis. After this last test, the shipment of the modules from the assembly to the bonding centres occurred

via commercial courier, using sturdy plastic boxes with internal Styrofoam cushioning on all sides (Figure 37). Each box could accommodate up to nine modules. These, sitting on their aluminium cradles with cover lids on, were kept from moving during transport by snugly inserting the cradle ends into slots carved in the Styrofoam cushioning of the box interior. For added safety during transport, the plastic box was sealed in a polyethylene sack to keep moisture out and was in turn enclosed in a larger box with additional soft padding on all sides.

5.8 Database operations

In the module assembly organization of the CMS Tracker, recording the characteristics of each produced module into an overall general Tracker Construction Database was required in order to have the information available during further operations such as quality control, assembly into the structure, Tracker alignment and so on. A gantry DB library was implemented to produce an output file for each assembled module containing all the information regarding the assembly phase in the format required by the Tracker DB. The comparison of the assembly parameters such as alignment angles or sensor and hybrid positions with certain input thresholds, was used to set a quality flag for each module after each action. The DB library allowed the assembly MMI program to communicate the information about the produced modules to the Tracker DB automatically via its output file (see Figure 38).
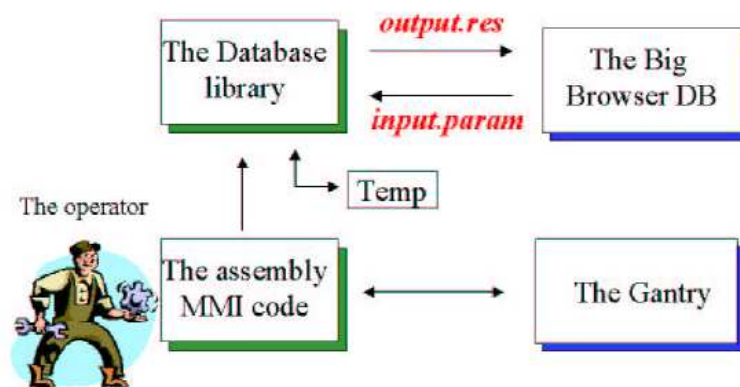

Figure 38: Gantry DB library

5.8.1 Database actions before the assembly job: DB library

Using the DB interface included in the assembly MMI code, the input database file with input parameters i.e. the maximum accepted value for the alignment angle, etc. was read. Some starting parameters (gantry ID, module type, etc.) were read from a local text file, whereas others (i.e. the barcode numbers of the modules to be assembled) were inserted by the operator. Temperature and humidity were automatically written by a digital thermometer in the output file together with the date and time taken from the PC clock.

5.8.2 Database actions after the assembly job

After sensor assembly, a validation flag for the assembling operation was automatically set. The flag was set to : 0 : if everything was okay otherwise the flag was : 1 : $flag_2$: $flag_3$: if something broke or the assembly failed. The flag codes were dependent on the module type.

For the sensors' assembling case, a flag for the hybrid assembling phase was set. The sensors' and hybrids' fiducial marks were then compared with the nominal marks read from an input database file. The alignment angles were computed from the actual fiducial marks and compared with the nominal angles. More details will be given in the section 6.1. A flag was automatically set after sensors' position check. If the measured values were within specifications, this flag was : 0 : . If outside specifications but the module could be accepted, this flag was : 0 : $flag_2$: , $flag_2$ being a positive number. If the module could not be accepted, this flag was : −3 : .

A flag was automatically set after the hybrid position check similar to the sensors' position check case.

All the data and flags thus generated were recorded into an output file, in XML format, which was then inserted into the construction database.

For each module cured, the program read the information from the temporary file, calculated the curing time,

asked for a comment on the visual inspection of the glue and recorded this information into an output file, in XML format, inserted into the general database.

6 Module assembly quality control

The implementation of all the controls made on the results of the glue curing, as described in the procedure section, assured the good quality of the modules, taking into account both the mechanical and geometric aspects directly connected to the precision of the placement of the sensor with respect to the precision pins located in the carbon fibre frame.

6.1 Module survey directly under the robot after assembly
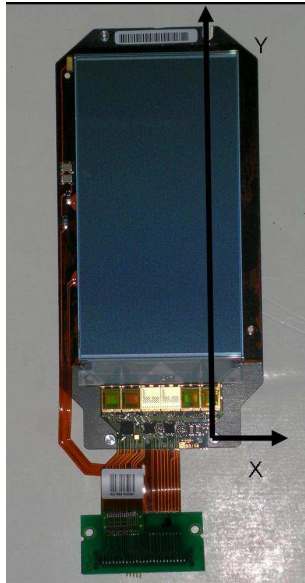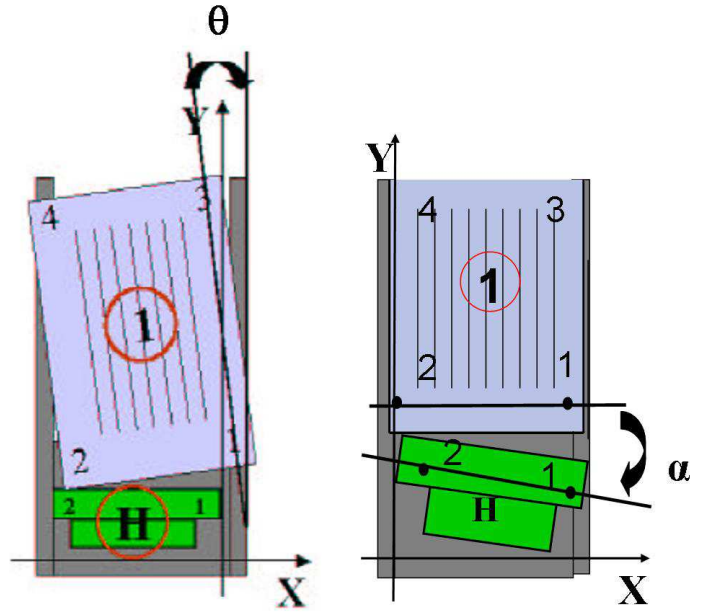

Figure 39: TIB module

Figure 40: TIB module schematic

Immediately after the assembly phase and before the glue curing, while still on the gantry, the position of the fiducial marks of the sensors in the frame coordinate system as shown in Figures 39 and 40, were measured with the help of the pattern recognition routine. Thus, for each module assembled, the coordinates of the four fiducial marks were written in the database together with their differences from the nominal values:

$\Delta x_i = x_i^{measured} - x_i^{nominal}$ (i = 1,4)
$\Delta y_i = y_i^{measured} - y_i^{nominal}$ (i = 1,4)

and along with the computed tilt angle θ for the r-ϕ modules and $\Delta\theta = \theta^{computed} - \theta^{nominal}$ for the stereo modules, in order to certify the position of the sensor with respect to the carbon fibre frame.
The same was done for the hybrids where the two fiducial marks were measured on the pitch adapter:

$\Delta x_i = x_i^{measured} - x_i^{nominal}$ (i = 1,2)
$\Delta y_i = y_i^{measured} - y_i^{nominal}$ (i = 1,2)

The module validation after assembly was done considering the alignment of the sensor with respect to the frame reference system, assigning a flag in the following way:
A flag (0) was assigned to those modules where the following condition was verified:

$|\Delta x_i| < 30\mu$m, and $|\Delta y_i| < 50\mu$m and $|\Delta\theta| < 10$ mdeg (**Class A**)

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A flag (1) was assigned to those modules where the following condition was verified:

$|\Delta x_i| < 39\mu$m, or $|\Delta y_i| < 65\mu$m or $|\Delta\theta| <$13 mdeg (**Class B**)

A negative flag (-3) was assigned to those modules where it was verified the condition:

$|\Delta x_i| > 39\mu$m, or $|\Delta y_i| > 65\mu$m or $|\Delta\theta| >$13 mdeg (**Faulty**)

Concerning the module validation, only the sensor positions were considered, while the quality of the placement of the hybrid on the module was assessed only to provide input information to the centre which would perform the next step of the module production that is bonding between the pitch adapter and the sensor bonding pads. A warning flag was written in the Tracker DB if the hybrid misalignment exceeded 200 μm or its tilt angle exceeded 200 mdeg.

At the end of the assembly period, the final distribution of module grade was 97% Class A , 2.6% Class B and 0.4% faulty modules. Both class A and B modules were considered suitable for mounting in the Tracker, with a preference for the class A modules in the innermost regions, where the highest precision is needed.

6.2 CMM sample survey of modules

Both Bari and Perugia assembly centres possessed a Mitutoyo CMM machine with the precision of about 3 μm. One out of each 100 modules was surveyed in the CMM machine in order to monitor the calibration of the robot. The differences in the measurements of the coordinates of fiducial marks of the modules did not exceed 10 μm.

6.3 Precision results on assembled modules

As mentioned in section 6.1, the mechanical precision of the modules was checked before and after glue curing by measuring the position of fiducial marks on sensors with respect to precision pins on the support frame.
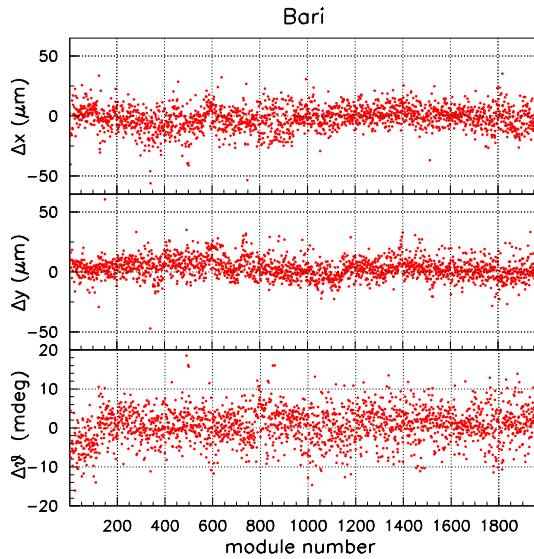

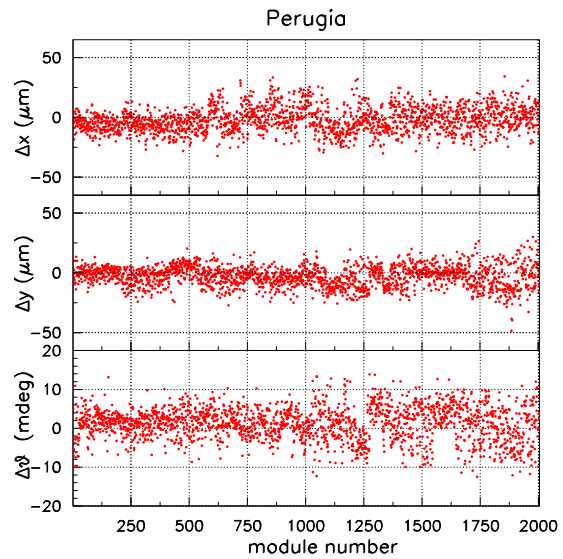Figure 41: Precisions in Bari vs. module number   Figure 42: Precisions in Perugia vs. module number

In Figures 41 and 42, the quantities Δx, Δy and $\Delta\theta$ of one of the fiducial marks vs. the assembled module number are shown for both Italian assembly centres.

In this representation it is possible to see the similar quality of the two assembly systems with respect to the precision and its time dependence, since the module number corresponds to its position in the fabrication sequence.

In Figures 43 and 44, the Δx and Δy distributions for the TIB and TID modules for all the statistics (3922 modules assembled) are shown. The blue arrows mark the Class A module acceptance limits while the black ones are related to the Class B limits.
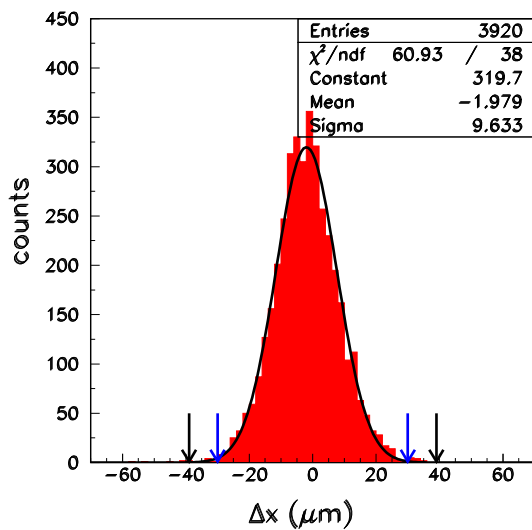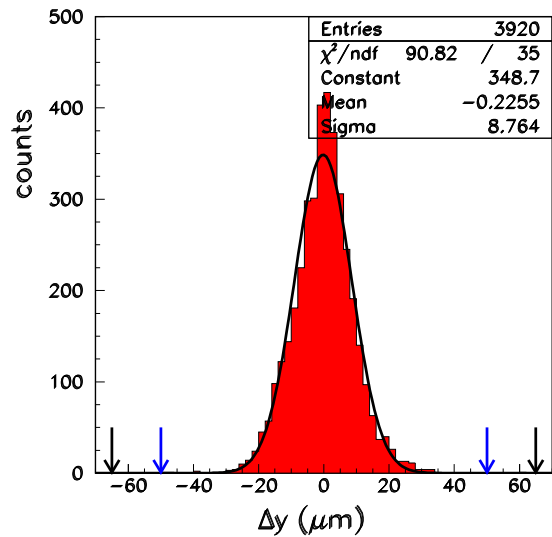
Figure 43: Precisions on X coordinate
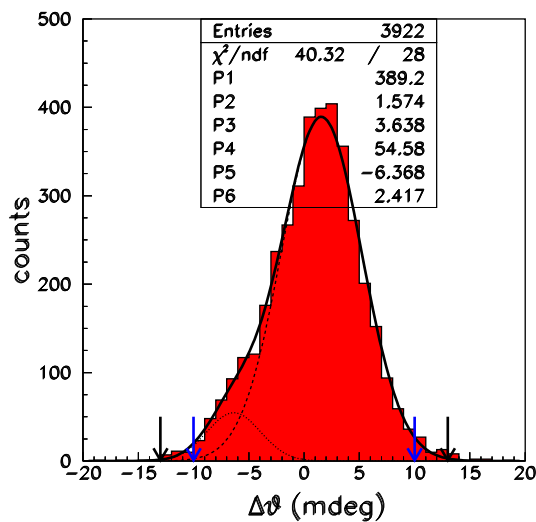

Figure 44: Precisions on Y coordinate

Figure 45: Precisions on angle

These distributions are well fitted by a Gaussian distribution function where:

$< \Delta x > = - 2.0$ μm, and $\sigma_{\Delta x} = 9.6$ μm
$< \Delta y > = - 0.2$ μm, and $\sigma_{\Delta y} = 8.8$ μm

Concerning the distribution of the tilting angles $\Delta\theta$, shown in Figure 45, the sum of two Gaussian distributions is needed to fit the data, where:

$< \Delta\theta >^1 = 1.6$ mdeg, and $\sigma_{\Delta\theta}{}^1 = 3.7$ mdeg
$< \Delta\theta >^2 = - 6.4$ mdeg, and $\sigma_{\Delta\theta}{}^2 = 2.4$ mdeg

In the same figure the arrows have the same meaning as the previous ones.
The distribution with the mean value around - 6 mdeg is due to the fact that sometimes there was a set of conditions related to a geometrical modification (a change of planarity of the assembly platforms or modifications in the support tools) that caused a shift in rotation. After a short delay to determine this issue, a correction was applied by the assembly code with an opposite shift. These modules, which were 8.5 % of the total number, were accepted

as they did not exceed the Class B module limits and thus were sent on to the bonding centres.

7 Timeline of the TIB/TID module assembly task

As observed in Figure 46, the production, which started in February 2004, suffered two long periods of interruption, essentially due to problems during hybrid construction.

A more continuous flow of hybrid (violet diamonds in figure) was established from January 2005 to February 2006. Nevertheless, as demonstrated in the previous section, this fact did not cause a dramatic change in the quality of the assembly job in terms of the precision achieved.

During the whole production period, a combined peak assembly rate of 21 modules/day and a mean assembly rate of 9 modules/day was achieved by the two Italian assembly centres.
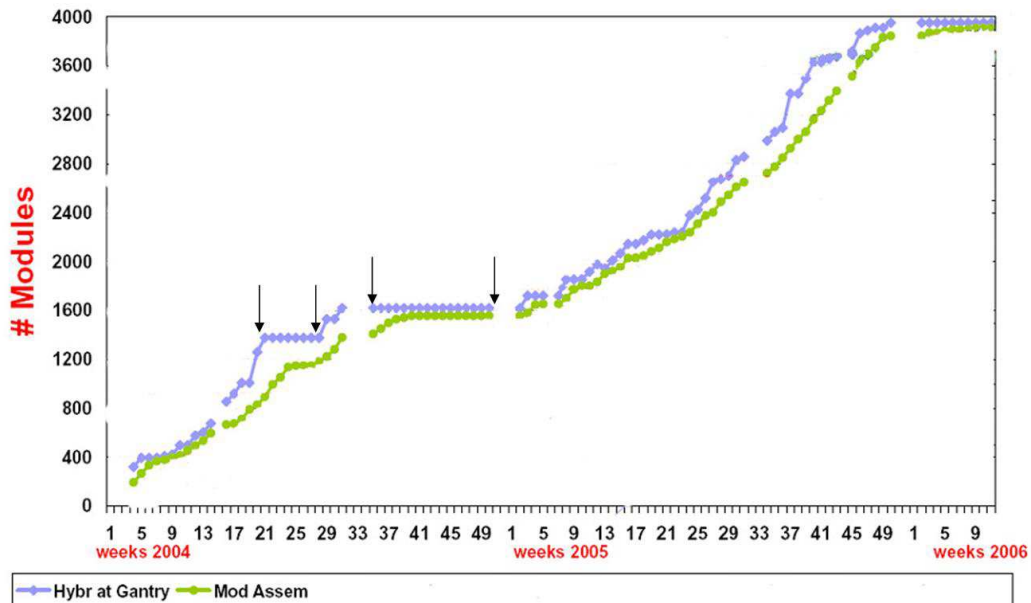

Figure 46: Module assembly timeline

8 Conclusions

In this note several aspects related to the robotic assembly of about 4000 TIB and TID modules have been described in detail.

Our experience demonstrates that it is possible to assemble a very large number of silicon strip detectors in a reasonable amount of time without compromising the required mechanical precision (10 μm). The robot was reliable. In fact neither system required servicing throughout the entire assembly process or mishandled module components. On the other hand, it took a significant effort to develop the robotic system. A set of well-defined procedures assured uniform quality of the assembly between the two Italian production sites and allowed for the completion of the project within schedule once the major problems related to the hybrids were solved.

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