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An Automated Silicon Module Assembly System for the CMS Silicon Tracker

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Abstract

The CMS Tracker requires the assembly of about 20000 silicon detector modules. To ensure the assembly of such a large quantity with high, reproducible quality, an automated system for module assembly has been developed based on a high-precision robotic positioning machine. This system allows a much higher throughput and will result in much reduced manpower requirements than for traditional manual techniques. This note describes the design and performance of the automated Silicon module assembly system which has been developed within the CERN CMS Silicon Tracker group.

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1 Introduction

Special explanation concerning this note: This note was completed in Sept. 2000 and it represents the completion of the pilot project phase of development of a robotic module assembly system whose goal was to prove the feasibility of such a system. It did not yet have tooling designed to produce the final design of the CMS silicon tracker modules which was still under development at the time. The next phase of the project was to produce the tooling and software for a production version of the system to be used for assembly of all CMS silicon tracker modules. This next phase of the project will be described in a separate note and journal submission.

An automated silicon module assembly system has been developed to ensure high throughput and high precision module construction for the CMS silicon tracker. The CMS silicon tracker requires the assembly of more than 20000 silicon detector modules. Details of the layout of the CMS silicon tracker can be found in [1].

Each silicon module consists of a carbon fibre support structure (frame) onto which the silicon sensors and the read-out hybrids will be glued. A photograph of a prototype silicon module is shown in Figure 1. The module assembly

Figure 1: *Photo of a prototype module showing the carbon fibre support structure onto which two silicon sensors and a read-out hybrid have been glued.*

to be performed by the automated system consists of the application of glue to the carbon fibre frame followed by pick and placement of the components (silicon sensors or read-out hybrid) onto the frame. The accuracy needed for component placement in a CMS silicon tracker module is as follows: silicon sensor to silicon sensor of $< 5\,\mu$m, sensor to frame of $< 10\,\mu$m, hybrid to frame of $< 20\,\mu$m.

The setup, shown schematically in Fig 2, is based on an Aerotech AGS 10000 gantry positioning system (shaded areas) which provides a large static working area, 4 separate coordinate (X, Y, Z, and ϕ rotation) positioning motors, and control hardware and software. The Aerotech system includes a dedicated processor running on an ISA slot PC card and a software interface program, called the Man Machine Interface (MMI), which resides on a standard PC. A component sensor platform, assembly platform and pick-up tools were designed at CERN using vacuum to hold the pieces to be assembled. In addition a glue dispensing system has been designed using air pressure to allow for automatic application of glues. The vacuum and air pressure valves are interfaced through a custom designed logic circuit which is under control of the robotic positioning machine. The identification and placement of the components and frames is done by means of video images from the CCD camera which are sent to a pattern recognition system that runs on the PC and interacts with the Aerotech interface program.

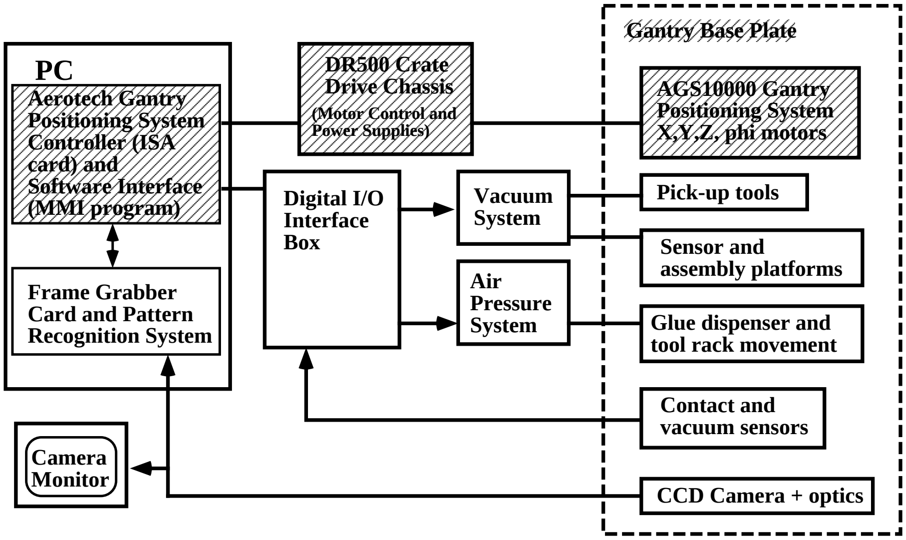

Figure 2: *A schematic overview of the automatic module assembly setup. Shaded parts show the purchased Aerotech gantry positioning system. All other parts of the setup were either purchased separately or were designed and constructed at CERN.*

Figure 3 shows an annotated photograph of the setup. The robotic positioning machine, *gantry*, is shown in the middle together with the PC (left) and the control electronics (right). A closeup view of the gantry setup showing two working platforms, an assembly and a sensor platform, in the front and the vacuum tool rack in the back can be seen in Figure 4. The coordinate system used for the setup is also shown in the figure. The X linear motors are located on the left and right side of the platform. The Y drive is a single linear motor located on the cross-beam near the back. The Z drive is equipped with a ϕ motor and a CCD camera to spot fiducial marks on the individual detector components. An additional camera is installed on the mechanical support structure of the Y linear motor to view the dispensing of glue.

With this particular setup, up to four silicon modules can be assembled at a time. This setup provides a placement accuracy of all components on the target carbon-fibre frame within 5 μm which equals or exceeds the specifications. The automated procedure of module assembly allows an assembly rate of approximately 100 modules/week.

The sequence of steps for the assembly procedure is shown in figure 5 with the operator actions and the automated gantry actions indicated separately. The gantry actions commence once the initialization of the hardware and software, preparation of the glues and placement of components on the platforms has been done. The first gantry actions involve finding and measuring the fiducial marks on the components. Glue is then dispensed on the carbon-fibre frames using specially developed glue-dispensing tools. The components are then placed in their final location on the carbon-fibre frame under the X-Y-Z-ϕ-control of the gantry system. The proper handling of the very delicate sensors during the pick and place operations is assured by means of flat teflon-coated vacuum pick-up tools with built-in pressure sensors that prevent any large forces from being applied to the sensor surfaces. Once the components are positioned, vacuum valves are enabled which secure the detectors and the frames into place on the vacuum chucks under each of those components. The platform containing the four assembled modules can be removed for glue curing and another platform brought in to start the assembly of the next four modules.

The note is organized as follows: A detailed description of the Aerotech gantry positioning system will be given in section 2. The mechanical setup which includes a description of the assembly and sensor platforms for the target silicon module and its individual components, a description of various vacuum tools together with a description of the glue dispensing system will be given in section 3. The vacuum system itself will be discussed in section 4. The control electronics which provides the interface between the control software of the robotic positioning machine and the auxiliary devices (vacuum valves, glue dispenser control, etc) will be described in section 5. A brief overview of the actual control software will be given in section 6. The optical equipment will be presented in section 7. The pattern recognition system will be discussed in section 8. The calibration procedure will be discussed in section 9. The performance of this automated module assembly procedure in terms of its placement accuracy and assembly rate capabilities will be presented in section 10. The gantry purchase order technical specifications, selected equipment parts lists, and some detailed schematics are contained in the appendices.

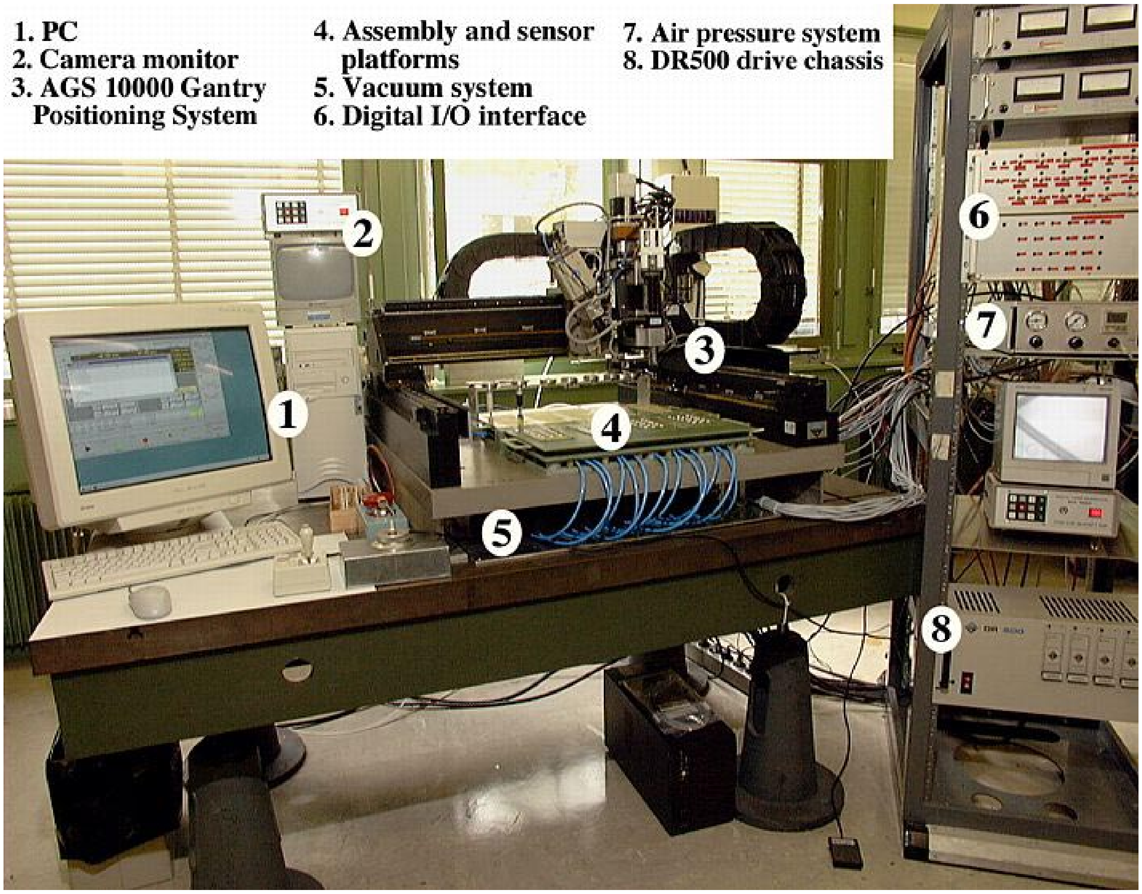

Figure 3: *View of the module assembly setup. The high-precision robotic positioning machine,* gantry*, is shown in the middle together with the PC (left) and the control electronics (right).*

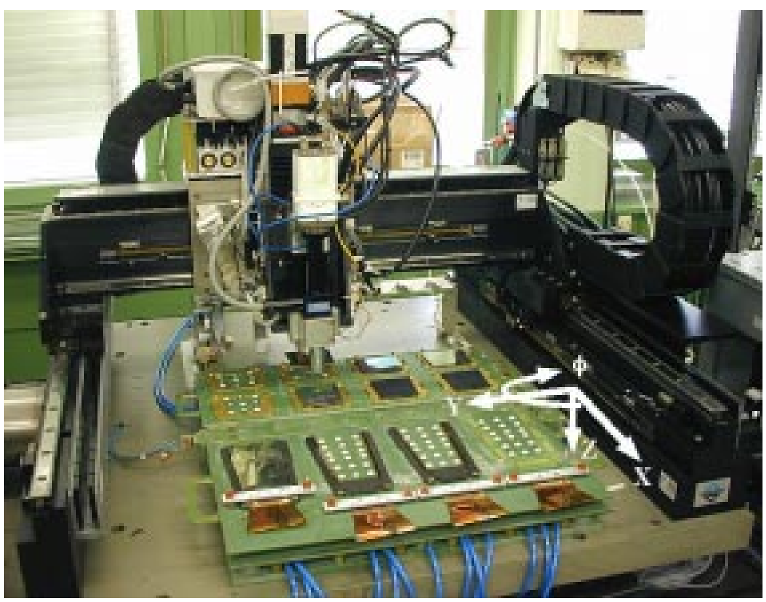

Figure 4: *Closeup view of the gantry setup showing the assembly and sensor platform in the front and the vacuum tool rack in the back. The coordinate system used in the gantry setup is shown in the bottom right corner.*

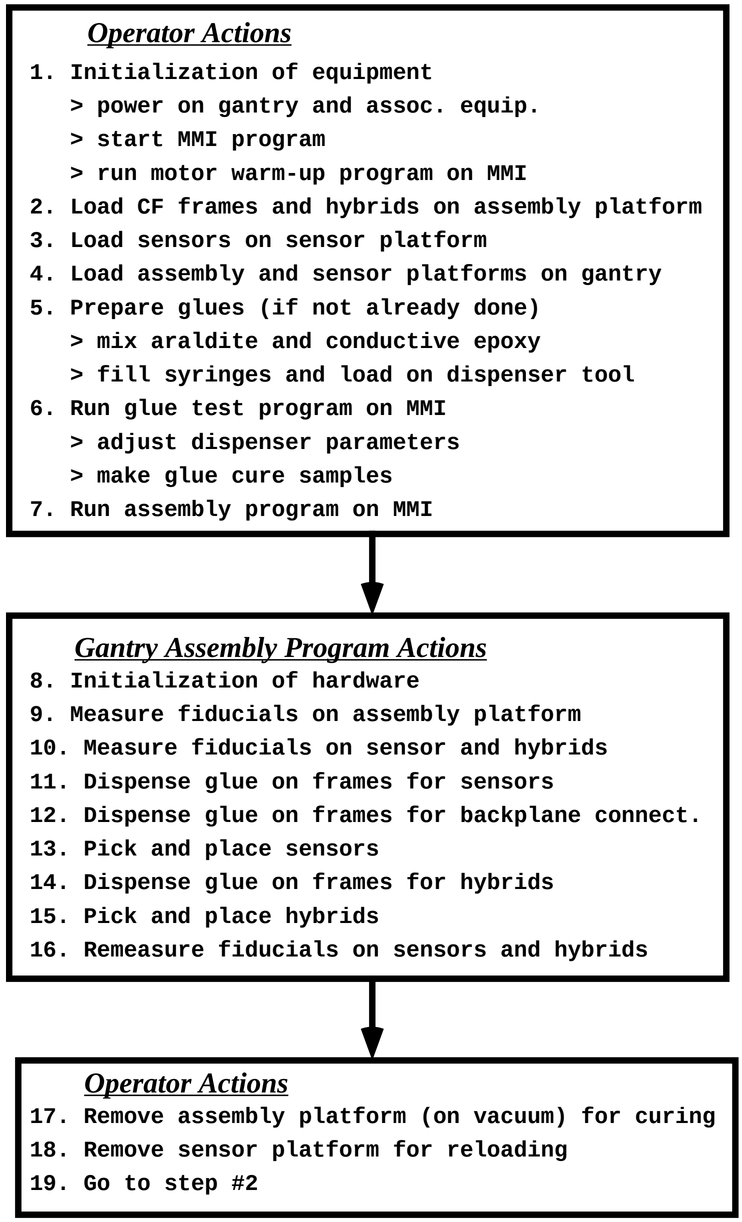

Figure 5: *Flow chart of principle assembly steps separated into those performed by the operator and those performed by the gantry module assembly program.*

2 Description of Aerotech Gantry Positioning System

The Aerotech Gantry Positioning System forms the basis of the robotic module assembly setup. This section describes the hardware and software of this system, focusing on the aspects that are used for the module assembly. Information concerning other aspects can be obtained from the system manuals or directly from Aerotech Inc. The specifications for the CERN system as written in the original purchase order is given in Appendix A and the parts list of the system as delivered is given in Appendix B.1.

2.1 Gantry Hardware

The AGS10000 Cartesian Gantry Positioning System is the product name of the gantry device manufactured by Aerotech, Inc. This system can be configured in a number of different ways depending on the purchasers needs. The CERN system has an active usable area under the gantry of 500 mm by 500 mm. The X and Y drives are linear motors with linear encoders which provide high speed, acceleration and accuracy. The Z and ϕ axis drives are options which were specified in the CERN system to give 100 mm movement in Z and 360 degree rotation in ϕ with reduced speed but high positional accuracy. The X axis drive in the CERN system is in fact two identical linear motor drives, each mounted on one of the two rails that form the basic footprint of the system. Two motors for the X axis is an option which was recommended in order to attain the high accuracy and reproducibility needed for our application. The Y axis drive is based on a single rail or beam that spans the two rails of the X axis. The ϕ axis drive is mounted on the Z axis drive which is, in turn mounted on the Y axis drive. The motor and rail system must be mounted on a base plate at the factory in order to ensure the specified accuracy. The type of base plate is also a purchaser option which in the CERN system was chosen to be a 5cm thick aluminium plate provided by the vendor. The cable plant of the system is well organized to allow for complete freedom of travel of all axes and can accommodate a fairly large number of user defined cables.

The motors, supports, base plate and local cable plant form the mechanical system. The other hardware elements are the motor amplifier and power supply crate, the PC card based motion controller and the cable system to connect these elements together. In addition, the CERN system contained the following optional hardware elements which were felt necessary or useful for the module assembly application: an expansion PC card with additional digital I/O channels, a joystick, and a handwheel. The motor amplifier and power supply (drive) crate is the DR500 drive chassis which is a modular system used for many different types of Aerotech positioning systems. The specific axis drive unit used must be matched to its motor. The drive chassis is a standard 19 inch rack-mount crate. The PC card motion controller is the U600 (also called the UNIDEX 600 in the Aerotech documentation) PC/AT Motion Controller which is a standard ISA bus card that contains a RISC processor and 32 MB of memory. The standard controller has digital I/O channels but not enough for our application so the optional expansion card was added. The expansion card is also a standard ISA bus card which implies that this system requires a PC with at least two free ISA slots. The PC was not supplied with the system. It should be noted that all the CNC-based motion control and processing is performed on the RISC processor of the U600 card, so the PC is not required for this function. It is used only to run the interface software which is described in the next subsection.

2.2 Gantry Software

The purchased Aerotech system includes interface software and program libraries. The interface software, called the MMI (Man-Machine Interface) runs under Windows NT on a PC and allows the user to directly control the gantry motors or to write programs that can be downloaded and executed on the U600 controller card. In addition to the MMI program, the Aerotech program library is needed as it contains the compiler and code base used to program and communicate with the controller card. The program library also contains the setup routines, motor tuning routines, and debugging routines.

The MMI contains an editor so the user can directly write programs. The MMI also allows compilation of programs (the programming language is particular to the Aerotech system but is similar to Fortran and C) which is done on the PC. There are also download and execute commands so the program can be immediately sent to the controller and run. In addition, the MMI interface allows direct motion commands to be sent to the motors. These are treated like single function programs by the MMI, e.g. the requested motion is just a compiled program which is downloaded and executed by the controller processor. In addition to this direct user control via the button driven (mouse click) visual interface, a simple set of commands can give motion control of axes to the joystick and/or handwheel for convenient direct manual control. Programs can be run in step mode with the MMI interface indicating which line is being executed in a program listing window. This allows easy debugging and understanding of program results. The program software allows communication with external hardware via analog and digital I/O channels. It can also read and write files on the PC file system as well as communicate with other programs running on the PC via the Windows DLL (dynamic link library) feature. These last features are needed for the integration of pattern recognition in the module assembly procedure.

In spite of the fact one has to learn a proprietary programming language in order to program the gantry system, the fact that it is very simple and similar to programming languages used in high energy physics and the fact that there is a very complete programming support environment allows for a very rapid learning curve. Basic motion control functions use an industry CNC (Computer Numerically Controlled) standard code syntax called RS-264 CNC. Learning the meaning of these codes and how they work is the large part of the task of mastering the programming language. A fairly complete and easily accessible help system is also available. More details can be found in section 6.

All motions are monitored on-line via displays showing the commanded and current drive axis positions. Interaction with the user from within a program is facilitated by use of pop-up windows and dialog boxes. These also can be used to display results and allow program flow changes.

The MMI also allows access to the large number of system parameters which are needed to define the initialization, operating conditions and limiting values of the machine. Parameter sets are stored as files on the PC and can be read and sometimes modified via the MMI. These parameter files are very critical to the correct and safe operation of the system. Examples of important system parameters include: maximum speed, acceleration and current limits for motors; motor feedback (tuning) parameters; software endstop position settings; enabling and disabling of position calibration; 'home' position definition and speed settings. Parameter files are discussed further in section 6.

2.3 Discussion of specifications and hardware capabilities

The specifications for the gantry hardware were determined by the requirements for silicon module assembly. In particular, the X, Y and ϕ positioning accuracies are critical parameters for achieving the required module component alignment. The goal to ensure that the two silicon sensors on a module are aligned with respect to each other to within $5\,\mu$m of their theoretical relative positions leads to the X, Y and ϕ specifications. In addition, the absolute positioning of each sensor with respect to the module frame positioning pins should be within $10\,\mu$m. Since relative alignment is most critical (one assume the absolute alignment errors can be calibrated using physics data), this implied that the reproducibility and relative accuracy was important. The gantry system has a reproducibility and relative accuracy (over a distance of a few centimeters) of nearly $1\,\mu$m although the absolute accuracy is much less good (tens of microns over the entire active area without calibration, on the order of $3-5\,\mu$m with calibration). The ϕ resolution and accuracy is also critical since sensors will have to be rotated at least slightly to align them correctly. The specifications are such that the X and Y position inaccuracy due to rotation will not be larger than that of the X and Y positioning. The gantry specifications should ensure that the mechanical positioning errors are much less than that required to meet the module alignment goals.

The specifications for the Z axis are much less critical since the height of the assembly platform and the thickness of the components will determine the module dimensions along that axis. The Z drive needs good stability and must hold position when not in use, which is the reason for the large gear reduction box (20:1). A lesser gear reduction would lead to movement of the Z drive under its own weight when not activated. The specifications for clearance allows for the possibility of moving all the required pickup and glue dispensing tools to travel over the active area. The specification for maximum travel was chosen to allow space for assembling 3-4 modules at once, while still preserving the required accuracy (a large active area would degrade the accuracy). The specifications for load capacity were chosen to allow the possibility for support structures, camera, and tooling that would have to be carried by the various axes. The specifications did not contain any speed or acceleration requirements due to our prior knowledge that the motors which would be used had maximum values much in excess of that needed for our application.

The gantry positioning system motors are always active, i.e. they are continuously maintaining position against the forces that are always present that try to move the axes (e.g. the cable plant or gravity). They are not turned off after a motion is made and there can be a small amount of vibration of the stage as the motor tries to maintain position. The motors can therefore be very sensitive to the load and forces acting on the stage because of this feedback mechanism. For this reason, the tuning of the motors is essential for proper operation of the machine. The tuning is normally done at the factory and again when the device is installed. However, if the load and active forces change which one expects due to the adding of equipment, the tuning will need to be redone. The user must be aware of this fact and must learn how to correctly use the provided tuning software.

2.4 Additional Gantry Control Hardware not provided by Aerotech

Essential to the operation of the gantry positioning system is a PC capable of running the WindowsNT operating system. In the CERN system, the PC was not purchased with the gantry system although the local (Swiss) distributor offered a PC as an option. The CERN system uses a CERN standard PC (Vobis 400MHz, Pentium II, 128MB memory, 6GB hard disk). This PC has 3 ISA slots and 3 PCI slots, more than the minimum required of 2 ISA slots for the gantry and 1 PCI slot for the frame grabber card (needed for pattern recognition). In addition to PC and monitor, the CERN system has a 1500VA MGE Pulsar uninterruptible power supply (UPS) which filters the mains and will provide battery backup power for a limited time in case of mains power failures. All electrical systems used in the robotic assembly system (vacuum and air pressure system, I/O electronics, PC, DR500 motor drive power and optical system) will use the UPS so that in case of power failure, the assembly in progress can be completed or safely interrupted.

3 Mechanics

The Aerotech gantry system needed to be equipped with a number of additional mechanical devices in order to assemble the silicon tracker modules. This section describes these devices, most of which were designed and constructed at CERN. The first device needed was a table on which to place the gantry system. Then a set of platforms were designed to be placed under the working area of the gantry which would hold the module components in place with vacuum. A vacuum system was chosen in order to assure a high level of precision in the assembly. This implied a working surface with a large number of vacuum chucks. There are 14 different types of tracker modules, each with a unique shape and dimensions. To avoid large numbers of vacuum connections and disconnections when changing module types, a vacuum distribution platform was designed to pass the vacuum to two removable platforms that would be tailored to the module type. The vacuum distribution platform is permanently fixed to the gantry base plate. One of the removable platforms holds the silicon sensors (sensor platform) and the other holds the carbon fibre frames and the read-out hybrids (assembly platform). In addition to these platforms, removable tools were needed to handle the components to be mounted and to dispense the glues. Finally a support system for the CCD camera which locates and measures the module components was needed.

3.1 Gantry Support Structure

As mentioned in the previous section, the gantry system comes mounted on a base plate. The user can provide a base plate or has a choice between an aluminium plate and a granite plate provided by Aerotech. For the CERN system we chose an Aerotech-provided aluminium base plate. The choice of aluminium was to facilitate the placement of tapped mounting holes that would be needed for fixing the various tooling (tool rack, platforms) to the base plate. The tapped holes were made by Aerotech following a pattern that we provided. Note that other tapped holes were made in the support brackets of the theta stage and in the mounting plate attached to the theta drive, according to our specifications, in order to provide support points for the cameras and for the pick-up tooling, respectively. The hole pattern should be obtainable from Aerotech by requesting the ”CERN gantry” hole pattern specifications.

There are no formal requirements for the table or object on which the gantry (+base plate) rests. The CERN system is currently placed on a four aluminium ”blocks” of approximate height 15 cm, which lie on a 1.5x1.5 m^2 high-mass thick iron table. The fourth block was shimmed to provide level support for all points. The use of these blocks allows the space under the base plate to be used to house the large number of electrovalves needed in the assembly system. This is not mandatory but if such a space is not made here, it will be needed elsewhere nearby. The CERN gantry was also tried on a vibration damped optical bench (has rubber-like damping pads) but this was found to be worse than on an undamped table because the large forces generated by the accelerations of the X and Y stages caused the whole table to vibrate. Since our aim was to minimize the vibration of the working platforms, it was found that a heavy solid table was better. It may be that if the floor of the room to contain the gantry is found to be subject to large vibrations (due to crane or heavy vehicle movements in the area), a vibration damped table may be useful nevertheless. It should be noted that if high accelerations are used for the X or Y drives, the gantry base plate may have to be securely fixed to the table to prevent shifting of the gantry plate with respect to the table. The use of high friction surfaces between the plate and the table may also prevent such shifting.

3.2 Vacuum distribution platform

The vacuum distribution platform, shown in figs. 6, 7 and 8, is bolted to the base plate and distributes vacuum to the various individual vacuum chucks on the sensor and assembly platforms. It has individual vacuum lines coming from the electrovalves which it passes via o-ring sealed vacuum feedthrough holes to the sensor and assembly platforms. Two of the vacuum lines are used to hold in place the sensor and assembly platforms, the rest are passed through to those platforms.

3.3 Sensor platform

The sensor platform has built-in individual vacuum chucks to hold in place the silicon sensors prior to their survey-mark scan and pick-up (fig. 9. The platform itself can be removed from the vacuum distribution platform which allows for loading of components on the platform away from the gantry area. It is therefore possible to use several different platform which can reduce assembly time by allowing component loading to occur in parallel with module assembly. In order to avoid direct handling of the sensors, each sensor is first placed on a thin metal foil carrier (fig. 10) which has tabs on each edge to prevent the sensor from sliding around on the carrier. The carrier is placed

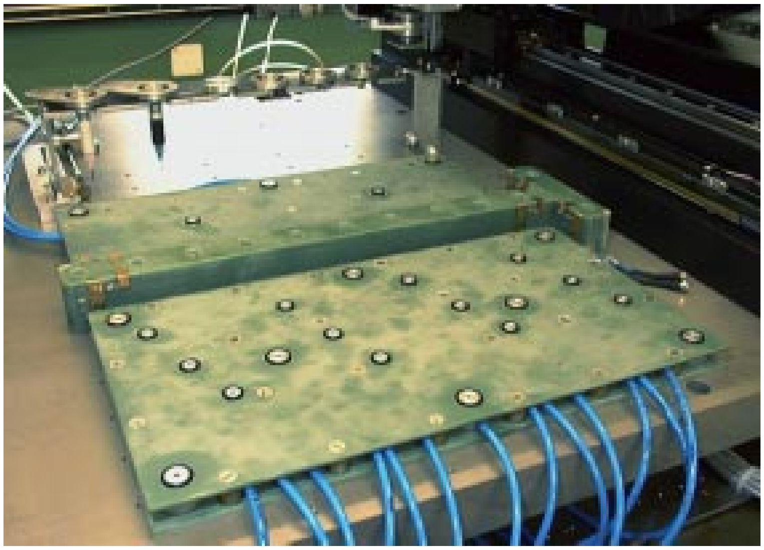

Figure 6: *Photo of the vacuum distribution platform mounted on the gantry baseplate. The assembly platform goes on top of of the front part of this platform and the sensor platform goes on the rear part.*

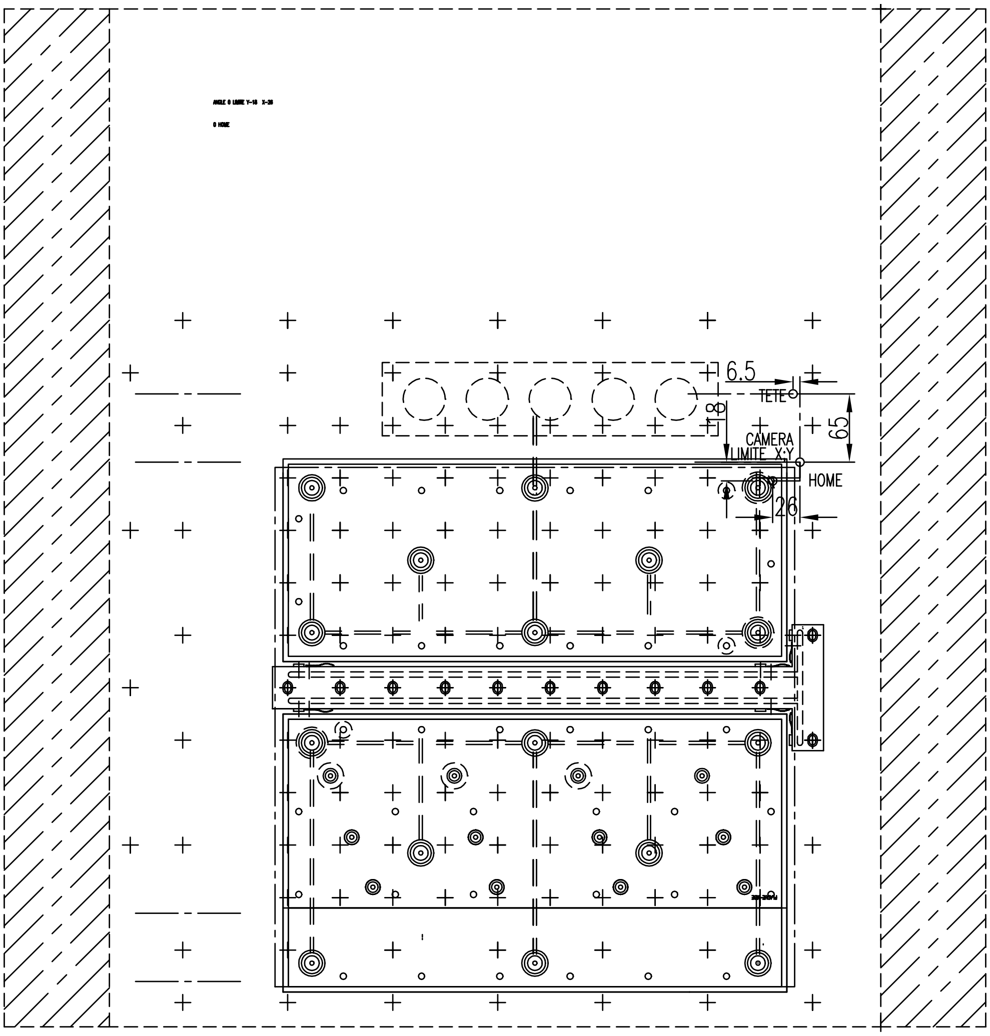

Figure 7: *Mechanical drawing showing an overview of the top of the vacuum distribution platform.*

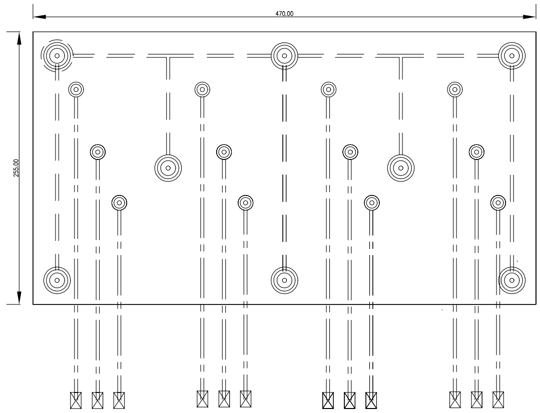

Figure 8: *Mechanical drawing showing the vacuum connections on the assembly platform part of the vacuum distribution platform.*

on the sensor platform and the positioning is achieved by means of positioning pins mounted in the platform which abut the carrier edges. When the carrier is placed such that it is constrained by the pins, as it is lowered the sensor is ”picked up” by the vacuum chuck and the carrier drops a few millimeters out of the way below the sensor.

3.4 Assembly platform

The assembly platform (figs. 9, 11 and 12) supports the CF-frames on which will be mounted the silicon sensors and read-out hybrids. This platform also holds the hybrids prior to assembly. It can be removed from the vacuum distribution platform, similarly to the sensor platform, thus allowing loading of the assembly platform with individual CF-frames away from the gantry area. The removable assembly platform has three individually controlled built-in vacuum chucks for each of the modules to be assembled (one for the CF-frames and two for each silicon sensor). The vacuum interface between the assembly platform and the vacuum distribution platform is as for the sensor platform.

The teflon pads which form the vacuum chucks contact surfaces on the top face of the assembly platform have been precision machined flat at a specified distance in Z as measured by the gantry. This was achieved by using the gantry to hold the milling machine. This was done so that the height of the contact surfaces are at an exact position in the gantry coordinate system. This removes the need for an absolute calibration of the gantry Z axis. The assembly platform has two precision pins for each module which positions the CF-frames. These pins define the positioning for all the components of the module. Two high precision fiducial marks are also placed on each assembly platform and all the module positioning pins must be measured relative to these marks. In this way, once the fiducial marks are measured, the location of all the module positioning pins are known.

The vacuum distribution, sensor and assembly platforms are built out of machined G10 sheets which are glued together. Details of the vacuum system can be found in Section 4.

3.5 Tool support head, pick-up tools, glue dispensing tools and tool rack

A tool support head was designed to interchangably pick up the component pick-up tools and the glue dispensing tools. This head is mounted on the ϕ axis stage and it uses vacuum to pick up and hold the tools in place (fig. 13). In total, three vacuum lines and one air pressure line are needed for the module assembly tasks and the additional lines are described in detail below. A large number of PVC tubes were pre-installed by Aerotech in the cable plant of the gantry at our request in order to bring these services to the tool support head.

Two different pick-up tools are needed for component pick and place, one for sensors and one for the readout hybrids (fig. 14). Both tools have vacuum passed through to the teflon vacuum pads which come in contact with the component. The tools themselves are held, using a separate vacuum line, to the tool holder support which is mounted on the ϕ axis stage (see figs. 15 and 16).

The glue dispensing tool (figs. 14, 17 and 18) is held from the same tool holder support but in addition has a separate air pressure feed-through connection which has its own vacuum line to hold it in place. Thus when a glue dispensing tool is used, two vacuum lines and one air pressure line are needed. The aluminium piece that is the

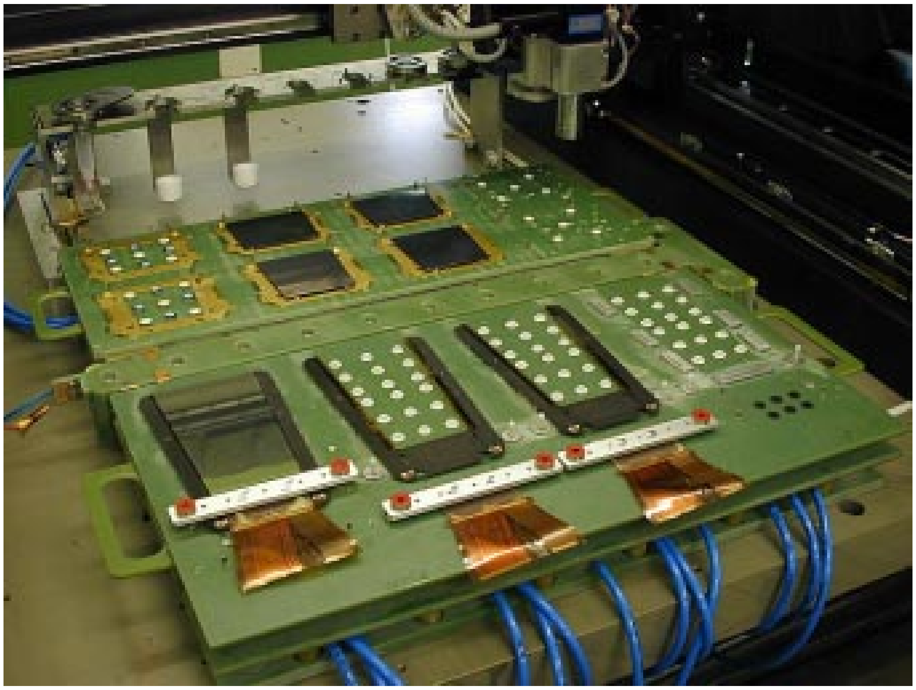

Figure 9: *Photo of the sensor (back) and assembly platform for 4 end-cap detector modules. 4 $\times$ 3 plastic pipes are leaving the assembly platform which provide the required the vacuum connection for one carbon-fibre frame support and two silicon sensors for each of the four end-cap detector modules. The vacuum tool rack in located in the back with the glue dispensing tools (left) and the vacuum pick-up tools (right).*

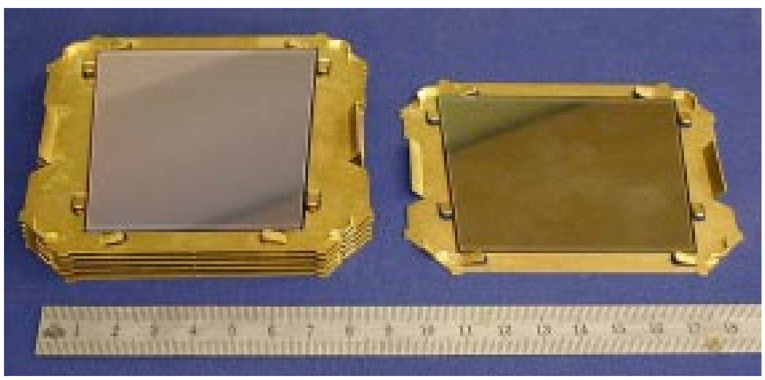

Figure 10: *Photo of stackable silicon sensor carriers with silicon sensors in place.*

glue dispensing tool is meant to receive a standard plastic syringe which fits over an o-ring sealed nozzle and is locked in place with a screw type fitting. The syringes are disposable and can be fitted with different size needles according to the needs of the glue to be used.

Both the pick-up tools and the glue dispenser tool are held in place on the tool support head with a small amount of 'play' such that when the tool makes contact with a fixed surface, the tool pushes a cylinder into a contact sensor located in the tool support head. The contact sensor has two contact circuits corresponding to two different displacements of the tool (one for initial contact and a second for emergency motor shut off in case of overdrive of the tool). The contact sensor is used to notify the gantry program that the component has been contacted so the motor should be stopped and the pick-up vacuum should be enabled. In the case of the glue dispenser tool, the sensor allows the program to know the height of the tip of the dispensing syringe needle (which can vary).

The pick-up and glue dispensing tools are stored in a tool rack when not being used. This rack is located at the back of the gantry base plate behind the sensor platform. It is moved forward and backward on air pressure pistons so that it can be displaced out of the way during gantry motions. There is space for three different glue dispensers and three pick-up tools on the rack. The custom pick-up tools, glue dispensing tools and tool rack are machined out of aluminium.

Figure 11: *Photo showing the top face of the assembly platform. The small white circles are the teflon vacuum chuck contact pads for the sensors and the rectangles are the aluminium vacuum chuck contact pads for the CF-frames.*

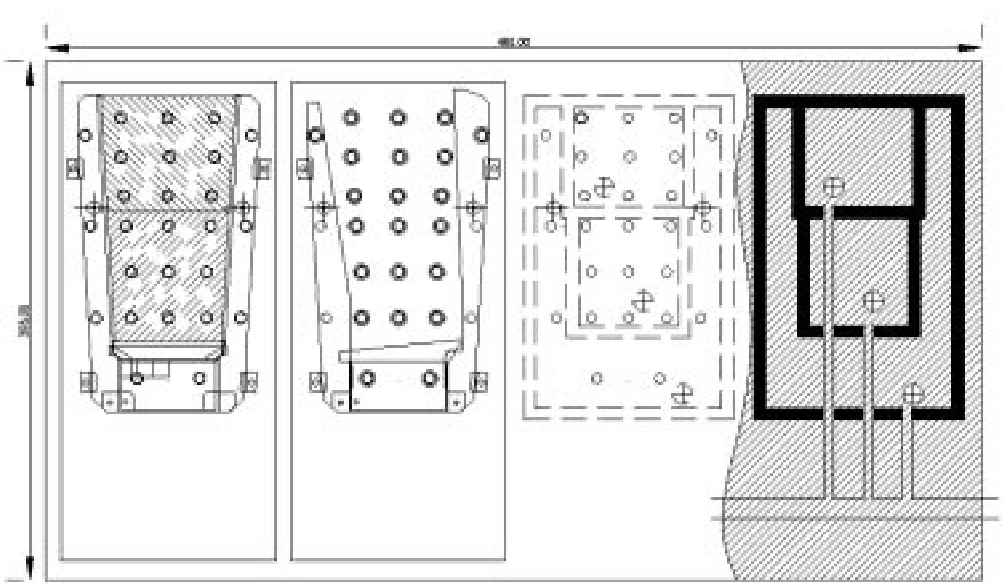

Figure 12: *Mechanical drawing of the assembly platform details. The first (leftmost) module position shows a schematic view of a completed module. The second module position shows a only a CF module frame as well as the positions of the vacuum chuck contact pads. The third module position shows the vacuum volume partitioning (inside the assembly platform) as well as the vacuum chuck contact pad locations. The fourth module position shows a cut-away view of the separate vacuum connections to the three vacuum volumes.*

3.6 Glue dispensing system

External to the glue dispensing tool is a Festo regulated air pressure glue dispensing system. This system provides a constant but adustable air pressure for glue delivery. This system can deliver a maximum pressure of 4 bar. As three different glues are to be used on module assembly (silicone based for sensors, araldite for hybrids, and conductive epoxy for sensor backplane connection), the adustability of the glue dispensing system is required.

3.7 Camera support

A machined aluminium support was designed to hold the CCD camera which views the components to be assembled through a high magnification optics. The support is attached to the Z stage by means of a plate held in place by the same screws used to hold the phi axis motor. The support clamps the lens tube of the optics and holds the optical axis approximately 6 cm in the positive X direction from the axis of the phi rotation (the pick-up axis). A second aluminium support was made that holds a second CCD camera with a low magnification lens at an angle of about 45 degrees with repect to the Z axis and looks at the point at which the glue is dispensed. It is also mounted on the Z stage and is used to check the quality of the glue dispensing.

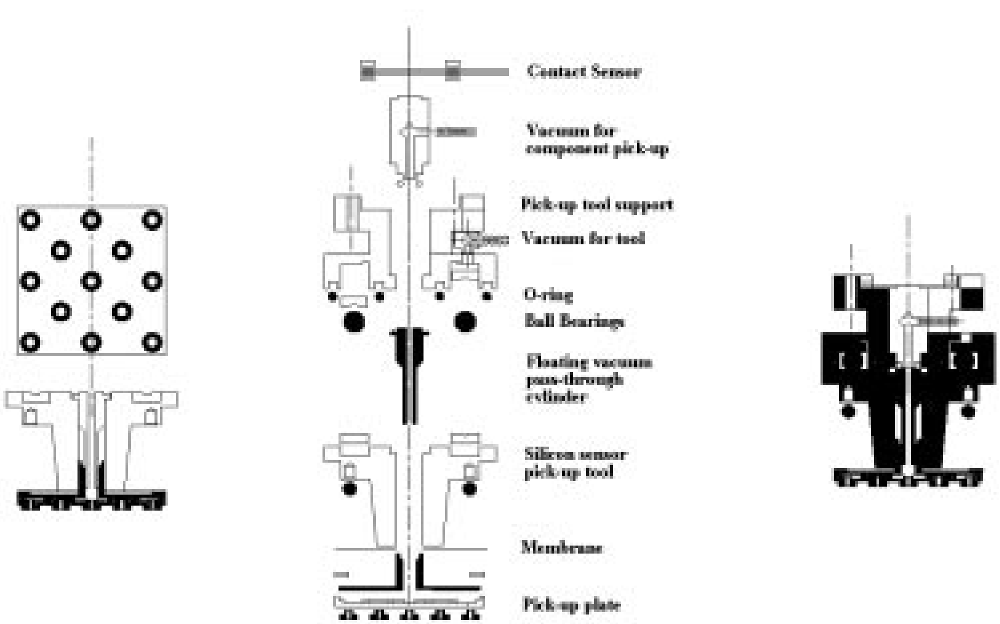

Figure 13: *Mechanical drawing of sensor pick-up tool.*

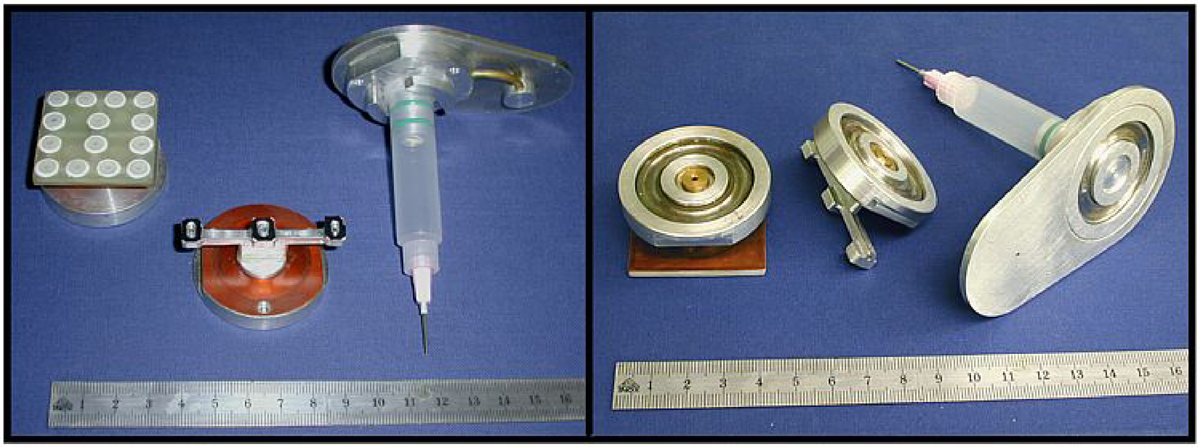

Figure 14: *Two views of the two types of vacuum pick-up tools and the glue dispensing tool.*

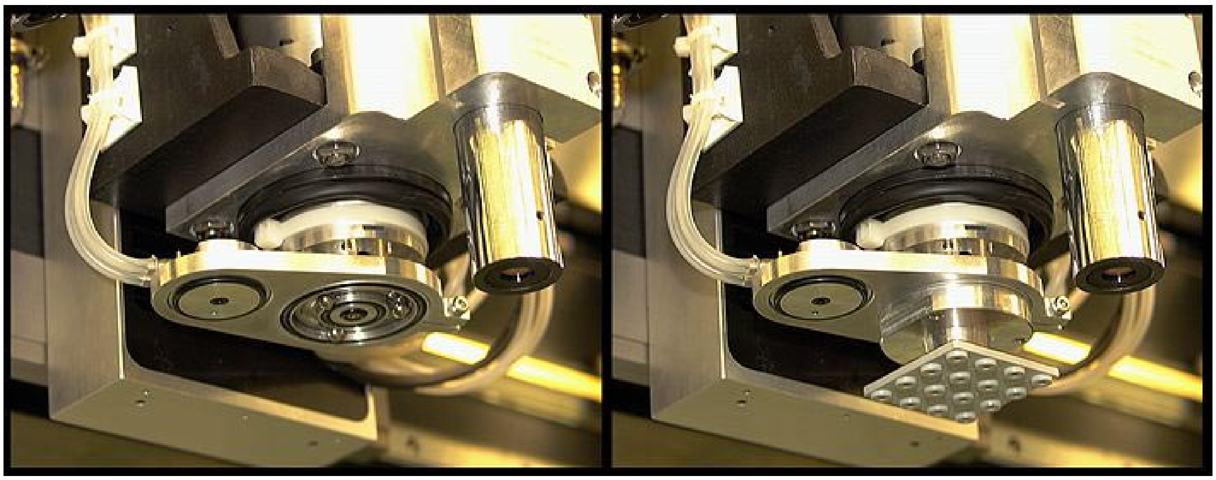

Figure 15: *Photos taken from below of tool holder head without and with the sensor pick-up tool in place.*

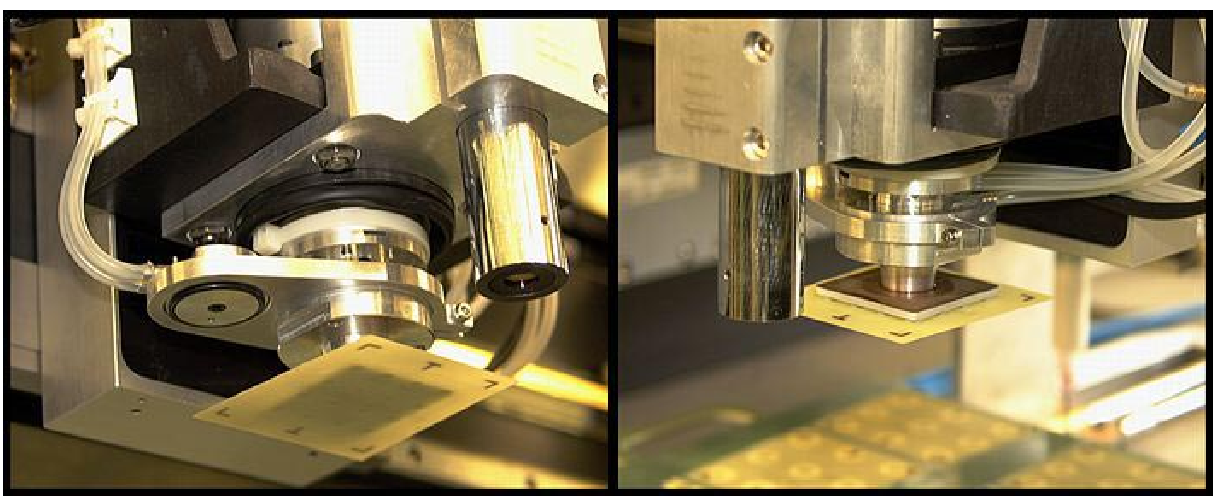

Figure 16: *Photos taken from below and above of tool holder head with sensor pick-up tool carrying a dummy sensor.*

Figure 17: *Photo of glue dispenser tool in action.*

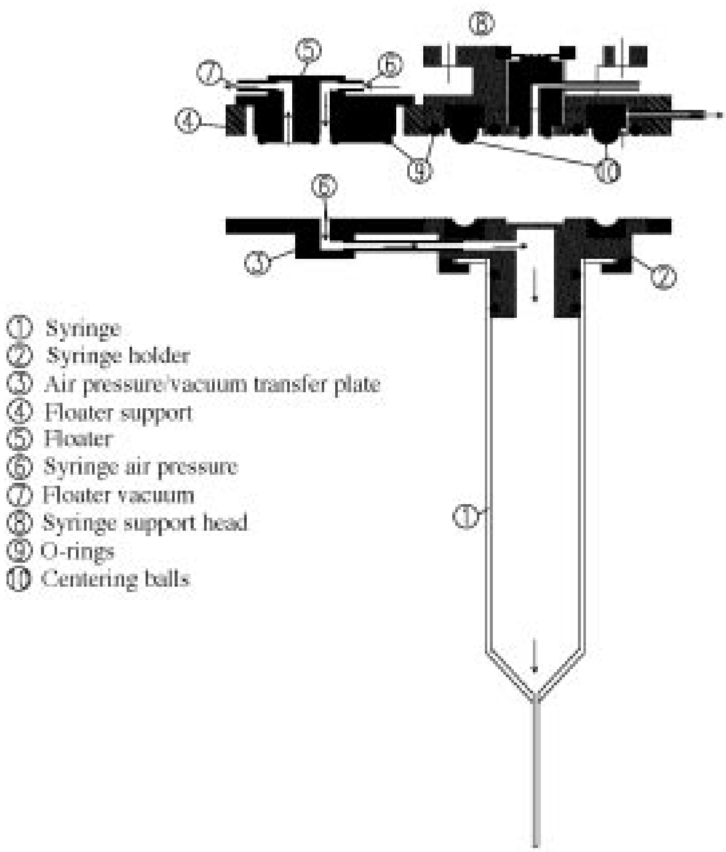

Figure 18: *Cross-sectional drawing of glue dispenser tool and the tool holder head.*

4 Vacuum system

The vacuum system is needed to hold in place the supply and assembly platforms on the vacuum distribution platform as well as to hold the components on the vacuum chucks of the supply and assembly platform surfaces. It also provides vacuum to hold in place the glue dispensing and pick-up tools on the tool support head as well as providing the pass-through vacuum used to pick-up the components with the pick-up tools.

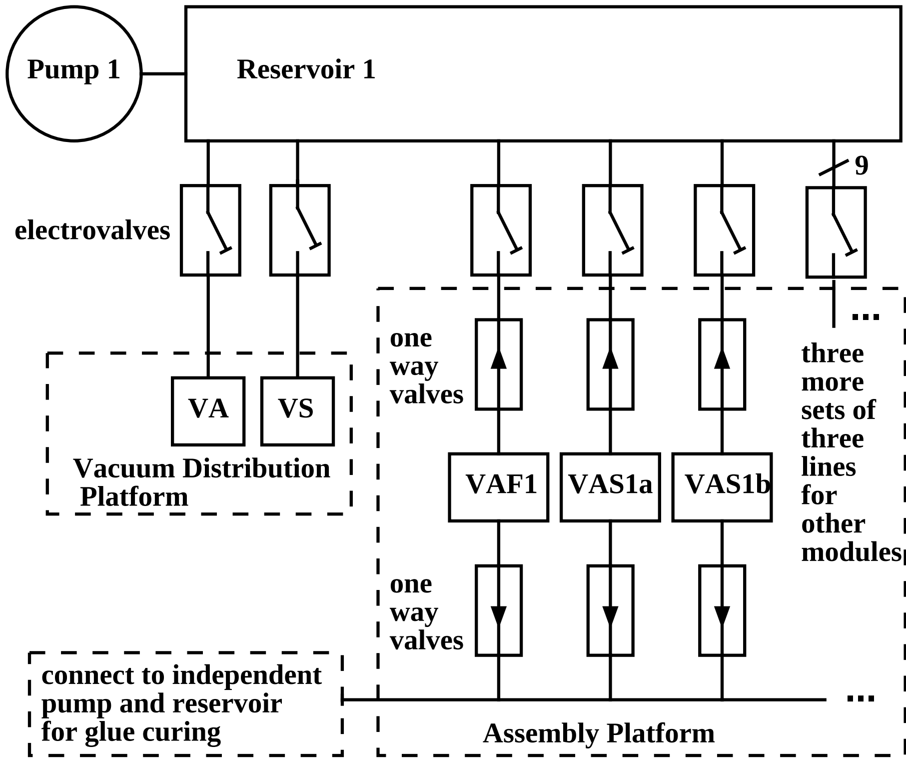

Figure 19: *Schematic overview of the sensor and assembly platform vacuum system.*

The system is divided into two independent vacuum systems which separate the glue dispensing and pick-up tool vacuum system from the vacuum system of the assembly and supply platforms. This assures a more reliable vacuum and dispensing system for the pick-up tool system which is more critical since it must handle and move the sensors.

Figure 19 shows the vacuum system of the assembly and supply platforms. A conventional mechanical pump (Pump I) with a capacity of about $1500\,\mathrm{l}$ per minute is connected to a cylindrical reservoir (Reservoir I) of a capacity of $20\,\mathrm{l}$. The reservoir is connected via 14 separate lines to the vacuum distribution platform. Two lines are used to hold the assembly (VA) and supply (VS) platforms in place. Three lines at each of the four module positions are passed through the assembly platform to the vacuum chucks for the frame and the two silicon sensors (VAFn, VASna and VASnb respectively, where n=1,2,3,4 denoting the module position). In the current configuration, the sensors are not held by vacuum when on the supply platform. This will be changed in the final configuration, such that each of the eight sensors will have individual vacuum connections. Furthermore, two vacuum lines for each read-out hybrid have been envisaged to allow for holding it in place before and after the pick and place operation. Thus a total of 16 additional vacuum lines will be added for a total of 30.

Each of the fourteen vacuum connections has a electrovalve in series so that it can be controlled by the gantry program. In addition, each of the 12 vacuum chucks on the assembly platform has built-in one-way valves to maintain vacuum for each of the vacuum chucks for when the assembly platform is removed from the distribution platform after the module assembly operation and put elsewhere for glue curing at the end of the module assembly operation. Furthermore, there is a separate vacuum connection which will go to an independent system which passes through another electrovalve and is connected to all 12 vacuum chucks through one-way valves. This connection will provide the vacuum to hold all the module components in place after the assembly platform is removed for the glue curing period.

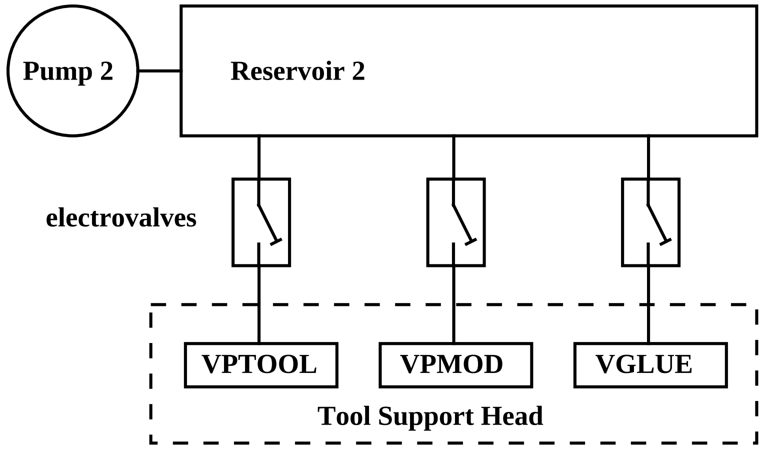

Figure 20: *Schematic overview of the vacuum system for the pick-up tools and glue dispenser.*

Figure 20 shows the vacuum system for the glue dispensing and pick-up tools. It also consists of a mechanical pump (Pump 2) with a capacity of about $1500\,\mathrm{l}$ per minute which is connected to a cylindrical reservoir (Reservoir 2) of a capacity of $10\,\mathrm{l}$. There are three lines going from this reservoir to the tool support head. These provide the vacuum to hold the pick-up or glue dispensing tool (VPTOOL), the vacuum that passes through the pick-up tool to hold the component (VPMOD), and the additional vacuum needed to hold the glue dispensing tool (VGLUE). The three lines have electrovalves in series so that they can be controlled by the gantry program.

Vacuum sensors provide a signal giving the status of the vacuum at various places in the vacuum system. The output of those vacuum sensors can be connected to the digital input interface to be used for the program flow of the module assembly operation. Those sensors have not been used in the current module assembly operation and have therefore been omitted from Figures 19 and 20.

The specifications of the electrovalves and the vacuum sensors can been found in Appendix A.

5 Control electronics

The Aerotech gantry system (U600 Controller Card plus the Encoder Expansion Card) provides 56 digital input and 56 digital output channels based on TTL level signals. These can be used within the software environment to add auxiliary devices to the gantry system and synchronize them with the actual gantry machine operation. For the module assembly application, the digital inputs are used for the reading of the state of the vacuum sensors, the built-in contacts of the pick-up tools, the contact sensor monitoring correct platform positioning, and the state of end-switches. The state of these inputs can be used to modify the program flow. A block diagram of the connection between the U600 main card and the expansion card and the input/output interfacing circuits can be found in Figure 21.

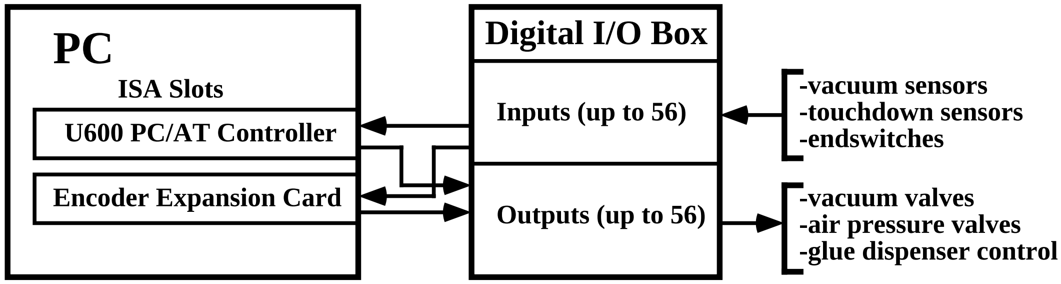

Figure 21: *Block diagram of the connections between the U600 controller, Encoder Expansion card and the custom built digital IO interface box which allows control and monitoring of external equipment by the gantry program.*

Similarly, the digital output channels are used for switching the vacuum valves and air pressure valves. The subsection below describes the digital input and output channels on the Aerotech controller boards and how they should be interfaced to external devices. The subsequent subsection describes the implementation of the digital input and output interfaces for the module assembly project.

5.1 Digital IO interface of the U600

5.1.1 Input interface

Figure 22 shows the electrical schematic of the U600 Input Bus Interface. Input states from devices such as vacuum sensors, contact sensors or end switches can be connected to the U600 Input Bus Interface through an opto-coupler.

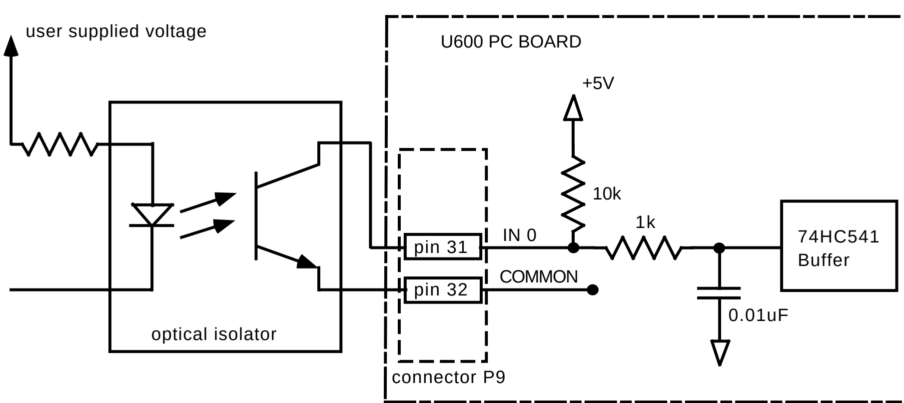

Figure 22: *Electrical schematic of U600 input bus interface.*

The main U600 controller card provides 16 digital input channels. Figure 23 shows a block diagram of the U600 main card indicating the location of the P9 50-pin connector which contains these 16 input signals. The encoder expansion card is shown in Figure 24 indicating the location of the 50-pin P8 and P9 connectors which are used for the 40 additional input channels. The pin allocation for all 56 input channels is summarized in Table 5.1.1.

INPUTS			
Board	Label	Virtual Binary Input #	Connector and Pin Numbers on the Respective Board
U600	IN0-15	0-15	P9 pins 31-1 (odd pins)
Encoder Expansion Board	IN0-15	16-31	P9 pins 31-1 (odd pins)
	IN16-39	32-55	P8 pins 47-1 (odd pins)
pins 2-50 (even pins) in all connectors above carry common (GND), pin 49 carries +5V			

Table 1: *Digital input channel mapping, pin and connector locations for the 56 available channels.*

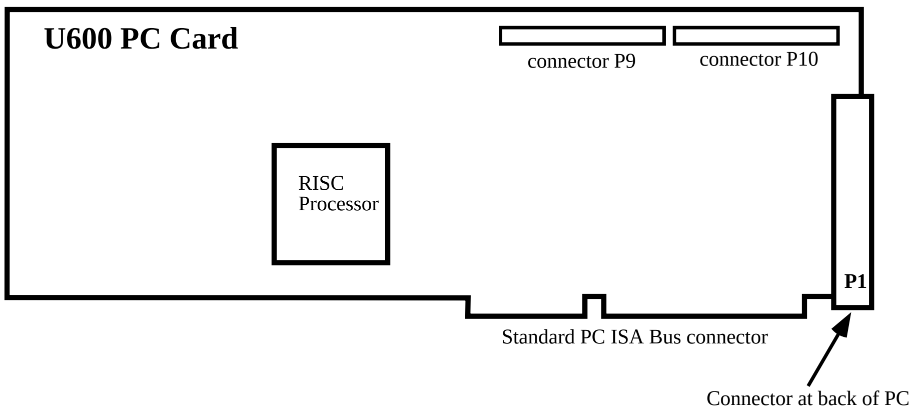

Figure 23: *Drawing of U600 main card showing connector locations. Digital IO channels are located in connectors P9 and P10.*

5.1.2 Output interface

The electrical schematic of the U600 Output Bus Interface is shown in Figure 25. External devices such as vacuum and air pressure valves can be controlled via the U600 cards digital output channels. The digital output channels of the gantry system should be electrically isolated from the external device electronics using opto-couplers.

The main card of the U600 system provides 16 output channels located in the 50-pin connectors P9 and P10 (Figure 23). The remaining 40 output channels are located on the encoder expansion card in the 50-pin connectors P7, P9 and P10 (Figure 24). The pin allocation for all 56 digital output channels is summarized in Table 5.1.2.

OUTPUTS			
Board	Label	Virtual Binary Output #	Connector and Pin Numbers on the Respective Board
U600	OUT0-7	0-7	P9 pins 47-33 (odd pins)
	OUT8-15	8-15	P10 pins 47-33 (odd pins)
Encoder Expansion Board	OUT0-7	16-23	P9 pins 47-33 (odd pins)
	OUT8-15	24-31	P10 pins 47-33 (odd pins)
	OUT16-39	32-55	P7 pins 47-1 (odd pins)
pins 2-50 (even pins) in all connectors above carry common (GND), pin 49 carries +5V			

Table 2: *Digital output channel mapping, pin and connector locations for the 56 available channels.*

5.2 The digital IO interface crate

For the CERN gantry configuration, of the 56 digital input and 56 digital output channels available, only 24 inputs and 24 outputs have been interfaced for external device control and monitoring. A separate crate in a standard 19” rack mount format was built to contain the interface electronics for the digital inputs and outputs which consists mostly of the opto-coupler circuits. Figures 26 and 27 show simplified electrical schematics for one digital output channel (controlling the vacuum valve for the first module frame, VAF1) and one digital input channel (e.g. for

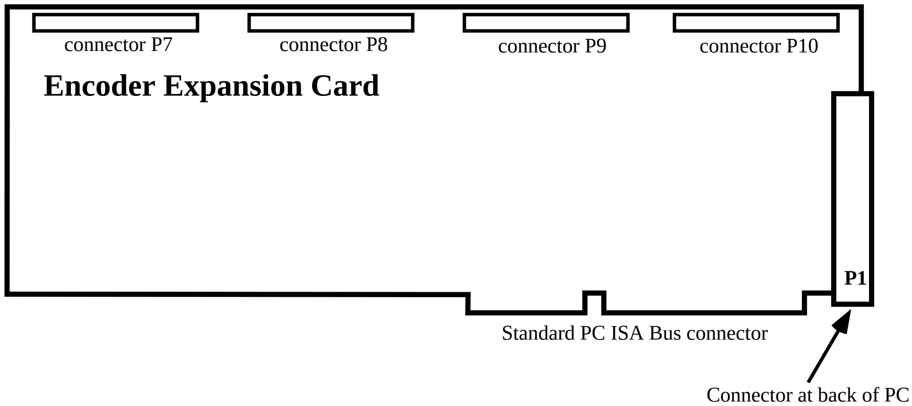

Figure 24: *Drawing of encoder expansion card showing connector locations. Digital IO channels are located in connectors P7 through P10.*

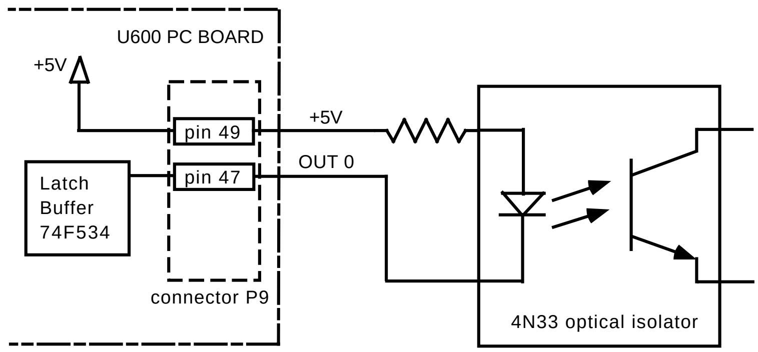

Figure 25: *Electrical schematic of U600 output bus interface.*

a contact sensor). For detailed schematics of the interface circuitry, see Appendix C. The interface requires 24V for the vacuum and air pressure valve operation and 5V for the opto-coupler circuit. In the current setup, those voltages are provided by external power supplies. As very few input channels were used in the development work, only 8 of the 24 input channels were cabled. The choice of using input channels IN8-15 of the U600 card and output channels OUT16-39 of the encoder expansion card meant that only two cables were needed to connect the digital IO channels going from PC to the digital IO interface crate. As can be seen from Tables 1 and 2, these two cables should plug into the U600 card at connector P10 and into the encoder expansion card at connector P7. These connectors are standard dual-inline 50 pin connectors and the cables used are standard flat ribbon cables.

For the output circuits (Figure 26), a front panel switch allows one to change between remote and manual operation of the electrovalves. In remote operation full control is given to the digital output channels. The state of a valve, i.e. on or off, is indicated by a green LED. In manual mode, each valve can be controled individually by a front panel switch. For the input circuits (Figure 27), the sensor state is transformed into a TTL level signal which is serves as input to the digital input channels. The state of a sensor is indicated by a green LED. Of the 24 input and 24 output channels contained in the interface, 19 outputs and 2 inputs are currently used in the gantry assembly program. These 21 signals and their correspondance to the digital IO channels are given in Table 3. The input and output channels are accessed through their respective virtual binary input and output number which are also indicated in Table 3. Input bits are read and output bits are set through ”M codes” (special U600 controller commands) using these virtual binary numbers. Example codes will be discussed in the next section.

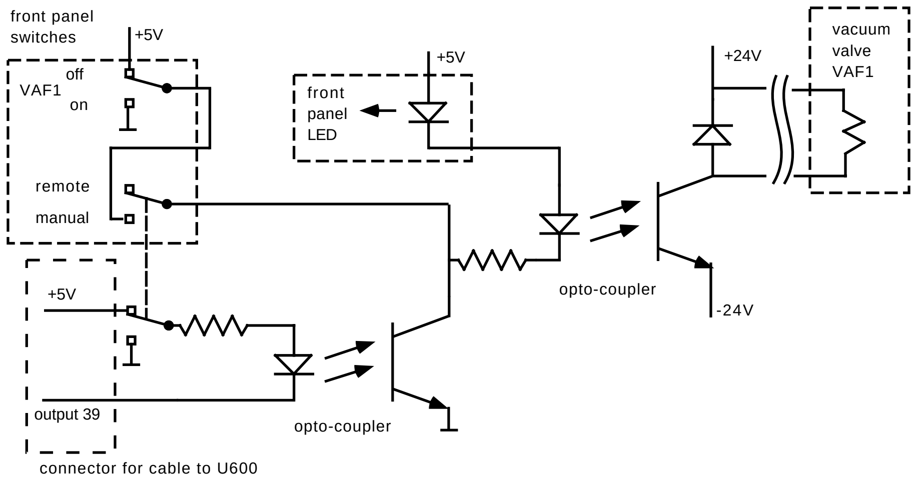

Figure 26: *Simplified electrical schematic for one digital output circuit in the interface box.*

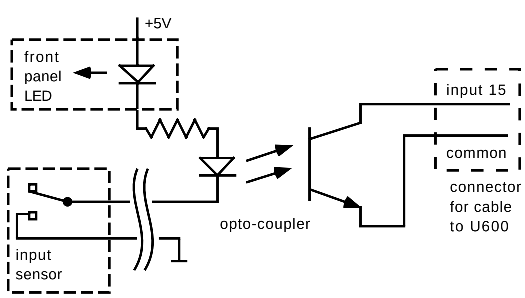

Figure 27: *Simplified electrical schematic for one digital input circuit in the interface box.*

IMPLEMENTED INPUTS AND OUTPUTS				
Signal name	Board	Label	Virtual Binary Input/Output #	Function
VAF1	Expan.	OUT39	55	Frame vacuum, module 1
VAS1a	”	OUT38	54	Sensor 1 vacuum, module 1
VAS1b	”	OUT37	53	Sensor 2 vacuum, module 1
VAF2	”	OUT36	52	Frame vacuum, module 2
VAS2a	”	OUT35	51	Sensor 1 vacuum, module 2
VAS2b	”	OUT34	50	Sensor 2 vacuum, module 2
VAF3	”	OUT33	49	Frame vacuum, module 3
VAS3a	”	OUT32	48	Sensor 1 vacuum, module 3
VAS3b	”	OUT31	47	Sensor 2 vacuum, module 3
VAF4	”	OUT30	46	Frame vacuum, module 4
VAS4a	”	OUT29	45	Sensor 1 vacuum, module 4
VAS4b	”	OUT28	44	Sensor 2 vacuum, module 4
VA	”	OUT27	43	Assembly platform vacuum
VS	”	OUT26	42	Supply platform vacuum
VGLUE	”	OUT25	41	Glue tool vacuum
VPTOOL	”	OUT24	40	Tool vacuum
VPMOD	”	OUT23	39	Component pick-up vacuum
ATOOL	”	OUT22	38	Tool rack air line
AGLUE	”	OUT21	37	Glue tool air line
TOUCH1	U600	IN14	14	Touch contact sensor
TOUCH2	”	IN15	15	Overdrive contact sensor

Table 3: *Digital IO channel mapping, virtual binary ID, and description of signal.*

6 Software

This section provides an overview of the available programming environment provided with the Aerotech gantry system and focuses on developed programs for the module assembly procedure. Each *gantry* user is expected to be familiar with the RS-264 CNC (Computer Numerically Controlled) programming interface and the usage of the Aerotech MMI (Man Machine Interface) program. This section is not meant to replace the Aerotech programming manuals.

6.1 The Aerotech programming environment

The Aerotech U600 Series Controller provides the capability of controlling axis motions and connected auxiliary devices through the digital I/O interface either manually (mouse or joystick operation using the MMI graphics menu) or remotely by a program.

The majority of programming tools are available from either of the two programming interfaces: the Library Program Interface or the CNC Program Interface. The two interfaces are different in terms of their underlying language syntax and the processor which executes a particular program.

In the Library Program interface, the user writes a program in C++, C or Visual Basic, and then compiles and executes it on the PC. Axis motion and auxiliary device operations are performed using function calls to the Aerotech program library which invoke motion controller functions through a device driver running on the PC.

The CNC program interface executes a particular user program directly on the axis processor. The user first has to write a program using the RS-264 CNC programming language, compile it on the PC and then download the executable on the axis processor using the device driver. Unlike for the Library Programming Interface, the CNC program can be executed independently from the PC and thus is independent of what programs are running on the PC, the speed of ISA bus and the speed of the PC. The drawback of the CNC program interface is that it lacks advanced language features as in C++ and has a somewhat limited program editor. However, it is very simple to use and flexible, allowing complicated multi-axis and auxiliary device operations which are required for the module assembly procedure. The direct control and feedback between program and hardware as well as the ability to debug programs on-line made this the clear choice for the module assembly application. Only the CNC program interface has been used for module assembly related work.

Running a CNC program has to proceed through the following steps:

1. write a CNC program (e.g. using the MMI editor)
2. compile the CNC program to produce a binary object file
3. download the binary object file to the U600 Motion Controller
4. execute the program on the U600 Motion Controller

6.2 Brief overview of relevant CNC program elements

Looking at a CNC program, one finds the following elements:

- **declaration of variables (using the DVAR command** (here, array of 10 elements):

  ```
  DVAR A[10]
  ```

- **motion control commands (G-codes)**: (here, perform linear motion in X by $10\,cm$ with the units and the type of motion (absolute or relative) to be specified by additional G-code commands:

  ```
  G1 X10.
  ```

- **digital I/O communication (M-codes)**: (enable external digital I0 channel # 33)

  ```
  M3033
  ```

- **motion parameter commands (F-codes)**: (here, set the speed of G1 motion in X)

```
F1000.
G1 X10.
```

- **extended commands**:

  IF-statements:

```
IF <conditional expression> THEN
...
ELSE IF <conditional expression> THEN
...
ELSE
...
ENDIF
```

  WHILE-DO statements:

```
WHILE <conditional expression> DO
...
ENDWHILE
```

  Definition of subroutines:

```
DFS MOD_SI
...
ENDDFS
```

  CALL to subroutine:

```
CALL <name of subroutine>
```

  Include statement of subroutine in main program:

```
#include C:\U600\PROGRAMS\[name of subroutine].PGM
```

  Message commands:

```
MSGDISPLAY 1 "This text will appear in the message window of the MMI"
```

  Message box: (pops up a message box on the PC with a response button)

```
$RESP=MSGBOX (DF_MSGBOX_YESNO + DF_ICON_QUESTION), "Click on Yes or No!"
IF $RESP == YES_BUTTON THEN
...
ELSE
...
ENDIF
```

  The variable `$RESP` has to be declared in the beginning.

  Output file: (write numbers XPOS and YPOS to file: SURVEY.DAT)

```
FILEWRITE "C:\U600\PROGRAMS\SURVEY.DAT",$XPOS," ",$YPOS
```

  Assigning variables: (using mathematical expressions, here SIN and COS)

```
$RADIUS=10.
$ANGLE=10.
$XPOS[$ID]=$RADIUS[$ID]*COS($ANGLE[$ID])
$YPOS[$ID]=$RADIUS[$ID]*SIN($ANGLE[$ID])
```

Comment lines: (everything to the right of a **;** is taken as a comment)

```
;-------------------------------------------------------------------
; PROGRAM:    MOD_GLUE_SI.PGM
; DESCRIPTION: routine to dispense glue for sensors
; AUTHOR:     A. Nonymous
; DATE:      29 Feb 1999
;
;-------------------------------------------------------------------
; 1.  DECLARATION OF VARIABLES
;-------------------------------------------------------------------
```

Note that all variables within a subroutine have to be declared in the main program, i.e. no local variables can be defined. This is quite different from the usage of FORTRAN. The main program itself starts with the declaration of variables (DVAR command).

6.3 Structure of the module assembly program

The module assembly program is started by the operator once the preparatory work has been performed. At this point the glue syringes have been loaded and all the components are in place on the sensor and assembly platforms. The module assembly program is loaded and executed via commands in the MMI. The structure of this program involves a main program (`MOD_MAIN.PGM`) which proceeds through the basic assembly steps by calling subroutines:

1. declaration of variables (`DVAR` statements)
2. parameter settings (`CALL MOD_PARMOVE` and `CALL MOD_PARAM`)
3. Reset of vacuum valves (`CALL VALVERESET`)
4. Turn on/off certain valves (`CALL VALVEON/VAVLEOFF`)
5. Read position of reference marks (`CALL MOD_REF` or `CALL MOD_REF_NOM`)
   - `CALL MOD_REF_HYB.PGM`
   - `CALL MOD_REF_SI_SI.PGM`
6. Gluing silicon part (`CALL MOD_GLUE_SI`)
   - Pickup of glue tool: `CALL MOD_GETTOOL`
   - Get glue parameters: `CALL MOD_GLUE_SI_PARAM`
   - Perform glue operation: `CALL MOD_GLUE_DISP`
   - Put down glue tool: `CALL MOD_PUTTOOL`
7. Pick-up first tool (`CALL MOD_GETTOOL`)
8. Moving of sensors (`CALL MOD_SI`)
   - Pick and place routine (`CALL MOD_PICKUP`)
9. Put down first tool (`CALL MOD_PUTTOOL`)
10. Gluing hybrid part (`CALL MOD_GLUE_HYB`)
    - Pick-up of glue tool: `CALL MOD_GETTOOL`

- Get glue parameters: `CALL MOD_GLUE_HYB_PARAM`
- Perform glue operation: `CALL MOD_GLUE_DISP`
- Put down glue tool: `CALL MOD_PUTTOOL`

11. Pick-up second tool (`CALL MOD_GETTOOL`)
12. Moving of hybrids (`CALL MOD_HYB`)
13. Put down second tool (`CALL MOD_PUTTOOL`)
14. Determine difference between measured and desired position (`CALL MOD_ACC`)

Due to the modular structure of the module assembly tasks, the sequence of operation can easily be changed, such as the dispensing of glue for both the sensors and hybrids before pick and place.

6.4 Parameter files

The parameter files define the machine specific parameters and configure the hardware and software to the users specifications. The principle parameter files are listed below, along with some of the more important parameters in each group:

- Axis Parameters (AxisParm.ini)
  - acceleration, decleration limits
  - position error limits
  - masks (fault, interrupt, abort, ...)
  - max current
  - motor tuning parameters (PGAIN, KI, KP)
  - end of travel limits
- Machine Parameters (machparm.ini)
  - number of decimal places to display position
  - motor counts per inch (calibration of motor feedback)
  - maximum velocity (feedrate)
  - homing velocity
  - home position (offset)
  - home movement type
  - jog velocity (manual control from MMI)
- Task Parameters (taskparm.ini)
  - define jog axes
  - emergency stop input definition
  - joystick port definition
- Global Parameters (globparm.ini)
  - emergency stop enable
  - servo feedback frequency switch2
  - 2D calibration enable
- Axis configuration parameters (Axiscfg.ini)
  - parameters defining type of motor
  - parameters defining type of driver
  - parameters defining type of encoder
  - 1D calibration file pointers

- 2D calibration files (calib.cal) : see section 9.

In general, the parameter files will be set up during the installation of the gantry machine by the Aerotech engineer. Then, certain parameters will be modified according to the application and desires of the user. The user has complete access to the parameters so care should be taken before modifying. An example of some modified parameter settings made for the module assembly program: maximum motor current, axis accelerations and axis speeds were set low to avoid dangerously quick movements and high forces. The X and Y linear motors can produce very high accelerations and velocities which can be a safety hazard and which are not necessary for the module assembly application.

The parameter files used at the CERN gantry setup can be used as a starting point for other setups with the same hardware. However, there will be certain parameters that are site specific such as motor feedback parameters which depend on temperature, load and dynamic resistance (e.g. from the cable plant) which must be determined locally. These site specific parameters are mostly found in the Machine Parameter group (machparm.ini file).

7 Optical equipment

The initial development of the gantry system as a robotic assembly device required visual sighting and aligning of fiducial marks by means of a CCD camera view through microscope optics carried on the gantry Z stage. This was replaced by a pattern recognition (PR) system which runs independently on the same PC as the gantry but is controlled by the gantry program via commands sent to the PR control program. Although all fiducial finding is done automatically by PR, much of the optical equipment is nevertheless needed by the PR system. Also, in the event of problems with PR (e.g. bad surface quality or damaged fiducial marks), manual optical sighting may still be necessary as a backup, so this equipment is still needed.

The following optical equipment is used on the CERN system:

- color CCD camera (2/3" CCD, 575 lines, CCIR color standard, C-mount fitting)
- high magnification microscope optics (200x)
- coaxial illumination optical element
- variable intensity illumination source and fiber optic light guide
- line generator (optional)
- color monitor for principal camera (optional)
- 2nd CCD camera for viewing glue dispensing (optional)
- lower magnification optics (100x) (optional)
- B&W monitor for 2nd camera (optional)

Both cameras are mounted from the Z stage using custom built supports (sec. 3.7). The high magnification camera views directly down along the Z axis and is positioned about 6cm toward the positive X direction from the phi axis of rotation (the pick-up axis). The end of the optics barrel should not extend lower in Z than the bottom of the pick-up tool holder. The coaxial illuminator is necessary to get enough light for good viewing at these high magnifications. The light source is mounted on the Y stage so as to keep the length of the fiber optic light guide as short as possible (the source was too bulky to mount on the Z stage). The optional line generator is used to provide a cross-hair in the case of manual optical fiducial finding. Although a color camera and monitor are used, it is likely that black and white would be sufficient for this application. The connection and cabling set-up for the optical system is shown in fig 28.

The second camera is angled at about 45 degrees and is aimed and focussed at the point where the glue is extruded from the syringe. This camera allows the operator to verify the proper application of the glues.

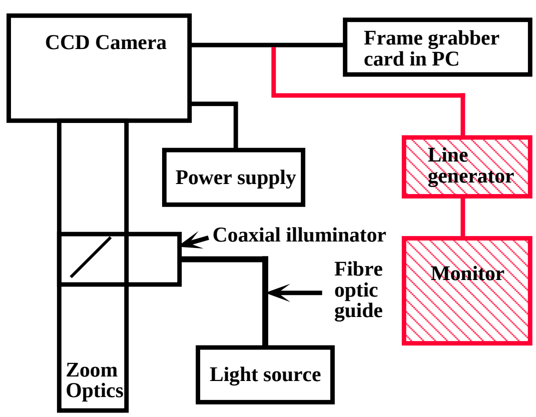

Figure 28: *Schematic showing the interconnection of the primary (high-magnification) optical equipment. The elements in the shaded boxes are optional.*

8 Pattern recognition

8.1 Introduction

The initial positioning by hand of the sensors and hybrids is not accurate enough to ensure proper alignment of the components on the modules with no further positioning adjustments in the assembly program. Thus the exact positions of the components (sensors, hybrid and frame) have to be obtained visually, either by the operator or by the machine. To enable the gantry system to localise automatically components to be assembled, a pattern recognition system was added. This system is also used to find the position of the assembly platform and thus the positions of the CF frames since their positions are defined by the precision pins mounted in the assembly platform. The system is also used to measure the positions of the sensors and hybrids after they have been glued in place.

The pattern recognition for the gantry systems consists of a frame grabber card and a software package. Two frame grabber cards with different software packages have been tested:

- **MATROX CORONA LC** can digitise up to four independent video sources and features a video card thus replacing the system video card. The frame grabber card allows real-time colour acquisition to PC memory and on-board true-colour display with true-colour non-destructive overlay. The software package Matrox Imaging Library (MIL) provides a variety of library functions to acquire, manipulate and analyse digital images. The library function are designed to be used with Microsoft Visual Basic or Visual C++.

- The **National Instruments PCI1408** frame grabber card can also digitise up to four video sources but does not the replace the system video card. The grabbing speed is slightly slower than for the Matrox CORONA system and real-time colour acquisition is not possible. The software IMAQ Vision from National Instruments provides all necessary function for image acquisition and analysis. It is used in the LabView environment.

For both systems applications have been developed to provide an user interface and a MMI interface to the pattern recognition.

8.2 Hardware

8.2.1 Matrox CORONA LC

The Matrox CORONA LC frame grabber card uses the PCI bus extensively and not all PC motherboards are compatible. Before buying a PC for the Gantry system it should be verified that the motherboard is contained in the Matrox CORONA compatibility list which can be found on Matrox web site (http://www.matrox.com). The Matrox CORONA LC frame grabber card requires one full length PCI slot for installation. Care has to be taken that the interrupt line for the CORONA LC does not conflict with the Gantry hardware. In the CERN PC a interrupt configuration different from the default value was necessary (DIP SW 2: 10). When installing the hardware drivers for the video card and the frame grabber sections it occurred in the CERN set-up that the hardware was crashing constantly when trying to access the frame grabber card although the motherboard (ASUS P3B) was on the compatibility list. The problem was pinned down to the DMA driver and solved by using an older version of the driver mtxdma0.sys in `wnt\system32\driver`. However no clarification why the new driver would crash the system and why the old driver would work could be obtained from Matrox up to now.

The connection of the video source and the frame grabber card is established with a special cable providing BNC connectors for interfacing the camera. The software uses only channel one (red cable) of the four digitiser channels. The camera that provides the video source is the high-magnification CCD camera described in section 7.

8.2.2 National Instruments PCI1408

The PCI-1408 uses one PCI slot. No compatibility problems have been reported by NI, however for good results a Pentium based processor or better is recommended. The installation of the card was according to the manual and no hardware problems occurred. The software drivers worked smoothly on two different CERN PC machines. However, also here care must be taken that no conflicts of IRQ lines and DMA channels arise due to other components in the system.

The connection from the camera to the frame grabber card is via the built-in BNC connector and a normal BNC cable. No special cable is needed for the camera.

8.3 Software

The objectives of the software development were to provide an easy-to-use front end program to let the user define patterns and test the pattern recognition. The second objective was to provide a way of exchanging data between the pattern recognition program (PR) and the Gantry software to allow the MMI to control the PR program.

As mentioned above the proprietary gantry language (MMI) allows to interface DLL and call executables. The communication between MMI and the PR has been implemented by using simple ASCII files which are written and read by MMI, PR, or, in the case of the National Instruments setup, another interface program (IP). The PR contains its own user interface (UI) which is separate from the MMI. The basic structure is sketched in the diagram in figure 29 for the Matrox system and figure 30 for the National Instruments system.

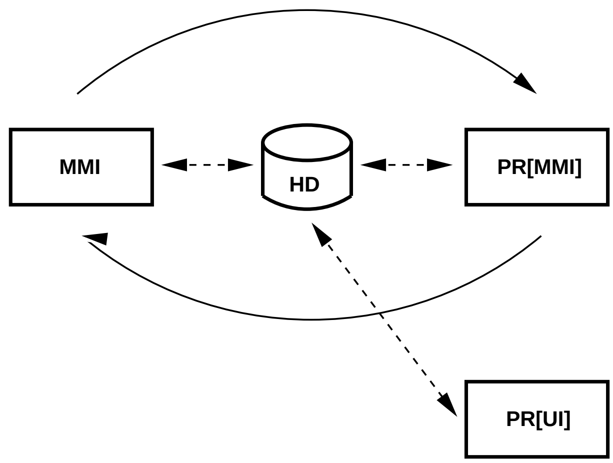

Figure 29: *The basic structure of the communication between the gantry program MMI and the Matrox based pattern recognition system.*

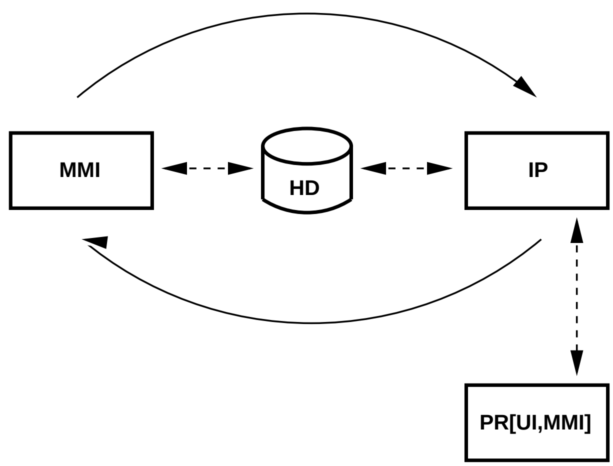

Figure 30: *The basic structure of the communication between the gantry program MMI and the National Instruments based pattern recognition system.*

When a pattern recognition operation is requested the MMI writes specific parameters for the operation in a text file (PR command file) and calls an external executable (PR[MMI] or IP) which communicates the data to the PR. The PR interprets the parameters and executes the requested operation, eg. finding a pattern A in the current view or loading a different pattern. The results of the operation (coordinates of the found pattern and matching quality) is then stored in a PR result file and control is returned to the MMI, which reads in the results and continues processing. The cycle time for a complete PR operation is of the order of 0.2 (Matrox) to 0.5 seconds (Nation Instruments) on the CERN PC. The simple scheme allows easy modification and extension of the PR capabilities.

8.3.1 Matrox Imaging Library

The pattern recognition algorithm uses a fit to match a predefined pattern with a portion of a image using the normalised grey-scale values. The result of the fit are the X and Y coordinates and the matching score which is a measure of the goodness of the fit. Optionally a rotation in phi can also be fitted.

Two applications were written using Microsoft Visual C++. One application provides the user interface to the pattern recognition. It can display the current camera view, define, load and save patterns and test the pattern recognition independent of the MMI. The second application reads in a predefined model, acquires one image, searches the image for the model and returns the result. This application is called from the Gantry MMI.

8.3.2 IMAQ Vision / LabView

The IMAQ Vision library also provides different algorithms to define and find patterns (see IMAQ Vision Users Manual, Chapter 9 for details). The search algorithm delivers the X and Y coordinates, a matching score as a measure for the goodness of fit and optionally the angle of rotation if the pattern was found in the view.

The LabView Environment was used to develop the software and implement a user interface. One LabView application (PR) is used for defining, testing, saving and loading of patterns in the usermode as well as loading and finding patterns in the MMI controlled mode. Data exchange with the MMI program is done with the interface program (IP) written in C++, which is called by the MMI. The structure of the data exchange is the same as for the Matrox card, so the usage of either the Matrox or the National Instrument system is transparent to the MMI. The IP reads in the PR command file and establishes a TCP/IP connection to the PR which handles the request and returns data (ie. the position and matching score for a pattern recognition operation) to the IP. The IP writes the received data to a PR result file, terminates execution and control is given back to the MMI. The PR indicates the current view in a window and draws a cross over the position where the pattern is found. Additional information is printed in the upper left corner of the view window.

A switch on the User Panel allows to put the LabView application either in the MMI controlled mode or the user mode. Different function can be selected by clicking on the functions menu in the User Panel. Figure 31 shows the front panel together with annotated explanations of the elements in the user panel.

8.4 Procedure for use in module assembly

In the case of module assembly, the pattern recognition is used on 4 separate occasions and requires 3 sets of stored patterns. The first occasion using the PR is to sight the two fiducial marks on the assembly platform. The 8 positioning pins that are used to precisely locate the module frames are pre-measured with respect to the two fiducial marks for every assembly platform. This data is kept in a data base and is used by the program to determine each frame X-Y location and orientation. The assembly platform fiducial marks are therefore the first set of stored patterns needed by the PR system. The second occasion is to sight the fiducial marks on the sensors. Two fiducial marks in each of two adjacent corners of a sensor are needed for the second set of stored patterns. In the case of two sensor modules, a total of 4 different sensor fiducial marks are needed for the stored patterns. The third occasion is the sighting of the fiducial marks on the read-out hybrids. Again there are two fiducial marks on the hybrids needed for the third set of stored patterns. The final occasion for the PR is measuring the locations of the sensor fiducial marks after the module assembly steps are complete. From this the alignment constants giving the location of the sensors with respect to the module alignment pins is obtained.

In practice, when the gantry assembly program executes the step to find the fiducial marks, it moves the camera to the expected location and sends the command to the PR program to grab the frame and locate the desired pattern. The PR program should return the coordinate of the pattern and the quality of the match. If the match quality is above the required threshold, the assembly program calculates the corrected position of the fiducial mark in the machines coordinate system. If the match fails, the operator is notified and can retry, make a manual movement of the gantry (if the fiducial is just out of the picture), or can find the fiducial mark manually (using the joystick to position the fiducial mark under the cross-hair). Control can then be returned to the gantry program.

8.5 Performance

Since the accuracy of the pattern recognition is primarily defined by the optics and the pattern both system show about the same performance. Under optimal conditions (the pattern is defined from the current image view) the resolution of the pattern recognition is purely due to noise in the image from the video camera. Under real life

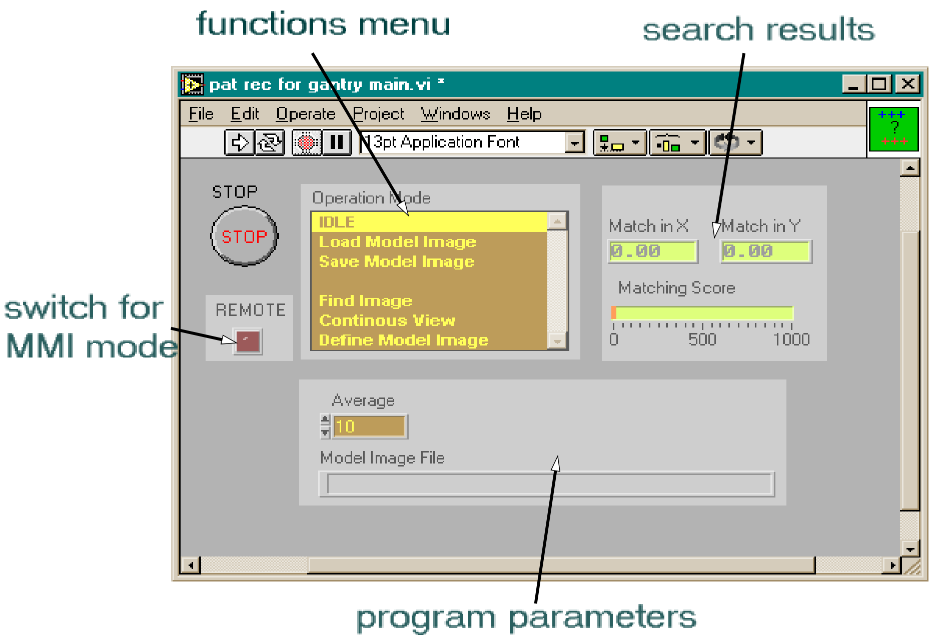

Figure 31: *A screen-shot of the user interface from the National Instruments pattern recognition system.*

conditions additional sources of uncertainty are dust or dirt on the surface, different illumination conditions due to tilting of the surface and defocusing due to surface bending of the silicon wafers and carbon fibre frames. First studies of these effects indicate an achievable resolution under realistic conditions of 0.4 microns.

8.6 Recommendation

The CERN group recommends the National Instrument system (PCI1408 frame grabber card and IMAQ Vision software library) for use in the Gantry based on the experiences we had with both the Matrox and the National Instrument system. The advantages are that the National Instruments system is more reliable, easier to install and costs less than the Matrox system. The only disadvantage is a slightly lower system speed, which is however of no relevance for the Gantry application. Another advantage might be that programming experience with LabView can be probably easier found in the working groups than Microsoft Visual C++ knowledge.

9 Calibration

The gantry specifications in X and Y required an absolute position accuracy of better than 5 microns and a reproducibility of 1 μm. We have made numerous measurements which verified that the reproducibility is indeed at that level. The absolute accuracy can only be achieved by means of a software correction of the machine positioning which uses a 2D calibration of the X and Y axes. This should be done only after any modifications to the gantry baseplate or moving parts, in particular, that the cable plant and payloads of the axis motors are in their final configuration and that the system is situated in its final working location. A direct measurement of the absolute accuracy for a limited number of locations in X and Y using a laser interferometer is done by Aerotech at the factory and is provided with the machine. However, they warn that this can change due to the difference in the support of the baseplate, the temperature and the change in the machine cable plant and loading. A second direct measurement was done by the CERN metrology lab also using a laser interferometer. The metrology measurements have an accuracy of 1 μm. The results of this measurement are shown in fig. 32. Twenty-five measurement in X are made at 20 mm intervals for each of three positions in Y (at 0, 240 and 480 mm). One sees that excursions of as much as 25 microns are seen in some locations. The CERN measurements had similar features as the Aerotech measurement but there were significant differences as well. It was clear from these measurements that to achieve an absolute position accuracy approaching 2 microns would mean that more points would be needed. A grid spacing of about 20mm was necessary to obtain a 2D calibration file with the required accuracy.

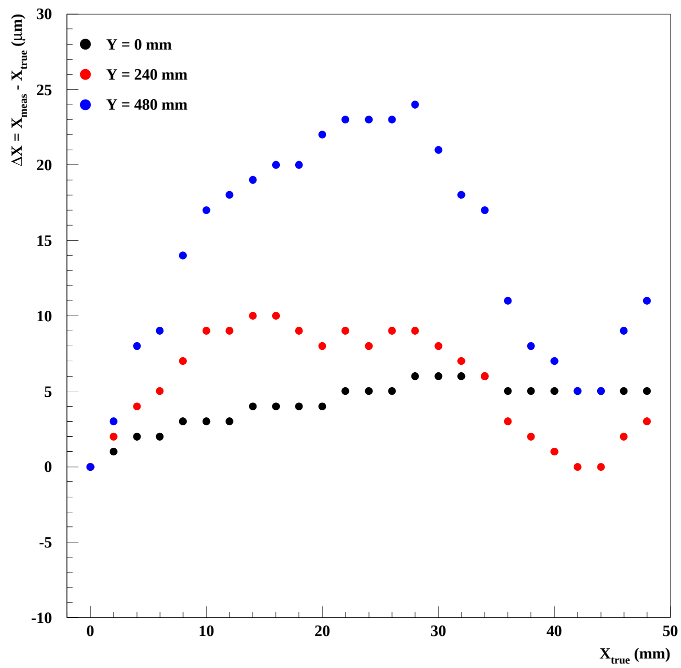

Figure 32: *Plot of positioning error in X as a function of X for 3 different Y positions. This plot was obtained using the CERN laser interferometer measurement system.*

9.1 2-D calibration procedure

To perform the 2D axis calibration an aluminium plate (dimensions 500 mm $\times$ 500 mm) has been used. Metal spheres (ball bearings) with a diameter of 1.5 mm have been positioned in a grid on the plate, with a grid spacing of 20 mm. The calibration plate is illustrated schematically in figure 33. The metrology laboratory at CERN provided a precise measurement of the relative position of the balls with respect to one ball in a corner which served as the origin and another ball at an adjacent corner which served to define the X axis. The plate was then put on the gantry with an initial alignment of the plate done manually to get the origin ball and the other corner ball to coincide approximately with the gantry origin and X axis. The positions of the balls were then measured by the gantry system. The two sets of measurements are then compared, and the difference between the position coordinates of each single ball on the plate, measured by the gantry and by the metrology, has been used to determine the calibration file. Since aluminium has a significant thermal expansion coefficient (22.5 ppm/°C), the dilatation of the plate can compromise the validity of the measurements if the temperature is not kept constant to much better than 1 degree centigrade. Therefore a new plate in carbon fiber is under construction.

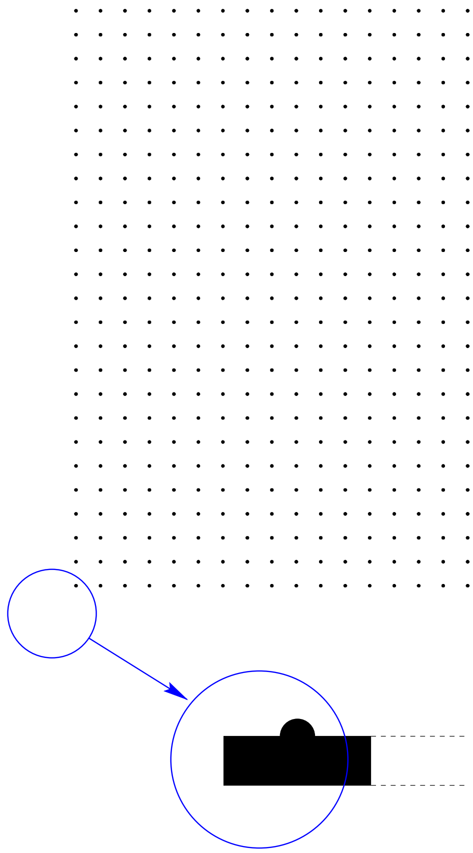

Figure 33: *Grid pattern of ball bearings on the CERN calibration plate. A side view of one ball resting in it hole in the plate is shown at the bottom.*

9.2 2-D calibration file

The following file is an example of a 2D axis calibration file. The text to the right of the semicolon are comments explaining the line entry.

```
:MULTI     ; Designator for multidimensional table information \\
1  2       ; input axes are #1 and #2 (X and Y in CERN system) \\
1  2  0    ; output axes are #1,2, '0' in 3rd entry means less than 3 axes \\
1000       ; 1000 machine steps between samples for input axes #1 \\
1000       ; 1000 machine steps between samples for input axis #2 \\
1000       ; machine X zero is 1000 machine steps into table \\
1000       ; machine Y zero is 1000 machine steps into table \\
5          ; 5 points / row, columns need not be specified.\\
1 1 0   2 2 0   3 3 0   2 2 0   3 3 0 ; Data reflects 2D correction since \\
2 1 0   3 2 0   3 4 0   3 5 0   2 3 0 ; element #3 is always 0. \\
2 3 0   3 3 0   4 1 0   3 5 0   2 1 0 ; Number of rows determined by \\
2 1 0   3 2 0   3 4 0   3 5 0   2 3 0 ; total # of entries in table. \\
1 1 0   2 2 0   3 3 0   2 2 0   3 3 0 ; This example is a 5x5 grid. \\
:END\\
```

The first point in the table is assumed to be at the origin. If it is not then the user must offset the table with the X and Y offset fields. The points in the table are for increasing X and Y input axes positions. If the axes are moving in the negative direction from the start of the table then the corresponding sample distance must be a negative number.

To enable the 2D axis calibration, on the Setup page of the MMI, one clicks on the Browse button to find and specify the 2D calibration file. Then one selects the Global Parameter page and sets the ”Enable2DCalibration” global parameter to 1 (0=disable). Finally one must do a ”hard reset” from the Setup page to activate the calibration. One can verify that the calibration file is being used by comparing the RAWPOS axis value and the MEASURED axis value in the axis coordinate readout display. The RAWPOS gives the uncalibrated machine value and the MEASURED give the calibrated value, therefore the values should be different when a non-zero calibration correction is being applied.

9.3 Results of calibration

The 2-D calibration file as determined by the above described procedure was activated in the MMI. The calibration plate was remeasured and the sphere positions were compared with those from the CERN metrology measurement. The difference in position between those two measurements is shown before and after calibration in figures 34 and 35, respectively. The differences are clearly reduced to 10 microns or below after calibration. To further check the quality of the calibriation, the plate was rotated by 90 degrees and the sphere positions were remeasured and compared to the metrology result. This comparison is shown in figures 36 and 37, again before and after calibration. The differences after calibration are again reduced to the 10 micron level or better although some systematic shifts are still present and are under investigation.

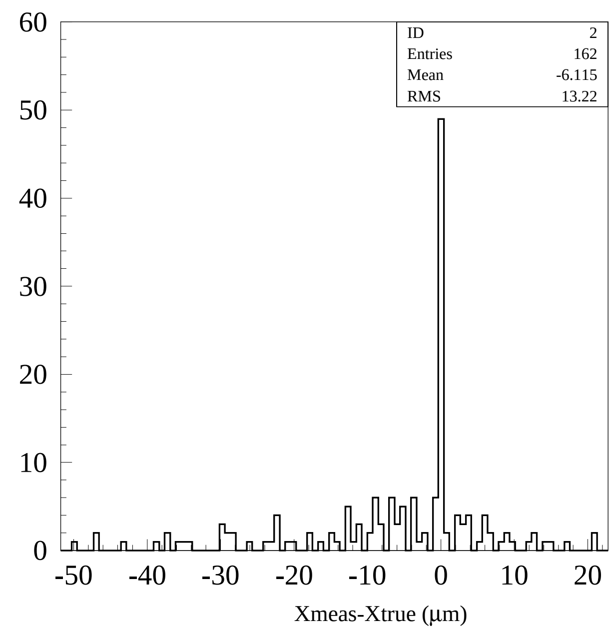

Figure 34: *Difference in measured X position of calibration plate spheres between gantry and CERN metrology, before calibration.*

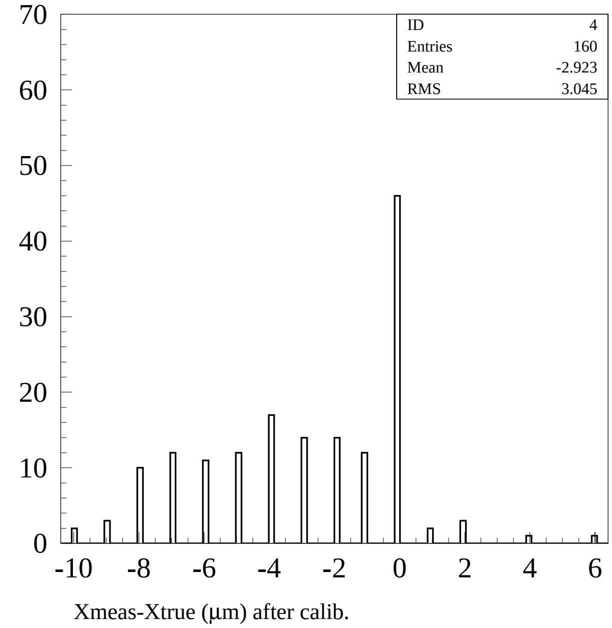

Figure 35: *Difference in measured X position of calibration plate spheres between gantry and CERN metrology, after calibration.*

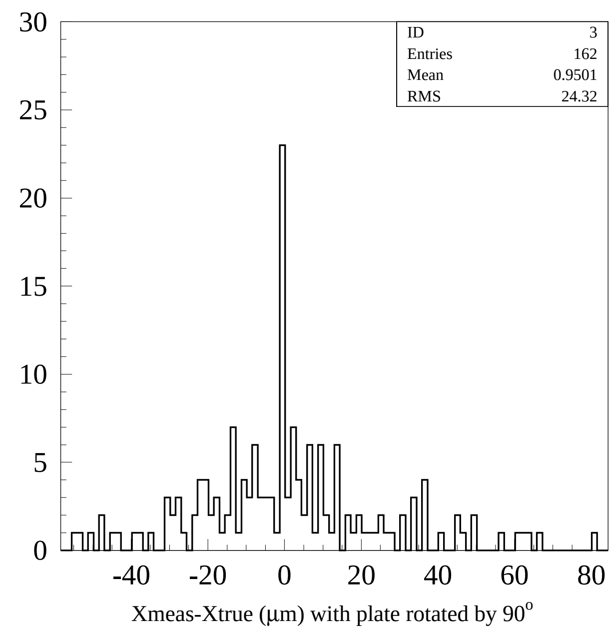

Figure 36: *Difference in measured X position of spheres on plate rotated by 90 degrees between gantry and CERN metrology, before calibration.*

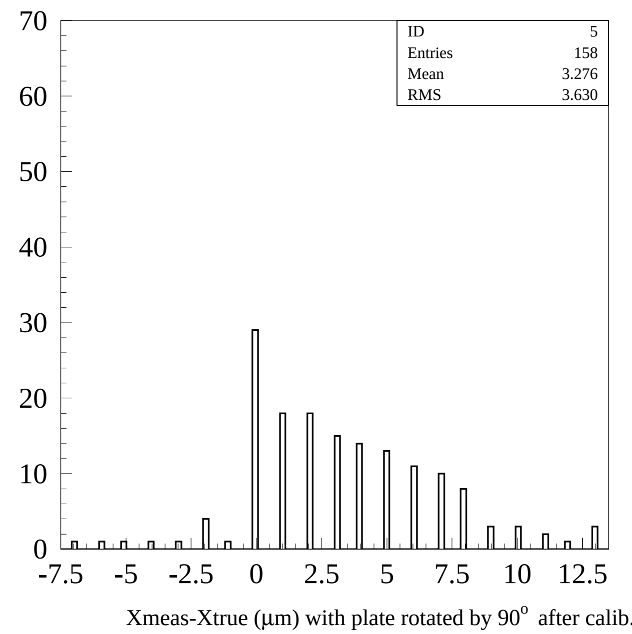

Figure 37: *Difference in measured X position of spheres on plate rotated by 90 degrees between gantry and CERN metrology, after calibration.*

10 Performance

The performance of the automated module assembly has been evaluated for accuracy and reproducibility of component placement, and for the speed of the assembly procedure.

10.1 Pick and place accuracy

The tests performed to measure the accuracy of component placement in the automated assembly were broken down to the basic steps in order to check where the inaccuracies occurred. The basic steps which can introduce inaccuracies are:

- measurement of the fiducial mark
- movement of the component during the pick-up operation
- inaccuracy of the X and Y displacement
- inaccuracy of the ϕ rotation
- movement of the component during the place operation
- movement of the component during the glue curing

The accuracy and reproducibility of fiducial mark measurement using the pattern recognition system has been discussed in section 8 and is less than 1 micron. In figure 38 the difference in X and Y positions before and after pick-up and place down of two fiducial marks on a sensor is shown. The pick-up head lifts up the sensor a distance of several centimeters and then replaces it without any X or Y motions. Both the means and RMSs of the distribitions are less than or on the order of 1 micron. A displacement of 6 cm in X is added to this test and the results are shown in figure 39. The means of the distributions show small offsets of up to 1.4 microns which can be attributed to the X and Y inaccuracies of the gantry motion. The RMSs are in the range 0.8 to 1.3 microns.

The accuracy of the ϕ rotation was measured by rotating a solid plate held by the pick-up tool under the camera view. The distance from the rotation axis to the camera viewing axis was 6 cm and a rotation of 0.1 degrees was used. The displacement of the fiducial mark was used to determine the absolute rotation. As shown in figure 40, the absolute rotation was correct to better than 0.001 degrees and the RMS was 0.0016 degrees. This corresponds to a error in position of a sensor fiducial mark of about 1.6 microns in the X-Y plane after rotation of a typical CMS silicon sensor. It corresponds to an error of about 1.1 microns for the sensor size (approximately 6cm x 6cm used in the following pick and place test.

The final test involved a realistic module assembly sequence where the glue was applied to the frames, the sensors were picked up, rotated appropriately, moved to the desired position over the frame and placed down. The difference in fiducial positions between the pairs of closest fiducials of the two sensors were then measured after overnight curing of the glue as shown in figure 41. Again, one sees a typical accuracy of relative placement between the two sensors of 2 to 4 microns in each coordinate. This gives an overall accuracy in the X-Y plane of 3 to 5 microns thus meeting the design goal of 5 microns.

10.2 Speed of module assembly

The time required for the complete assembly process for 4 modules has not been measured precisely owing to the absence of a realistic hybrid for mounting. However, an estimate has been made based on the prototype assembly pieces. The expected time for assembly of 4 modules with pattern recognition is about 30 minutes not including the glue preparation time. This time would increase by 10-15 minutes without the use of pattern recognition. Including 15 minutes of preparation for one set of glue syringes needed per hour (the typical working time of likely glues), the total throughput would be 12 modules per hour.

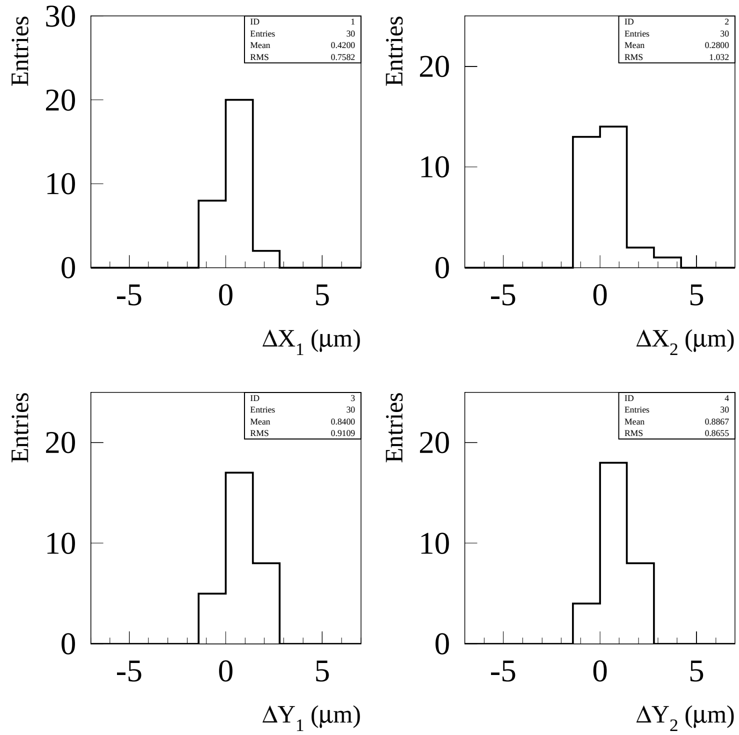

Figure 38: *Accuracy of X-Y positioning of sensor after pick, Z motion and place down.*

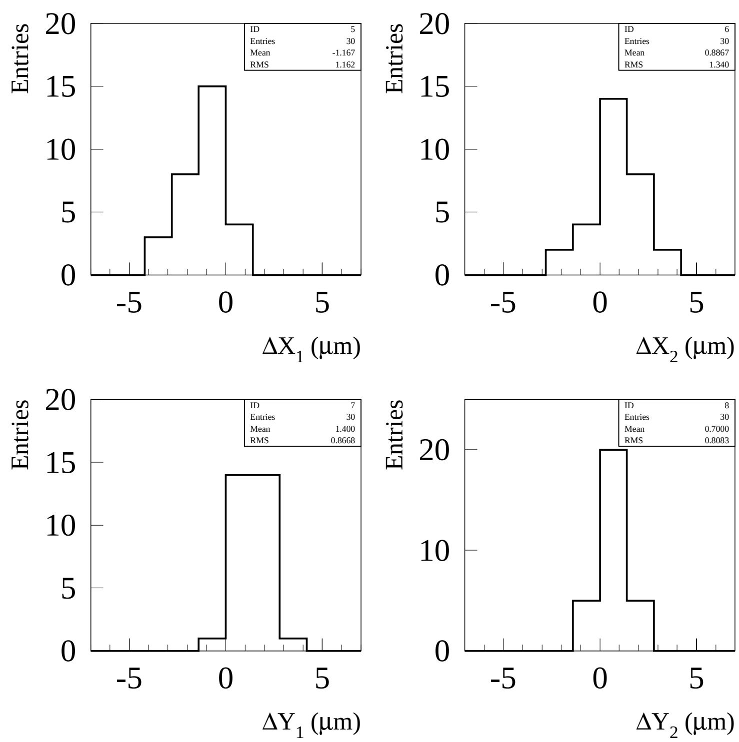

Figure 39: *Accuracy of X-Y positioning of sensor after pick, Z motion, 6cm X motion and place down.*

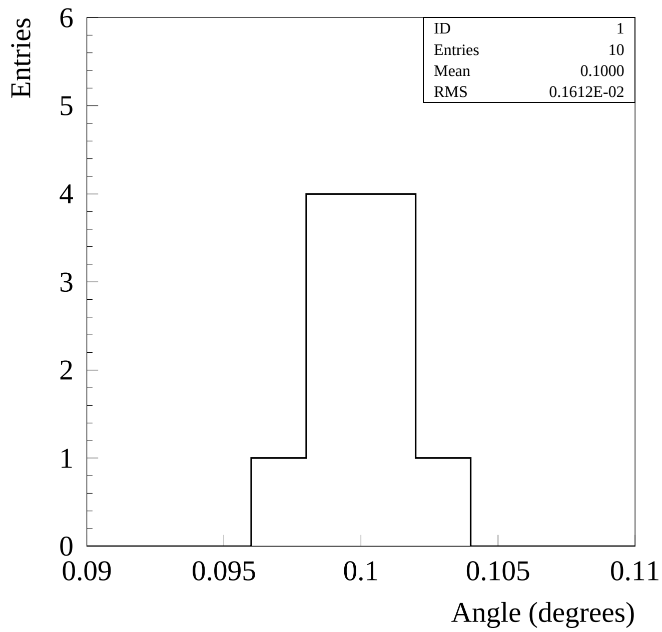

Figure 40: *Distribution of measured ϕ rotation after requested motion of 0.1 degrees.*

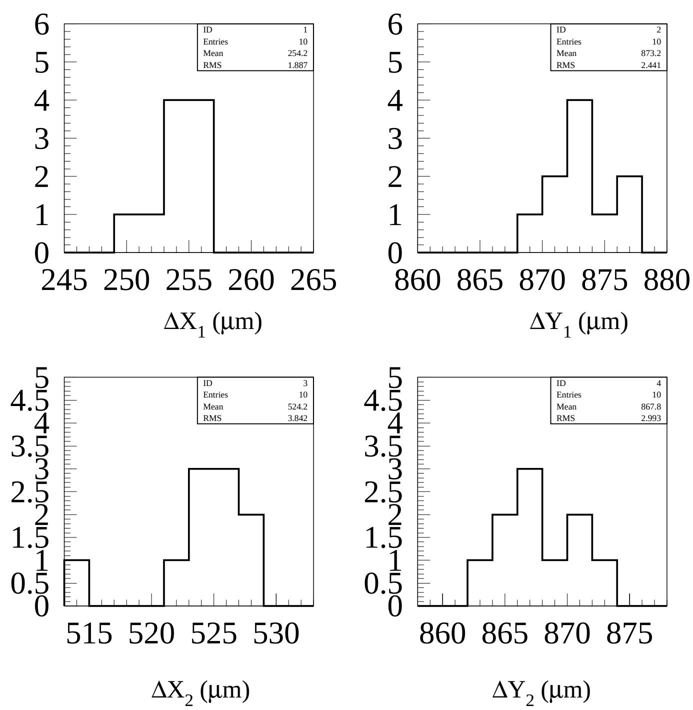

Figure 41: *Accuracy in X and Y of relative positioning of sensor after full module assembly sequence including gluing.*

A Gantry specifications from CERN purchase order

The specifications for the CERN gantry system as given in the original purchase requisition are as follows:

1 GANTRY SYSTEM, based on turn key system where CERN only need to supply a PC

- 500 x 500 mm travel range with linear motor and linear encoder on both sides of bottom axis and upper axis
- 100 mm travel in vertical with reinforced bearing for heavy payload and high accuracy
- Phi axis with harmonic drive zero backlash
- U600 PCI PC based controller for up to 8 axis with drive rack and all cabling needed for operation (PCI based controller was never fabricated, we agreed to use the U600 PC/AT controller with the addition of one 4EN-PC encoder expansion card)

optional equipment ordered:

- 1 Joystick
- 1 Handwheel assembly and cable to connect to DR500 rack

Note: system is mounted and orthogonalized onto a baseplate to meet the following specifications:

X-Y : accuracy $\pm$ 5 microns

- resolution 1 micron
- payload $\leq$ 50 kg
- minimum clearance between plate and y axis: $\geq$ 100 mm

Z : with reinforced bearing

- accuracy $\pm$ 3 microns
- resolution 1 micron
- payload $\leq$ 20 kg

ϕ : accuracy $\pm$ 5 arc-sec

- resolution 1 arc-sec
- payload $\leq$ 17 kg

B Parts list

B.1 Aerotech Gantry Positioning System

1. AGS10000 Cartesian Gantry Positioning System with 4 axis motion (X,Y,Z,U) and a working area of X=50cm and Y=50cm.
2. Dual X axis linear motor drives type BLM325 with Renishaw (glass rule) encoders
3. Y axis linear motor drive type BLM264 with Renishaw encoder
4. Z axis rotary motor drive type BM75E with 20:1 reduction gearbox
5. U axis rotary motor drive type BMS100 with 1000 line amplified sine encoder and a 250x multiplier box. A custom pattern of 4 tapped holes of diameter M3 on each side of the U axis support bracket, and custom pattern of 8 tapped holes of diameter M3 on bottom of plate attached to the U axis drive is furnished by supplier (note: custom hole pattern reference can be found on CERN gantry order drawings at Aerotech).

6. Aluminium base plate of size X=96.52cm, Y=91.44cm and thickness 5.04cm with custom pattern of tapped holes of diameter M5

7. DR500R-4-B-80 19” rack mount drive chassis with 4 brushless servo amplifiers matched to the motor drive types

8. U600 Series Motion Controller system consisting of a U600 PC/AT ISA bus card containing a 4-axis motion controller using a 66MIPS i960 RISC processor with 4MB memory

9. U600 4EN-PC 4-axis encoder and drive interface expansion ISA bus card

10. Cables between U600 cards and DR500 drive chassis and cables between DR500 drive chassis and the 4 gantry axis motors

11. JBV Joystick

12. HW500-SBX Handwheel assembly and cable

13. MMI600 Machine Man Interface software package

B.2 PC

CERN standard PC + monitor at time of purchase (March 1999):

1. 400 MHz Vobis Pentium II, running Windows NT, 128 MB memory, 6 GB hard drive, 3 ISA and 3 PCI slots.

2. 21” IIyama Vision Master 502 color monitor.

B.3 Optical components

The following optical equipment is used on the CERN system:

1 CCD camera EEV PC46320 Photon Colour CCD Camera, 2/3” CCD with image area of 8.5 x 6.6 mm.

  - Number of active lines: 575
  - Number of pixels per line: 576
  - Horizontal resolution: 300 Tv lines
  - Colour system: CCIR standard
  - Video Output: BNC, 75 ohm
  - Has standard C mount lens fitting

- microscope optics (100x, 200x magnifiers from Marcel Aubert SA, Switzerland)
- coaxial illumination optical element (705 E-77 29950/92 from Marcel Aubert SA)
- variable intensity illumination source and 1m fiber optic light guide (Volpi Intralux 20HE, Volpi AG CH-8952 Schlieren, Switzerland)
- digital lines generator [optional], (Marcel Aubert SA)
- 14” color monitor for principal camera (Sony Trinitron PVM-1440QM)
- 2nd optional CCD camera for viewing glue dispensing
- B&W monitor for 2nd camera

The measured field of view of the primary camera will depend on the monitor used (some have nearly square shape). We currently use a standard TV monitor with a 4/3 aspect ratio. Our field of view is 2.4mm by 1.7mm with the lower (100x) magnification optic which was used for the calibration procedure. The normal assembly procedure uses the 200x magnification optics.

B.4 Pattern Recognition System

The parts lists for the two pattern recognition systems that were tested are given below.

For the Matrox based system:

- Matrox Imaging Library MIL-32/CD LIbrary 6.0 for Windows NT
- Matrox Corona LC/4/E PCI frame grabber card
- DH44-TO-8BNC/O cable adaptor

For the National Instruments based system:

- LabView 5.0 (software package)
- IMAQ Vision Library, P/N 777411-03
- PCI-1408 Frame Grabber, P/N 777361-01

B.5 Vacuum system

list of relevant vacuum system parts to go here

C Digital IO interface schematics

Figures 42 to 44 make up the complete circuit schematic for the 24 digital outputs in the digital IO interface box. Figure 45 gives the schematic for the 24 digital inputs.

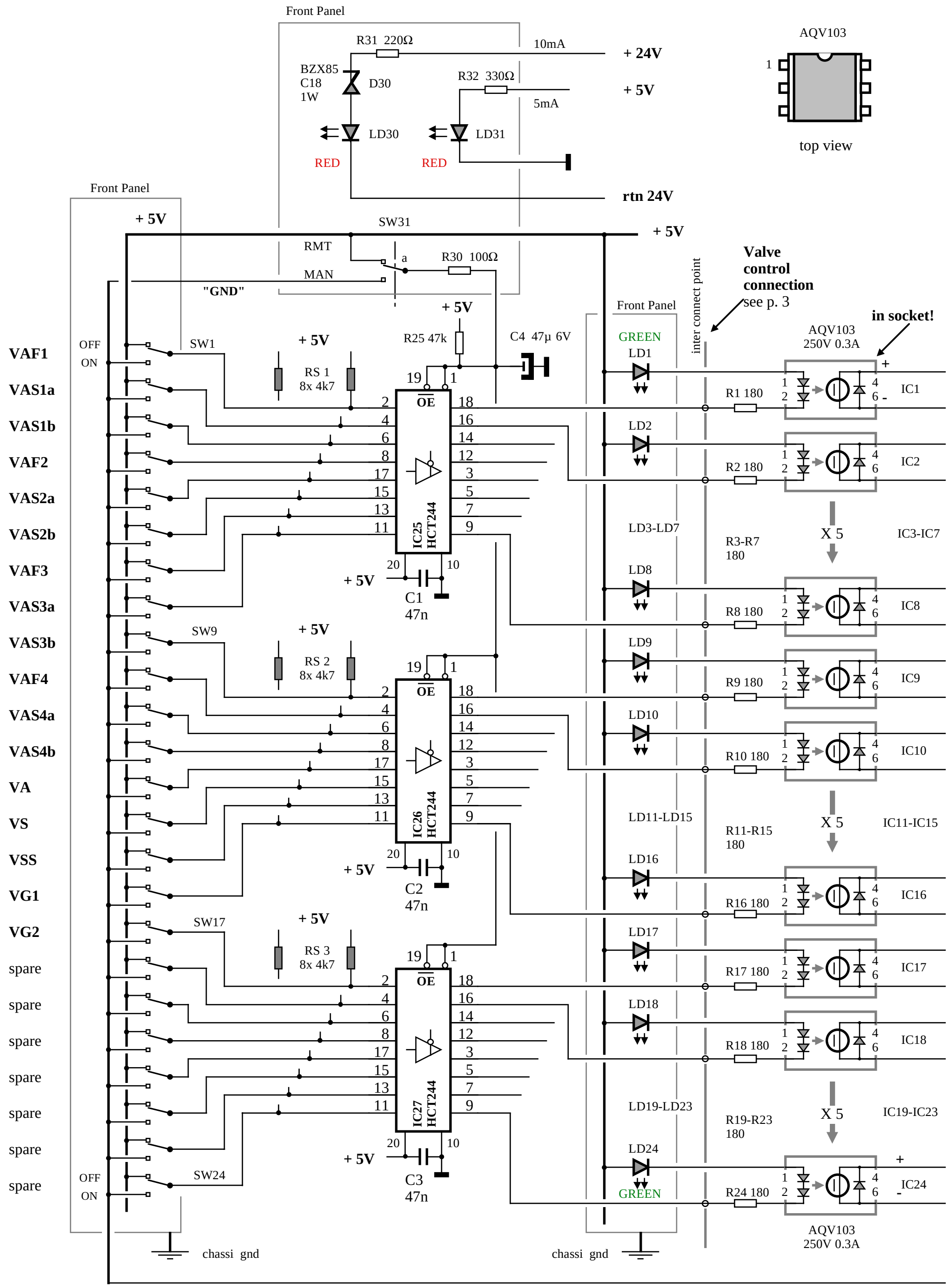

Figure 42: *Electrical schematic for the digital output box front panel.*

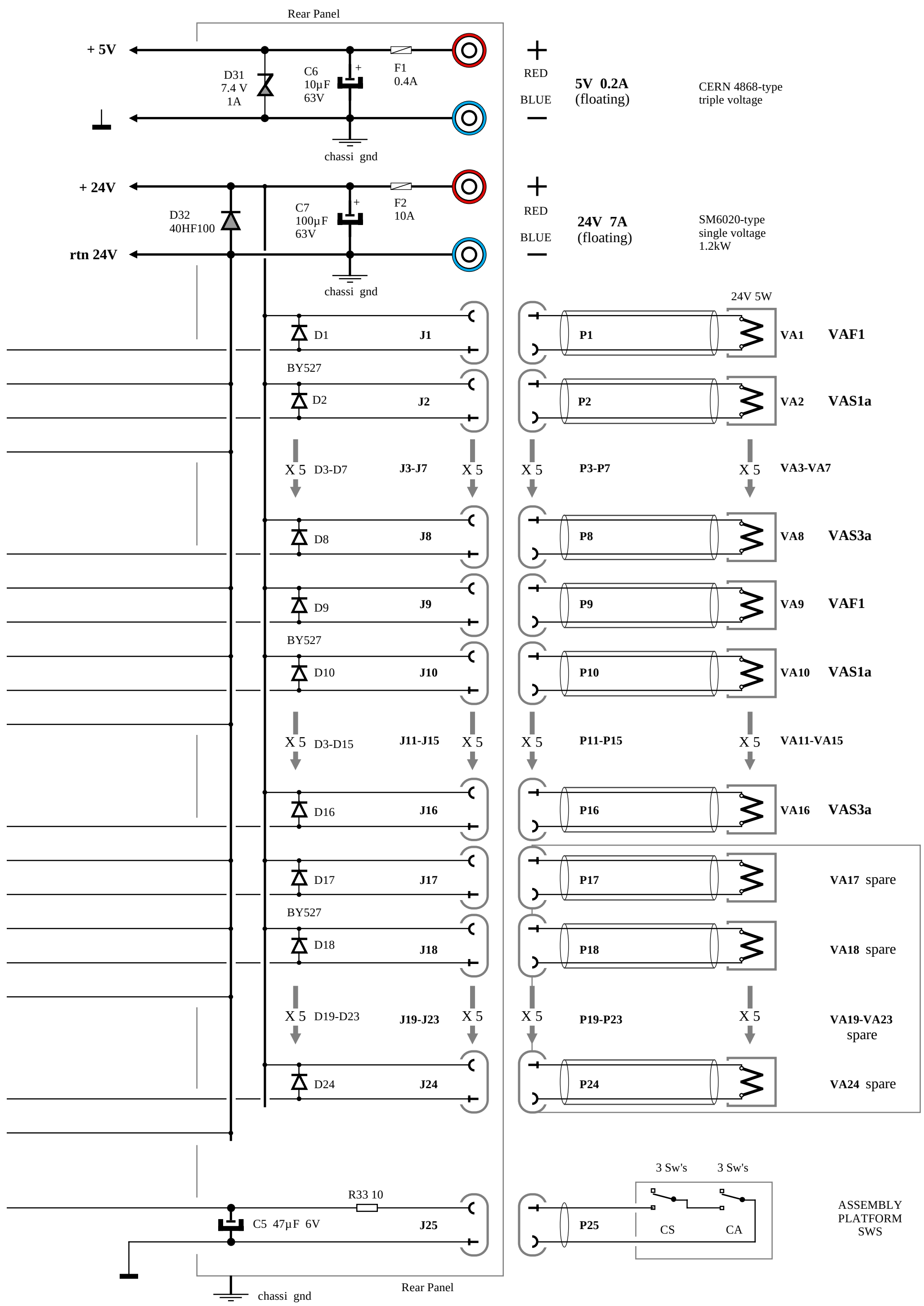

Figure 43: *Electrical schematic for the digital output box back panel.*

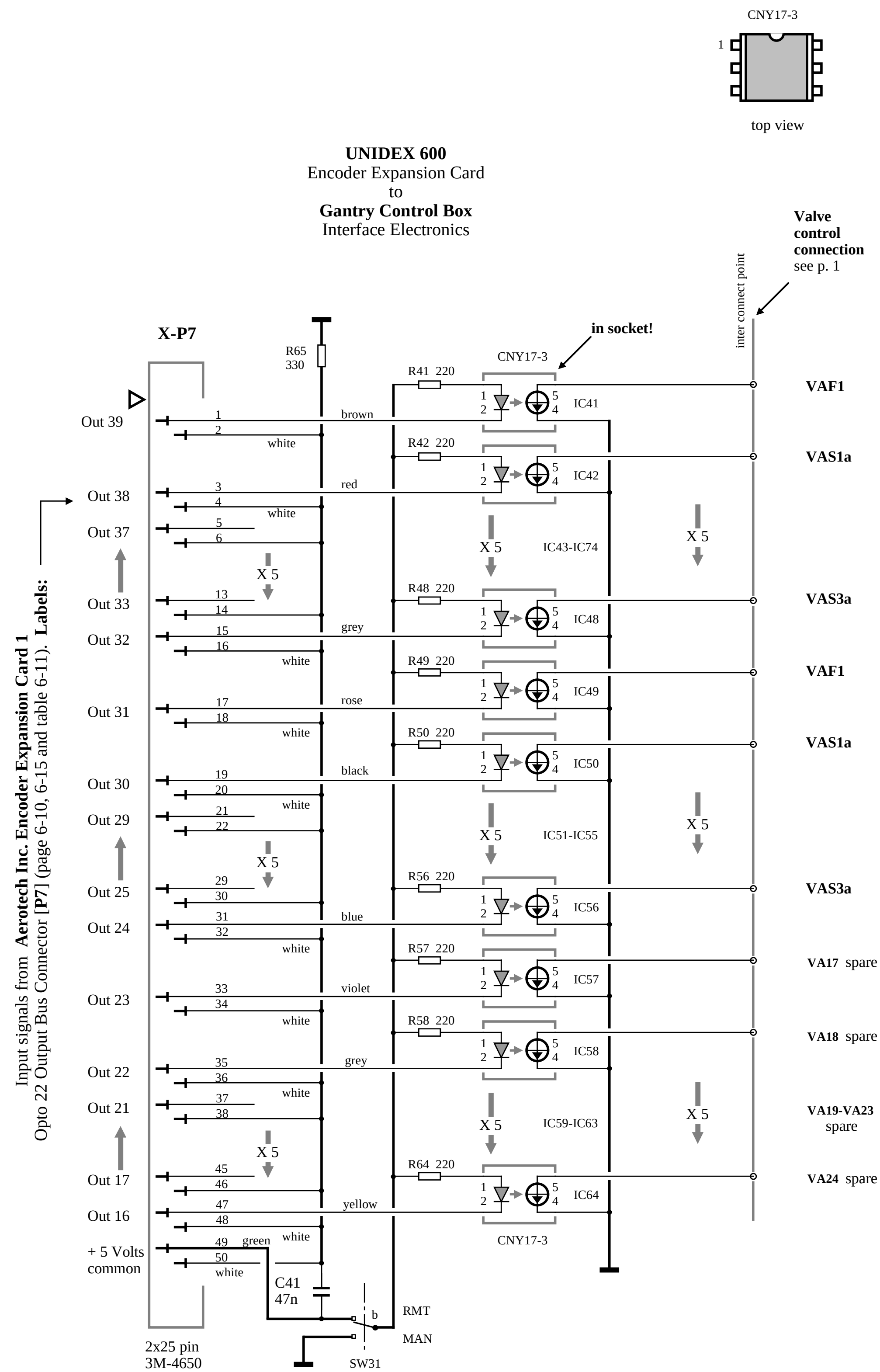

Figure 44: *Electrical schematic for digital output signals giving mapping between encoder expansion card connector pins and some of the assembly program signals (vacuum valves).*

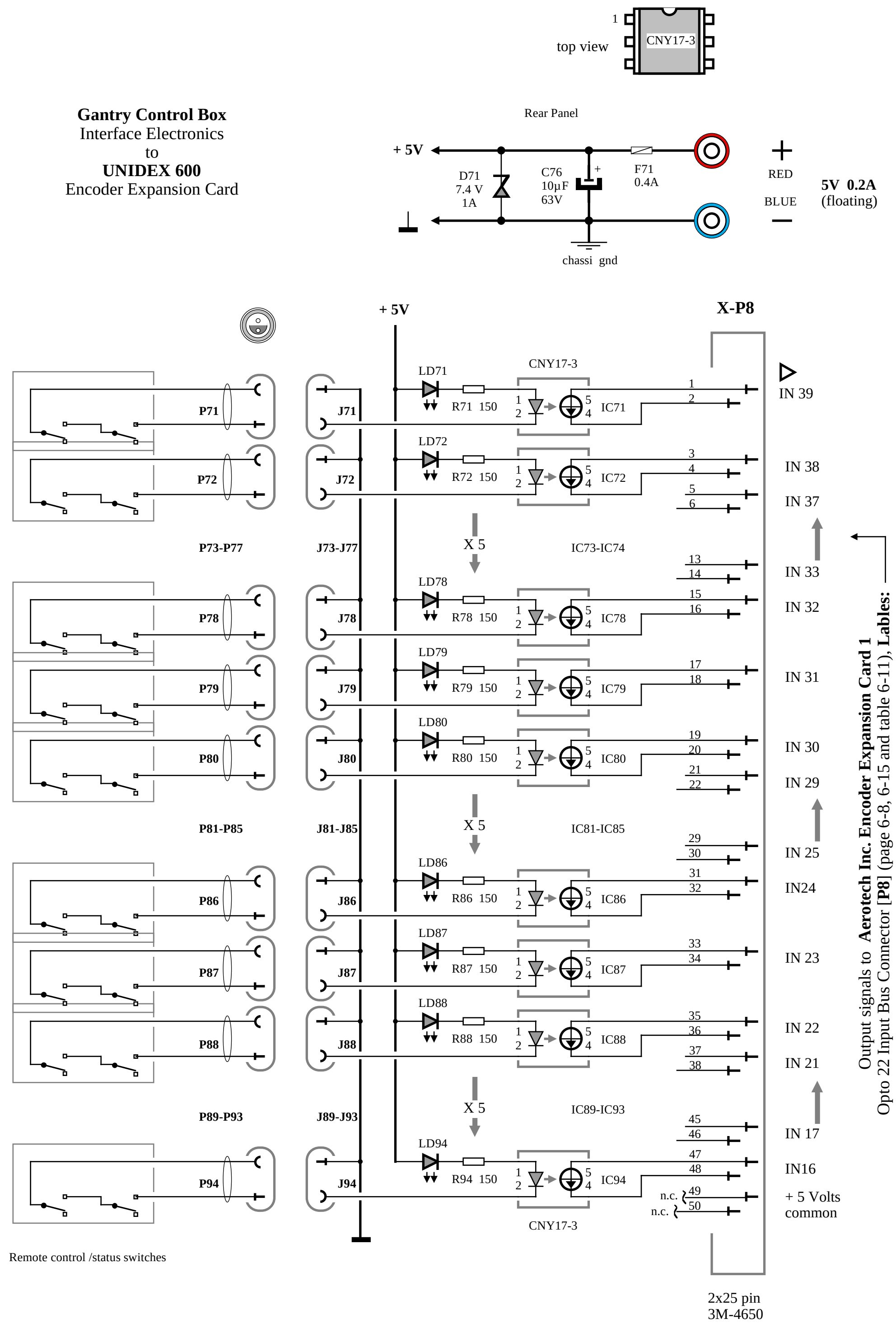

Figure 45: *Electrical schematic for digital input signals gving mapping between encoder expansion card connector pins and the external input sensor circuits.*

References

[1] Technical Design report of the CMS Tracker,
CERN/LHCC 98-6, CMS TDR 5, 15 April 1998,
Addendum to the CMS Tracker,
CERN/LHCC 2000-016, CMS TDR 5 Addendum 1, 21 February 2000.