



STM Digital Control System

Versions 06 & 08

Brief Technical Description

Sigma Scan

Moscow

2011

1. Introduction

Digital control system is designed to control different STM scanning modes, lithography, obtain the surface spectral characteristics, etc., at low level of noise and high speed.

The document contains a brief technical description of the digital electronic control system (DCS), versions 06 and 08, its structure and composition, the basic modes of operation and specifications.

DCS version 06 is used with low temperature (LT) scanning tunneling microscope (STM) GPI-CRYO.

DCS version 08, derived from version 06, is used with Omicron's LT STM and STM-1.

Versions 06 and 08 differ in high voltage (HV) board used for positioners, remote boxes and software.

1.1. The main distinctive features of the electronic control system

Distinctive features of the DCS versions 06 and 08 are as follows:

- Digital signal bus on the motherboard. All Digital/Analog Convertors (DACs) are placed directly on the functional boards to reduce the impact of digital signals on analog circuits and increase the number of DAC channels and, accordingly, the number of actuators to control. The digital signal bus can use DACs with both parallel and serial interfaces.
- Parallel PC interface is connected to DSP board directly, without any use of the bus on the motherboard.
- 16-bit ADC AD7677 from Analog Devices with a small conversion time (1 μ s), high linearity (less than 1 LSB) and low-noise (S/N + D: 94 dB) is used for the tunneling current measurement.
- X,Y scanning signals are formed with 3 DACs – scanning, scaling and offset. The scaling and offset DACs enable the system to scan large areas at high resolution and low non-linearity. 16-bit DACs with a small differential and integral nonlinearity (DNL and INL \leq 1LSB) from Linear Technology Company are used.
- For precise Z movement control ultra-low-noise 20-bit DAC AD5791 from Analog Devices is used.
- Three direct digital synthesizers (DDS) form sinusoidal signals with software-controlled amplitude, frequency and phase for software-driven scanning tunneling spectroscopy (STS and IETS) without the use of external devices.
- Superfast high voltage amplifier (HVA) PA94 from APEX Company is used for Omicron's STMs positioners (DCS of modification 08). It provides up to 800V (\pm 400V) control signal with slew rate 100V/ μ s at positioner piezo load.

1.2. Digital Control System structure

Fig. 1.1 shows a block diagram of a control system version 06.

For LT STMs a current-to-voltage converter (I/U converter) is situated outside the vacuum chamber since its components are not designed to work at helium temperatures. In STMs operating at room temperature (GPI-300 and Omicron STM-1), I/U converter is located inside the STM head close to the probe (tip). In that case the output signal of the converter is

applied directly to the instrumentation amplifier (see section 3.2 for details) bypassing built-in I/U converter in a box.

The central part of the DCS version 06 is ADSP/ADC board. This board carries a Digital Signal Processor (DSP) from Analog Devices with program memory and flash memory. DSP executes a program loaded into its program memory. The main part of the program is PID-controller with various additional features available in the same time – such as the accumulation of data from ADC, the generation of signals at the DACs output, etc. The program memory is loaded from flash ROM at power-on time. Alternatively, it could be loaded directly from a file on PC disk. Firmware in flash memory can be updated as well.

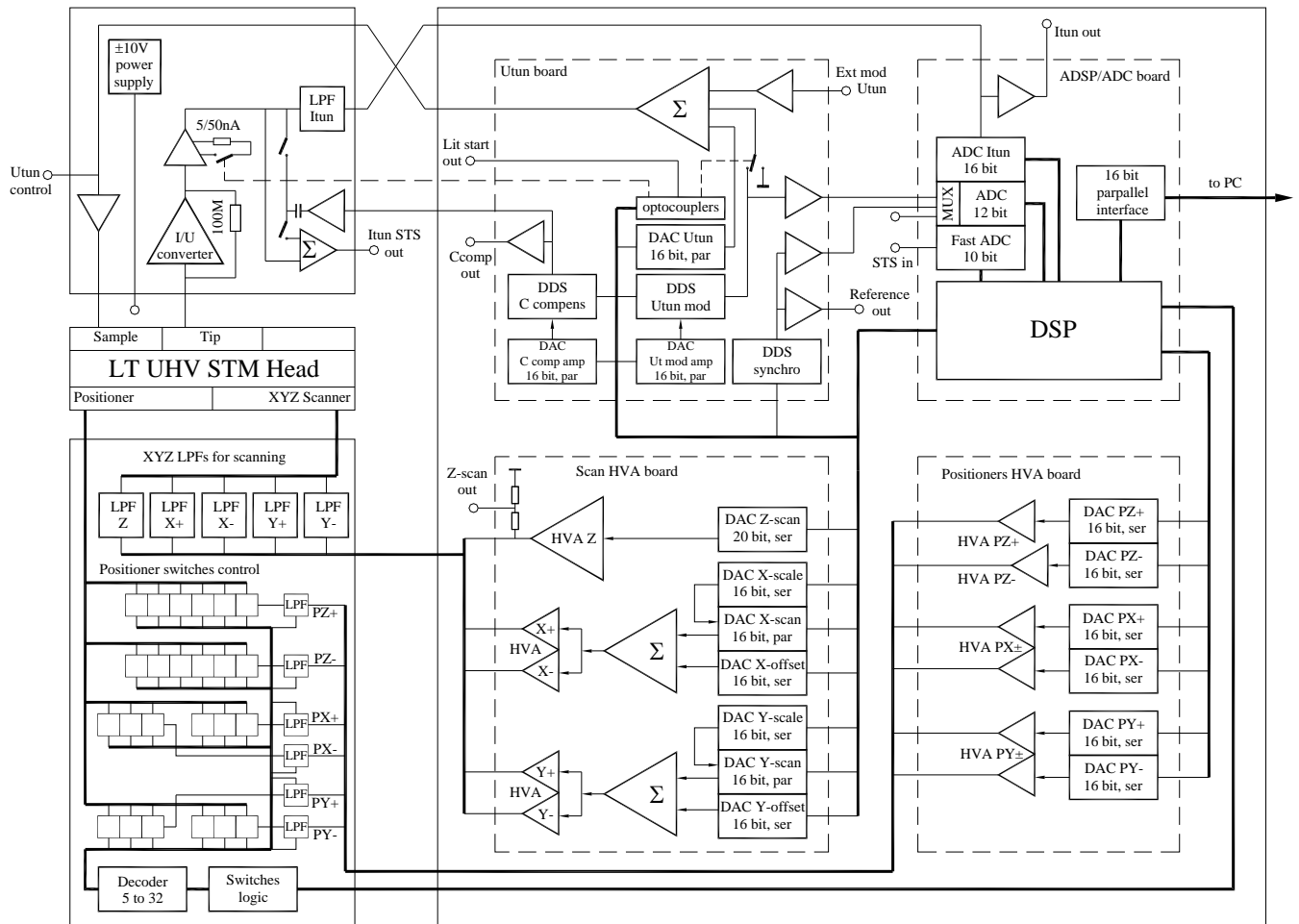


Fig. 1.1 A block diagram of control system version 06

The amplified signal of the tunnel current is fed to a 16-bit Analog/Digital Converter (ADC I_{tun} 16 bit), which forms the input 32-bit word for the PID-controller. DSP performs 64-bit computing for the correct 32-bit output value. If necessary, output could be amplified up to ± 210 V. In case, 32-bit PID-coefficients are properly configured one can obtain a linear control with 32-bit accuracy for any input signal in 16-bit range. DSP makes it possible to accumulate and store up to 131072 16-bit values, taken from the ADC or recorded by the user. DSP communicates with the host computer by means of a parallel interface accepted by the board, which is installed in the host personal computer (PC).

The ADSP/ADC board consists of:

- Digital signal processor with RAM, flash memory and 16-bit output register logic of TTL level;

- 16-bit ADC for tunneling current measurement (ADC I_{tun} 16 bit);
- 10-bit fast ADC for fast processes measurement (Fast ADC 10 bit);
- Multiplexed 12-bit ADC (MUX ADC12 bit);

Amplified analog I_{tun} output for monitoring by an oscilloscope (I_{tun} monitor), as well as Fast ADC input ("STS in") is available on the ADSP/ADC board.

U_{tun} board is dedicated for tunneling gap voltage formation as well as its modulation. Tunneling gap voltage is formed by 16-bit parallel DAC (DAC U_{tun} 16 bit, par). It is possible to choose internal or external source of modulation. For external modulation a coaxial input (Ext mod U_{tun}) is provided. In case internal U_{tun} modulation reference signal and signal for stray capacitance compensation are formed on this board too. Frequency and phase of sinusoidal modulation, reference and compensation signals are formed by three separate DDSs and can be set by software independently. Amplitude of U_{tun} modulation signal (U_{mod}) and compensation signal (C_{comp}) is regulated by 16-bit parallel DACs (DAC U_t mod amp 16 bit, par and DAC C_{comp} amp 16 bit, par correspondingly). Amplitude of reference signal is constant. There are coaxial outputs "Reference out" and "Comp out" on the board. In addition compensation signal is fed to remote box for mixing with the I_{tun} signal there. Two inputs of MUX ADC 12 bit are loaded with modulation and reference signals in order to have opportunity to perform in future lock-in processing digitally by DSP firmware.

Tunneling gap voltage, modulation (U_{tun} mod) and external modulation signal are fed to an adder (Σ). It is possible to disable the modulation by optocoupler switch, software controlled. Also, it is possible to run an external device or process with software generated pulses, e.g. to form lithographic pulses by external generator. A coaxial output (Lit start out) is devoted for this purpose.

Scan HVA board is designed to generate high-voltage signals Z, X, Y to control STM scanner. For precise Z movement control ultra-low-noise, 20-bit DAC AD5791 from Analog Devices is used. DAC output is amplified to $\pm 210V$ and then feeds Z piezo. Also there is an attenuated (1/2.5) coaxial output (Z-scan out) on the board. It can be used for monitoring Z signal on an oscilloscope.

Each of X,Y scanning signals is formed with three DACs – scanning (DAC X,Y-scan 16 bit, par), scaling (DAC X,Y-scale 16 bit, ser) and offset (DAC X,Y-offset 16 bit, ser). Scaling DACs control gain scale from 1/65536 to 1. Offset DACs outputs are summed with scanning DACs outputs to perform permanent while scanning offset of scanned area. Resulting signal is amplified with two paraphase HVA, X +, X- and Y +, Y- up to $\pm 210V$. In remote HV-box, close to STM scanner, these signals are passed through low-pass filters LPF Z, LPF X +, LPF X-, LPF Y +, LPF Y-.

High-voltage stabilized power $\pm 220V$ is used to supply Scan HVA board.

There are two remote units in the system: "HV-box" - for scanner control signals and "LV-box" for low analog signals such as I_{tun} and U_{tun} .

LV-box includes an I/V converter with instrumentation amplifier and low pass filter (LPF) of the tunneling current channel and a tunneling voltage output buffer amplifier. Software-controlled switch makes two ranges of tunnel current measurement available - $\pm 5nA$ and $\pm 50nA$. Besides regular (through LPF) output, tunneling current channel has a wider bandwidth output for the spectral measurements (I_{tun} STS out). Both output I_{tun} signals may be mixed with C_{comp} signal for stray capacitance compensation.

The contour of the feedback loop includes a tip, I/U converter, instrumentation amplifier, LPF, 16-bit ADC, 32-bit PID-regulator in the DSP, the Z DAC, HVA Z with a low pass filter (LPF Z) and Z piezodrives of the STM scanner to control the tip-sample distance.

If DCS version 06 is used with LT STM GPI-CRYO, 6-channel card (Positioners HVA board) should be used to control the positioners of this STM. This board is intended to generate high-voltage ($\pm 210V$) control signals (PZ+/-), (PX+/-), (PY+/-) of a special shape. The signals are formed by serial DACs, amplified with HVAs and sent to the 24 high-speed switches with appropriate logic. Fast switches provide a sharp front for slip-stick motion of the piezo-positioner. To prevent extra noise on positioner ceramics, LPFs at outputs can be switched on while slip-stick motion is not required. LPFs, switches and logic are assembled in remote HV-box.

If DCS version 08 is used with Omicron's STMs, 1-channel ultra high voltage card (Positioners UHVA board) should be used to control the positioners of this STM. This board is intended to generate high-voltage ($\pm 400V$) control signals PZ, PX, PY of a special shape. The signals are formed by one serial DAC, amplified with UHVA and sent to positioners through dispatcher switches with appropriate logic. To prevent extra noise, all positioner ceramics can be grounded while slip-stick motion is not required. While use Z positioner as an additional Z-direction driver, LPF PZ can be used to reduce noise amplitude. LPFs, switches and logic are assembled in remote HV-box.

Block diagram of DCS version 08 is shown in Fig. 1.2.

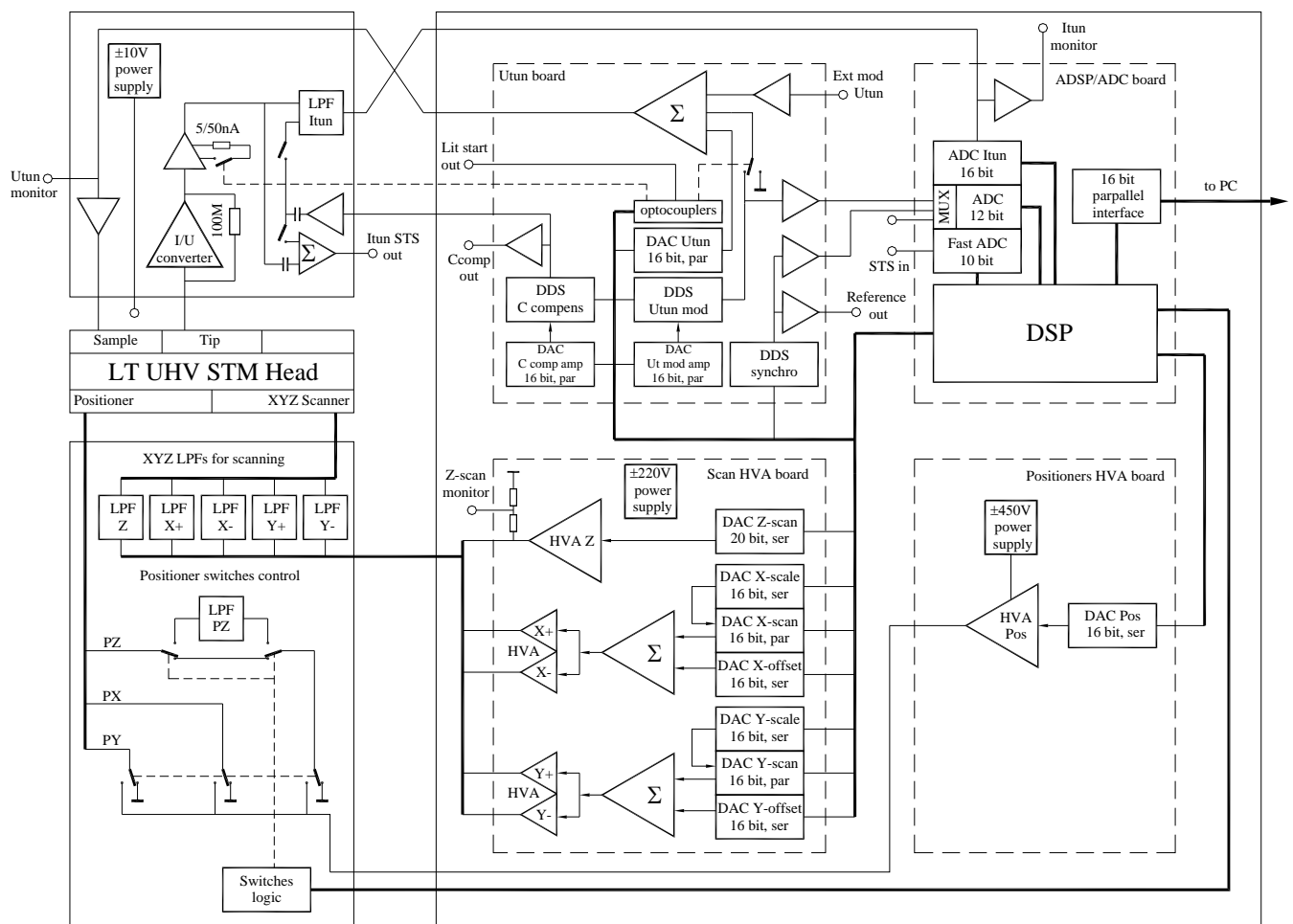


Fig. 1.2 Block diagram of a digital control system version 08

1.3. Software

The software consists of two main parts:

- Top-level program running on the host computer controls the STM by commands sent to DSP. Top-level program manages PC-DSP data exchange, displays current parameters and characteristics, the scan and measurements results, and performs a mathematical data processing.
- Low-level program (firmware), that is loaded into DSP memory, implements direct control of the functional units of the system, as well as data transfer to the host computer.

Detailed software description one can find in a separate manual.

Firmware upload

In normal mode at power-on, DSP loads its program memory with the firmware from the flash ROM and runs it. Alternatively, it could be loaded directly from a file on host-PC. To do this one should first disconnect the only slide switch, situated in upper-left corner of the ADSP/ADC board. This will force DSP to wait for uploading from PC. Then power-on DSP and load the firmware with a help of *IdmaLoad.exe* program. For normal operation the slide switch should be connected back.

Firmware upgrade

To upgrade the firmware DCS should work in normal mode (with connected slide switch). First check if the system is able to transfer data between PC and DCS. Just run *brd.exe* and see reasonable data read from DSP. Then run *Flashload.exe*, specify the path to a **.bnm* file with updated firmware, erase old one and upload new one. After this you should turn DCS off and power it on again. This will force to reset the signal processor and load the new version of the program from flash ROM into DSP memory. Run *brd.exe* again and make sure that the new version is running.

A more detailed description could be found in a separate software manual.

2. DCS Features and Specifications

DCS Functionality

- safe tip to surface approach;
- digital feed-back loop for tunnel current stabilization;
- automatic positioning of the sample surface with respect to the probe;
- sample surface scanning in several modes;
- spectroscopic measurements of the sample surface;

Electronics unit

- digital signal processor (25 ns cycle and 80Kb memory on the chip) with 128Kw RAM and 128Kb flash ROM;
- low noise (0,6 fA / $\sqrt{\text{Hz}}$), low input bias current (1 pA) tunneling current preamplifier;
- high-speed (1 MSPS) 16-bit ADC with high linearity (INL: ± 1 LSB Max) and low-noise (S/N + D: 94 dB Typ) for the tunneling current measuring;
- 8-channel (200 KSPS) 12-bit ADC for various control signals;

- high-speed (20 MSPS) 10-bit ADC for scanning tunneling spectroscopy;
- high linearity (DNL and INL: 1 LSB Max) 16-bit parallel DAC with a low pass filter for the tunneling voltage;
- three DDSs with 10-bit integrated DAC for scanning tunneling spectroscopy:
 - DDS with controllable amplitude for U_{tun} modulation;
 - DDS with controllable amplitude for Ccomp signal;
 - DDS with constant amplitude for reference signal
- three DACs scheme to form X and Y scanning signals:
 - scanning 16-bit parallel DAC with high linearity (DNL and INL: 1 LSB Max);
 - scaling by a factor of between 1 and 1/65536, 16-bit serial DAC with high linearity (DNL and INL: 1 LSB Max);
 - offsetting 16-bit serial DAC with high linearity (DNL and INL: 1 LSB Max);
- 20-bit DAC with ultra low noise for the scanner motion in Z direction;
- five high-voltage, low-noise amplifiers $\pm 210\text{V}$ for X, Y, Z scanner, X and Y has paraphase outputs;
- six 16-bit serial DAC with high linearity (DNL and INL: 1 LSB Max) and six high-voltage, low-noise amplifiers $\pm 210\text{V}$ for X, Y, Z positioners of LT STM GPI-CRYO (PZ +, PZ-, PX +, PX-, PY +, PY-);
- 24 high-speed (6kV/ μs), low resistance while opened (no more than 6 ohms) MOSFET switches with a 5-bit decoder for slip-stick motion positioners X, Y, Z;
- one 16-bit serial DAC with high linearity (DNL and INL: 1 LSB Max) and one UHV superfast low noise amplifier $\pm 400\text{V}$ for X, Y, Z positioner of Omicron's STMs;
- 19" (4U) industrial chassis with a motherboard that has a digital signal bus with 9 slots.
- 16-bit parallel interface with the host-computer;

The tunnel current stabilization feed back loop

32-bit digital PID-controller based on DSP with a maximum sampling rate of 10 microseconds. All PID-controller parameters are software controlled.

Tunnel current (I_{tun}) channel

I/U converter	AD795 (OP111 – for Omicron STM-1)
Type of ADC	AD7677
ADC capacity	16 bits
I/U converter transfer ratio, k	100 mV/nA (estimated); R = 100 MOhm
The range of the tunneling current	$\pm 5 \text{ nA}$; $\pm 50 \text{ nA}$ (estimated)
I_{tun} transfer ratio (up to ADC input)	500 mV/nA, 50 mV/nA (estimated)
ADC LSB value	0.15 pA / code; 1.5 pA / code (estimated)
I/U converter frequency range	1.4 kHz
The noise level at the ADC input (p-p)	6 pA max.

The tunnel gap bias voltage (U_{tun}) channel

Range	$\pm 10 \text{ V}$ (estimated)
U_{tun} DAC capacity	16 bits
DAC LSB value	0.305 mV (estimated)
Frequency range	110 kHz min.
The noise level (p-p)	0.070 mV, max.

Scanning tunneling spectroscopy

U_{tun} amplitude modulation range	from 0.5 mV to 1150 mV
U_{tun} modulation frequency	from 1 Hz up to 1 MHz
The modulation phase	from 0 to 360 degrees.
C_{comp} amplitude range	from 0.25 mV to 1050 mV
C_{comp} frequency	from 1 Hz to 1 MHz
C_{comp} phase	from 0 to 360 degrees.
Reference	square wave, ± 1 V
Reference phase	from 0 to 360 degrees.
STS ADC type	AD876
STS ADC capacity	10 bits
STS input signal range	± 5000 mV

X, Y, Z scanning high-voltage amplifiers

	Zsc	Xsc \pm / Xoffset	Ysc \pm / Yoffset
Output voltage range (max)	210V	$\pm 210\text{V} / \pm 210\text{V}$	$\pm 210\text{V} / \pm 210\text{V}$
DAC capacity	20	16 / 16	16 / 16
DAC LSB value	0.40 mV	6.4 mV / 6,4 mV	6.4 mV / 6,4 mV
Scaling DAC capacity	-	16	16
Scaling factor	-	from 1/65536 to 1	
Noise level (p-p)	$\pm 0,5$ mV	$\pm 0,5$ mV	$\pm 0,5$ mV
Frequency band	$\leq 4,17$ kHz	$\leq 3,33$ kHz	$\leq 3,33$ kHz

LT STM GPI CRYO positioners high-voltage amplifiers

	PZ + / PZ-	PX + / PX-	PY + / PY-
Output voltage range	$\pm 210\text{V} / \pm 210\text{V}$	$\pm 210\text{V} / \pm 210\text{V}$	$\pm 210\text{V} / \pm 210\text{V}$
DAC capacity	16	16	16
DAC LSB value	6.4 mV / 6,4 mV	6.4 mV / 6,4 mV	6.4 mV / 6,4 mV
Noise level (p-p)	$\pm 0,5$ mV	$\pm 0,5$ mV	$\pm 0,5$ mV
Frequency band	4.44 kHz	4.44 kHz	4.44 kHz
Frequency band with LPF	0.33 kHz	0.33 kHz	0.33 kHz

Omicron's STM positioners high-voltage amplifiers

Output voltage range	$\pm 400\text{V}$ min.
DAC capacity	16
DAC LSB value	12.2 mV
Noise level (p-p)	$\pm 0,8$ mV
Frequency band	40.16 kHz
Slew rate at positioner piezo load	100 V/us
Frequency band with LPF	0.048 kHz

STM lithography

Waveform	Rectangular
Amplitude	from 0,4 V to 5,0 V
The duration and duty cycle	software controlled