A USB-based Data Acquisition System Designed for Educational Purposes*

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Data acquisition (DAQ) systems play an increasingly important role in science and technology school laboratory practice at all levels of education. Laboratory exercises employing DAQ systems supported by a variety of sensors and actuators have brought modern electronics to science and technology teaching. As a key device in microcomputer-based laboratories (MBL), a DAQ system needs to fulfil some specific requirements in order to be used successfully in an educational environment. Deriving from more then ten years of experience in MBL development, we promoted an EU project, one of the final products of which is a USB-based multifunction DAQ system designed for educational laboratory use. The architecture, characteristics and features of that system are presented in this paper.

INTRODUCTION

RAPID ADVANCES in modern electronics have influenced the teaching of electronics at different levels of education. Moreover, such electronics has also had a major influence on science and technology teaching. One of the most obvious impacts is the use of data acquisition systems (DAQ, sometimes called 'data loggers') in school science and technology laboratories. A laboratory based on DAQ systems supported by various sensors and actuators is also called a microcomputer-based laboratory (MBL). The application of MBL in education started at the very beginning of the 'computer era' [1, 2] and development has continued up to the present day [3, 4].

The use of MBL has spread across different levels of education and across most science disciplines. Most often pupils encounter MBL for the first time at lower-secondary education (age 12+) in science and technology classes [5] but its use also extends to higher levels of education including university courses [6, 7]. The application of MBL to the teaching of science disciplines has been described in a variety of papers, including experiences of applying MBL in physics [8], chemistry [9], biology [10], mechatronics [11] and electronics [3, 12].

While a DAQ system is a key instrument in the computer-based school laboratory, the choice of system is not trivial. In general, two different approaches can be adopted. The first option is the purchase of a commercial general-purpose multifunction DAQ system; very diverse products are available from National Instruments, (USA, www.ni.com). The second possibility is the building of a MBL based on DAQ systems specially developed for school laboratories. Various companies provide DAQ systems, sensors and software for education, such as Vernier (USA, www.vernier.com), Pasco (USA, www.pasco.com), Philip Harris Scientific (UK, www.phscientific.co.uk), etc.

There are reasons why the second choice is preferred, especially for use in secondary schools. Educational equipment must be robust, compatible sensors must be supported by the DAQ system without adaptation and the associated software needs to fulfil the requirements of specific teaching goals. Educational applications need continuity of operability but general-purpose DAQ systems tend to become obsolete after a period of time. One of the essential reasons for their obsolesce is the rapid development of personal computers that involves changes of internal buses. Many DAQ systems were developed for the ISA-compatible bus which is no longer available in contemporary computers. Interfacing the DAQ system via external interconnections (parallel port, RS232, USB) seems to be a more appropriate solution since external ports tend to maintain backward compatibility with their earlier versions.

MBL was introduced to Slovenian schools in the mid 1980s and, during the subsequent decade, a multifunction DAQ system based on the ISA bus was designed in Slovenia for educational purposes. The system was supplemented by software, instructions, didactic materials, sensors and actuators. The whole collection, called e-ProLab, implemented an extensive range of experiments and laboratory exercises [4, 13].

In 2001, the University of Ljubljana Faculty of Education started to coordinate a pilot project under the EU Leonardo da Vinci 2 Community Vocational Training Action Program. The project, named ComLab-SciTech [14], commenced in 2001 in a partnership involving nine countries (BG, CZ, E, EL, IE, LT, PT, SK and SI). The results are two versions of a newly designed DAQ system together

with four courses on computerised laboratory in science and technology teaching. The advanced version of the DAQ system, named ComLabUSB, based on the universal serial bus (USB) is the subject of this paper.

REQUIRED CHARACTERISTICS OF THE DATA ACQUISITION SYSTEM

The system was designed and developed in accordance with the requirements of the Com-LabSciTech partnership team, most of whose members had previous experiences with different DAQ systems. The following requirements were recognised as essential:

1. The Universal serial bus (USB) was the preferred external connection for the DAQ system since it is the newest interface standard with a long-term perspective [15].
2. The DAQ system needed to be multifunctional, adequately supporting analogue as well as digital inputs and outputs.
3. The required resolution for analogue input was 12-bit and the number of inputs should be at least 8. The maximum sampling rate should be more then 1M samples/second per one channel. Input voltage ranges needed to be compatible with standard analogue sensors that operate between 0 V and 5 V. A second input range of −10 V to +10 V was required for direct connection of AC signals.
4. The minimum number of analogue outputs was 2 with the precision of 12 bits.
5. The maximum output data rate should be the same order of magnitude as for the analogue input. Output voltage range should be able to cover intervals from 0 V to 5 V and from −10 V to +10 V.
6. Digital input and digital output should have at least 8 bits.
7. Analogue or digital output and analogue or digital input should operate simultaneously at the rate more then 1M samples/second.
8. The minimal size of data series being sampled and/or generated should be 256K.
9. Different triggering modes were required.

All the required features were specified from consideration of the set of experiments viewed as essential for school science and technology laboratories. High sampling rates are needed for sonic experiments in liquids. The simultaneous operation of analogue output and input provides the same functionality as a combination of a function generator and an oscilloscope. The analogue output can be used to generate an arbitrary waveform; in sound experiments, for example, the analogue output can be used to excite a loudspeaker with a mixture of harmonic spectra while the corresponding microphone signal can be sampled via the analogue input.

An example of an experiment where a high number of samples is required is the study of projectile motion. A projectile launcher is used to shoot a ball. The ball intercepts a light beam directed onto a photodiode and at the end of its trajectory the ball strikes a piezoelectric plate. The signal from the light sensor is used to determine initial speed of the ball (diameter known) while the signal from the piezoelectric detector allows the time of flight of the projectile as well as its vertical momentum to be determined. Signals from the light sensor and the piezoelectric sensor are short; hence a relatively high sampling rate is necessary. Since the time of flight of the projectile is much larger, a large number of samples need to be obtained between the start and the end of the motion.

The acquisition of signals at the stated sampling rates also provides a way to measure various parameters of interest that are otherwise not easily obtainable. During the course of building an audio amplifier it is possible to obtain the Fourier spectrum of its output signal almost instantly and interactively. Students can observe changes in non-harmonic distortion of an amplifier on a PC screen while changing its parameters through variable resistors or by varying the amplitude of the signal to be amplified.

Triggering is critical for implementation of certain experiments. For example, we would like to sample a short voltage pulse (few tens of microseconds) where the signal itself is contaminated with a significant noise component. A special triggering mode is also necessary to observe the entire rising edge of a pulse, including the zero-voltage quiescent state prior to the rising edge, for example that associated with a transient in an LCR circuit.

Commercially available DAQ systems utilising the USB port do not fulfil all of the requirements listed above. For one thing, most of them are slower. National Instruments Company and Data-boards (UK, www.databoards.co.uk) offer USB DAQ systems with no more than 100K samples/second while the low-cost system produced by LabJack (USA, www.labjack.com) offers a mere 8K samples/second.

ARCHITECTURE AND FEATURES OF THE ComLabUSB SYSTEM

The ComLabUSB system needs to support many different modes of operation through which a wide range of choices of precision, speed, number of acquisition channels and other parameters are available to the user. The overall architecture of the system is represented in Fig. 1.

The ComLabUSB system is connected to a host computer through a USB connection. The on-board USB full speed interface (12 Mb/s) is implemented with a dedicated integrated circuit USBN9603 from National Semiconductor [16], rather than using a microcontroller with built-in
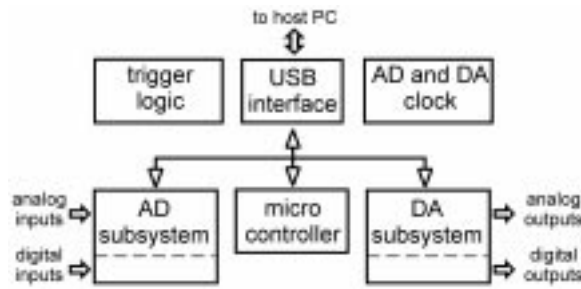
Fig. 1. The architecture of ComLabUSB system.

USB functionality. Thes solution is somewhat more complicated and slightly less cost effective but is preferred for the following two reasons. Firstly, DA and AD subsystems can exchange data with the USB interface without going through the microcontroller's internal buffers. Secondly, the choice of suitable microcontroller is not restricted to the subset of devices with full speed USB functionality built-in.

The microcontroller controls the activities of the ComLabUSB system as a whole. The model PIC18C442 from Microchip [17] is selected for the task since it offers good price/performance ratio (around 3.00 for the OTP version, maximal speed of 10 million instructions per second and a powerful instruction set). The choice was also influenced by our past experiences with Microchip micro-controllers.

The ComLabUSB system provides signal generation functionality via the digital-to-analogue subsystem (DAS; bottom right of Fig. 1, further details on Fig. 2) with two 12-bit 2.5-MHz DA channels. The user may disable one of the DA channels by means of which an 8-bits wide digital output port is enabled; in this way it is possible to directly excite analogue as well as digitally controlled actuators. Data acquisition is provided by the analogue-to-digital subsystem (ADS; bottom right of Fig. 1, further details on Fig. 3) consisting of two 12-bit 5-MHz AD channels. In a similar way to the DAS case, the user may disable one of AD channels and enable an 8-bit wide digital input port that opens up the possibility of sampling one sensor with digital output or a group of bits indicating various states of a process.

Both subsystems support two fundamental modes of operation. In the on-line regime, every sampling of data through AD and/or change of generated output through DA is separately initiated by a host PC and requires a separate USB packet transfer. Currently, the maximal number of transfers per second is around 150, which is limited by the overhead imposed by the ComLabUSB system and USB protocol in addition to the overhead imposed by MS Windows.

The off-line mode of operation exploits the full potential of ADS and DAS, namely sampling two 12-bit channels at sampling rates of up to 5 MHz and simultaneously exciting two 12-bit DA channels at frequency up to 2.5 MHz. Since full speed USB connection cannot keep pace with such data rates (22.5 MB/s), the ADS and DAS provide their own on-board static RAM (S-RAM) to hold data during an experiment.

The utilisation of the ComLabUSB system in the off-line mode is generally as follows. First, the patterns of functions to be generated by the DAS are uploaded to the DA S-RAM. Second, a host PC initiates the experiment. The DAS starts exciting the outputs with the contents of the DA S-RAM. The ADS starts sampling the inputs to the AD S-RAM immediately or at a preset later time depending on the trigger configuration, as described below. When requested data is acquired, the experiment stops. At an arbitrary later time a host PC can download the sampled data from ADS S-RAM for analysis and further processing.

Digital-to-analogue subsystem

Figure 2 represents a block diagram of the DA subsystem. As described above, it comprises two 12-bit DA channels capable of working at a maximal frequency of 2.5 MHz. DA conversion is performed by two integrated circuits DAC7545 produced by Texas Instruments [18]. The output from each DA channel delivers three independent output signals with different voltage intervals: from 0 V to +5 V, from −10 V to +10 V and from −5 V to 0 V.

As indicated at the left side of Fig. 2, the DA S-RAM consists of 3 banks each of which is 8-bits wide. The capacity of each bank is 512KB, which amounts to 1.5MB total capacity of DA S-RAM. With current implementation of USB interface it takes slightly less than five seconds to fill all three banks with data provided by a host PC. If a lesser
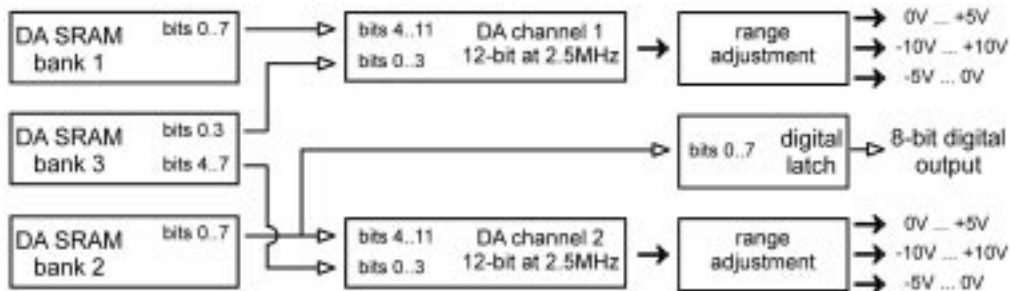

Fig. 2. Block diagram of DA subsystem.

amount of memory is needed, the effective size of S-RAM banks can be reduced by host software in steps of power of two down to 4KB (512KB, 256KB, 128KB, . . . , 4KB) with the proportional reduction in the time needed to upload data to the banks.

The organisation of S-RAM banks is as follows. Banks 1 and 2 hold the upper eight bits of DA channels 1 and 2, respectively. The remaining four bits of both channels are provided by bank 3. Such memory organization is fairly flexible and adapts to the different requirements imposed by a variety of experiments. If 8-bit precision suffices, it is only necessary to fill banks 1 and 2. In addition, if only one DA channel with 8-bit precision is needed, it is only necessary to fill the appropriate one of the banks.

The second DA channel can be disabled and an 8-bit digital output enabled. In this case, the DA output keeps a constant voltage at its output. Similarly, the digital port preserves its latest value when the DA channel is re-enabled. By careful use of these features it is possible to perform a range of different experiments utilising both types of output in a mutually exclusive manner without any physical disconnection and reconnection of actuators in between.

One further feature of the DAS is worth mentioning. The excitation of DA channels from values in the S-RAM lasts an arbitrarily long time when operating in the so-called repetitive mode. Upon reading the last sample in the S-RAM (according to its size selected by the host software), a rollover is performed and the process continues at the beginning of the S-RAM. The second possibility is operation in the one-shot mode, where the hardware blocks further writing to DA upon reaching the end of the S-RAM.

Analogue-to-digital subsystem

The AD subsystem (Fig. 3) consists of two 12-bit AD converters, ADS803 from Texas Instruments [19], capable of sampling at frequency 5 MHz. The specifications and organization of the AD S-RAM banks are completely analogous to the DA case above. All settings (the effective S-RAM size, repetitive or one-shot operation, transferring of 8- or 12-bits to a host PC) are independent of the DAS operation. The second AD channel can be

disabled to enable 8-bit digital input that loads data into S-RAM bank 2.

The first analogue input is sampled through an analogue 8-to-1 multiplexer 74HC4051, which increases the number of physical analogue inputs and decreases their individual sampling speeds. The system enables selection of 1 (no multiplex), 2, 4 or 8 effective multiplexed inputs depending on the specific needs of the experiment. In each AD clock period one of the multiplexed inputs is sampled into the AD S-RAM. The host PC software can easily demultiplex the contents of S-RAM into separate input waveforms.

Not all eight multiplexed inputs have the same characteristics. The first six of them provide for input in the range 0 V and +5 V, whereas the last two of them operate at voltages between −10 V and +10 V. This allows for connection of many available and standardized sensors without additional circuitry. The following sampling combinations are possible:

- 1 input in range 0 V . . . 5 V,
- 1 input in range −10 V . . . +10 V,
- 2 inputs in range 0 V . . . 5 V,
- 2 inputs in range −10 V . . . +10 V,
- 4 inputs in range 0 V . . . 5 V,
- 2 inputs in range 0 V . . . 5 V, 2 inputs in range −10 V . . . +10 V
- 6 inputs in range 0 V . . . 5 , 2 inputs in range −10 V . . . +10 V

Triggering

When performing an experiment in the off-line mode of operation the utilization of the trigger logic (TL; upper left of Fig. 1) enables acquisition of data in various time intervals relative to a triggering event. TL is basically a voltage comparator that compares trigger source signal with a voltage between 0 and 5 V from an additional 8-bit DA converter. The trigger source can be specified as the input line of one of the AD channels or it can be an external line. The detection of rising or falling edge can also be selected.

When starting the off-line mode, the following actions can be specified.

It is possible to disable DAS during the experiment, which prevents unintentional excitation of actuators in cases where only data acquisition is performed. It is also possible to disable ADS if
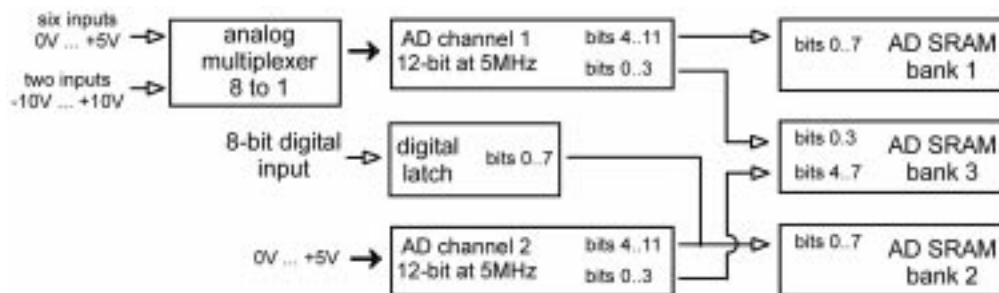

Fig. 3. Block diagram of AD subsystem.

only function generation is needed. When ADS is enabled, the time interval for the acquisition can be selected in four different ways:

1. DA excitation and AD acquisition start simultaneously, which is useful for obtaining the transfer function of the measured system.
2. DA excitation starts (if required), however AD is suspended till trigging occurs. Then data acquisition starts and is performed until the specified size of the AD S-RAM is filled by the acquired values. That mode of operation is useful when the post-trigger processes need to be examined.
3. Both, DA and AD start simultaneously presumably in repetitive mode. The acquisition stops when a trigger occurs. That way an event before the occurrence of the trigger may be captured.
4. The same situation as in the previous case except that DA acquisition does not stop immediately upon occurrence of the trigger but at a specified number of samples later. The possible choices are spread by powers of two from 2048 to 262144. In this mode of operation it is possible to track an event before and after the trigger event occurs.

Programmable clock

During the off-line experiment the programmable clock (top right of the Fig. 1) determines the operating frequency of DAS and ADS. It is obtained from microcontroller's 10 MHz clock by dividing it with an integer in the range from 2 to 65535. That way a large choice of sample rates from up to 5 MHz down to less than 200 Hz is possible. Some of the interesting possibilities include 2.5 MHz, 2 MHz, 1 MHz, 500 kHz, . . . , 2 kHz, 1 kHz, 500 Hz and 200 Hz. The same clock source is utilized by both ADS and DAS.

However, the actual clock for DAS can be the same as ADS clock or it can be divided further by a factor of two. The additional division is fully controlled by the user of the system except when AD clock is higher than 2.5 MHz. In these cases the ComLabUSB system forces the additional division in order not to overclock the DA channels.

EXAMPLE APPLICATION

A typical application of the ComLabUSB system involves a series of experiments directed towards the study of sound which were prepared for pupils at secondary school level in Slovenia. The experiments start with two tuning forks each emitting sound at a different frequency (Fig. 4). The signal from the microphone is connected to the analogue input. Initially only the first tuning fork is excited. Subsequently the experiment is repeated by exciting the second tuning fork alone and, finally, with both tuning forks emitting sound simultaneously. At this point, the Fast Fourier Transform utility is introduced in an empirical fashion, that is with emphasis on what it does without consideration of its mathematical foundation.

The next experiment is based on the analogue output connected to a loudspeaker. An output voltage is generated according to a data series calculated beforehand and uploaded to the S-RAM of the ComLabUSB system. Each component can have different frequency, amplitude and phase. Students first listen to a pure harmonic (sinusoidal) tone with variable frequency and amplitude. Then they listen to a sound being a mixture of two harmonics both with variable frequency and amplitude. Changing the phase between first and second harmonic one can conclude, that human's sense of hearing cannot
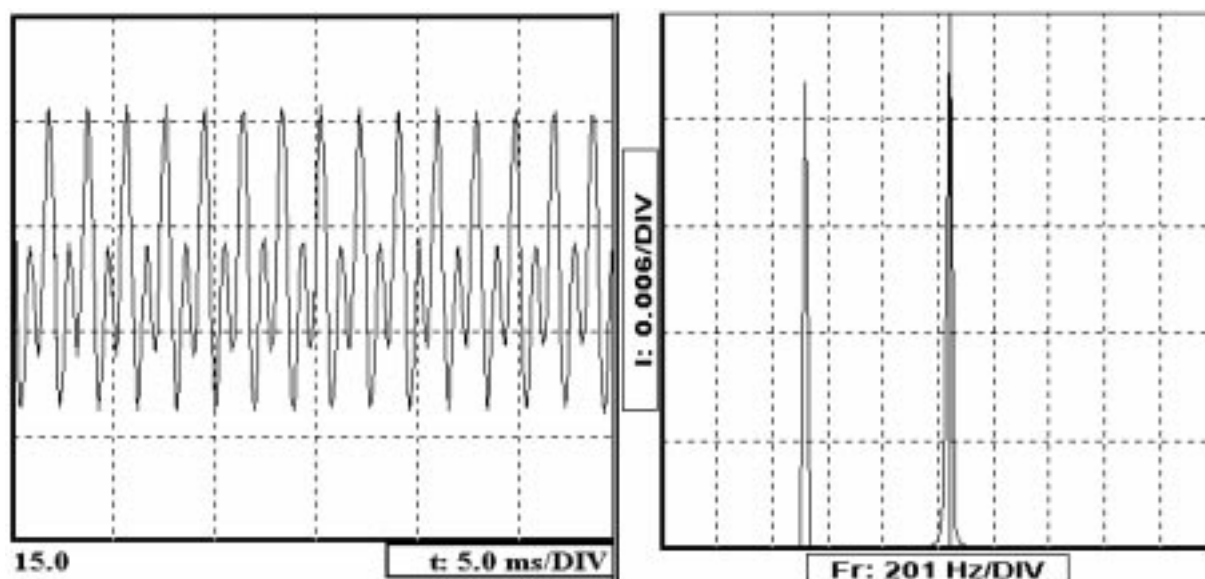

Fig. 4. Signal from the microphone when two tuning forks are excited (left) and the corresponding Fourier transform (right).

detect the phase difference. The experiment continues with a microphone that samples the sound generated by the loudspeaker being connected to the analogue input. In this concluding experiment, both AD and DA systems operate simultaneously at relatively high sampling rates.

CONCLUSIONS

The preliminary tests of the ComLabUSB system in a school laboratory environment are encouraging. No difficulties were encountered in employing the new system in experiments for which the ISA-bus DAQ system had been used previously. Current experiences in science and technology laboratory applications intended for secondary education confirm that the requirements for backward compatibility with the previous system and a continuity of operation are indeed fulfilled. Moreover, features of the new system prompted by the partnership of the ComLab-SciTech project extended the possibilities of MBL at all levels of education. The advanced characteristics of the ComlabUSB system offer possibilities of its utilisation in undergraduate electrical engineering laboratories. This has already been considered at the Laboratory of Industrial Electronics, Faculty of Electrical Engineering in Ljubljana where the system was successfully implemented in a Fourier analysis of audio frequency electrical signals, for which a more expensive spectrum analyser had previously been used. The ComLab-USB system is affordable enough so that one can be made available to each student, an arrangement that would have been prohibitively costly using spectrum analysers.

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