DESIGN of an ULTRASONIC INTERFACE for a GRAPHICS TABLET

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Abstract

A cost-effective design of an ultrasonic interface to a graphics tablet is accomplished by means of PIC microcontrollers. This paper analyses the design and implementation from requirements capture through high-level design to circuitry. Ultrasonic transducers enable direct placement of the tablet mechanism above an LCD so that the image is viewed as it is created. Results show that the prototype tablet has up to 0.8 mm resolution.

Keywords: graphics tablet, ultrasonic, artists' interface

1. Introduction

This paper is concerned with the design of a prototype ultrasonic interface to a graphics tablet. The complete design process is considered: a requirements analysis, choices between various transducers, and then passing from the high-level design of the prototype hardware and software, to the detailed design of the circuitry, and, finally, to calibration tests and tests for positional accuracy. The emphasis is upon hardware design, while other parts of the process are included to give a complete picture. Tests with a prototype design show that tracking is possible to 0.8 mm resolution. The paper will be of interest to those considering the methodology for constructing a small-scale interface, including the experimental procedure for estimating the accuracy of the tablet.

The motivation for constructing the ultrasonic interface is as follows. When an artist moves a pencil across the surface of a sheet of paper to draw a shape, he/she makes use of hand-to-eye coordination to control the speed and direction of the pencil, as well as the feedback given by the line being formed under the pencil's tip to continue the line and form the shape. With a normal graphics tablet, the artist can move the stylus along the surface of the tablet but the line being produced by it appears on screen, so that the artist can either watch their hand travel along the surface of the tablet to maintain hand-eye coordination, or watch the screen and adjust the course of the stylus, based on the visual feedback given by the line appearing on the screen. The system described in this paper seeks to overcome this problem by placing the tablet mechanism directly above an LCD, allowing input from a stylus-like device capable of interacting directly with a display. Allowing the stylus to be used directly on the surface of the display restores the artist's hand-eye control, transforming it into a virtual canvas. Unfortunately, unless special measures are taken, normal graphics tablets rely on electromagnetic sensing. In which case, the LCD's electronics interfere with location detection on the tablet. Therefore, a principal concern of this paper is the spatial accuracy achievable by means of ultrasonic transducers.

The remainder of this paper is organized as follows. Section 2 is an overview of the requirements study. Section 3 considers a variety of graphics tablet technology leading to current systems. This paper is concerned with ultrasonic systems and Section 4 specializes to ultrasonic systems. Section 5 considers the hardware design of the system and forms the kernel of this paper. Section 6 considers testing of the ultrasonic-driven stylus. Section 7 is a discussion of possible improvements to the stylus, while finally Section 8 draws some conclusions.

2. Requirements study

The starting point for the artists' interface was a study of six artists, who were observed and filmed. Three had skills in drawing with pencils and the other three were painting on paper or a canvas. The subjects were not asked to create anything specific but simply filmed while they worked, so that their interactions with tools and materials could be observed. The still images shown in Figure 1 were taken from the video footage and show each of the artists at work in various stages of completion. Though in the course of this small study a number of features were observed that one would ideally require in an artists' interface, some of these were beyond the scope of this paper. This paper reports the immediate findings in respect of hardware accuracy and response time and not other human factors.

All artists surveyed formed a line through hand-to-eye coordination, as he or she 'dragged' the implement across the surface. In a study for a different purpose of a portrait painter at work [1], it was noted "his eye closely followed the drawing hand, with fixations on, or very near, the line being drawn" (though there were also other eye movements to regard the model). The well-known and highly skilled artist was studied with the help of close-up video filming, an eye tracker, and movement sensors. Given these comments and internal experiments for this research, a crucial finding is that, for an artist to interact with a computer in an accustomed manner, the computer must provide an interface that the artist can use without having to re-learn any skills they may have acquired while using traditional artists' tools such as pencils, brushes, air-brushes, knives; even chalks, pastels and charcoals.

When an artist uses a tool like a pencil or paintbrush, the implement appears to respond instantly if it is dragged along a surface. An electronic version of the pencil or stylus must be designed to mimic the behaviour of pencils and brushes but, because it is an electronic device, it cannot respond immediately. What must be determined is the minimum rate at which the position data from stylus should be sampled and transmitted to a computer. An artist was filmed rapidly filling out a large area of canvas. A stroke from right to left then another from left to right was found to take 17 frames at 25 frame/s. Painting with brushes is often slow and precise, so that laying a large area of colour demonstrated one of the most rapid series of movements an artist might make. Even so this rapid movement took place in 680 ms, which was a comparatively long time in which to update a display. In Figure 2 (a), the trajectory of the brush has been sampled in each frame and lines drawn between the points. The effect of sampling every two frames is illustrated in Figure 2 (b), showing that the probable minimum sampling rate is 80 ms.

Perhaps the most important aspect of a device specification is to find the resolution or how accurately the system can track the stylus of whatever type. Examination of what implements artists actually use reveals that the finest pencil lead available for artist' use is 0.5 mm, so that ideally the system should be developed with an accuracy of less than ± 0.5 mm. This is a maximum and the artists were actually able to draw to within 1 mm accuracy, which is already more accurate than common graphics tablets.

3. Graphics tablet technology

The position of the stylus on the page is vital when drawing on paper and equally so when drawing with an artists' interface. This leads to the question: what technologies can support sufficient accuracy *and* do not require an artist to acquire new drawing/painting skills?

An acoustic system, as developed in this paper, is not completely without precedent. The graphics tablet, the most obvious input-device, was first developed as an alternative input device to the joystick, long before the mouse. The earliest of these were electro-acoustic and used strip-microphones in the X and Y planes to detect the location of a stylus, which used a high voltage spark to create a short burst of sound. This approach was highly vulnerable to interference from audible sound sources, so that later versions improved on the design by using an electromagnetic system to locate the stylus. The RAND corporation tablet [2] was a digital electromagnetic device that used Gray code to locate the stylus within a 1024 by 1024 grid of metallic strips, each of which carried the digital Gray code signal. A field coil in the tip of the stylus detected the signal, as it passed over the metallic strips, and the location of the stylus was determined by reading the Gray code signal detected by the stylus.

3.1 Graphics tablets

The active area of an electro-magnetic-based tablet is a grid of conductive strips set at one cm intervals into a rigid, insulating material. A stylus contains a field coil that can detect an electromagnetic signal passed along any one of the strips. The signal is scanned in the X and then the Y plane. By knowing which strip is transmitting the signal and the signal strength detected by the stylus, the position of the stylus can be found, even when the stylus is between the strips. The response of the tablet is determined by the speed of the microcontroller imbedded into the tablet and the communications link with a host PC.

Because the tablet uses an electromagnetic (EM) scanning system to locate the stylus, the system is potentially vulnerable to external sources of EM noise. This is not a problem in most situations, because tablets are not typically used in electromagnetically noisy environments.

The requirement arising from the study of artists conducted in Section 2 is that a traditional interface should allow an artist to work in the same way as if using a sheet of paper or canvas, so that what they draw appears where they draw it, directly underneath the stylus. To achieve this, a flat LCD panel could be placed over the top of a graphics tablet, so that the stylus could draw onto the LCD panel and the active grid beneath could track its location. When a low-cost Genius 12” by 12” graphics-tablet [3] was placed over a 17” LCD, then the location of the stylus could not be found accurately due to the noise produced by the display. Of course, this is by no means a criticism of the Genius 12” by 12” graphics-tablet, which was never designed for this purpose and which was found to be fully suitable for its own purpose.

Turning to the design of tablets, an absolute coordinate system is more suitable than a relative coordinate system because it can accurately track the movements made by the stylus, whereas a relative system becomes increasingly inaccurate with successive movements. The active area of the tablet represents the area of the PC's screen or monitor. This, however, can cause a problem if the active area of the tablet is not the same as the area of the monitor.

If an artist has a screen with a diagonal size of seventeen inches – approximately twelve by twelve inches square – and a cheap tablet which is six by five inches in size – a tablet size used widely by home users – then problems can arise. Every movement made by the stylus is amplified, giving a highly unrealistic drawing experience. Ideally, the area of the graphics tablet should be identical to the area of the display so that movements made by the stylus are reproduced accurately by the display.

3.2 Modified graphics tablets

This section considers two candidate solutions that can produce a traditional artists' interface and are fully worked out alternatives to the proposal of this paper.

The Escritoire [4] is a graphics tablet that can be used in conjunction with a personal projected display, intended for use with documents. The Escritoire makes use of a desk-sized digitiser (graphics tablet) with two digital projectors that are combined and projected onto the digitiser surface to create what Escritoire's originators refer to as a 'Foveal Display'. The system uses a low resolution – periphery – display to cover the whole desk surface, and a high resolution – fovia – display for the focal area, where items can be viewed in detail creating a large, interactive desktop display. If used as a drawing surface, as the display is projected from above, there is a potential for an arm moving in the desktop area being projected, though the originators do not see this as a significant problem.

WACOM, a company that specialises in graphics tablet technology, has, however, solved this problem using an electromagnetic resonance system that allows a specialised LCD panel to be used in conjunction with their own electromagnetic stylus tracking technology. WACOM's Cintiq [5] range of interactive pen displays not only have the ability to track the stylus accurately – to a specified resolution of ± 0.25 mm – and display the drawings made with it as a sheet of paper would but also capture the pressure applied between the stylus and the LCD panel, solving three of the requirements for a traditional artists' interface.

WACOM devices, of which the Intuos and Graphire2 are others [6], are being applied to tablet PCs, which have been developed by a range of well-known computer companies.

4. Ultrasonic tracking

Consider the Mimio Xi [7], which is an ultrasonic (acoustic) tracking system, designed to capture the information written onto a whiteboard. It can be attached to any whiteboard up to 2.4 by 1.2 m in size and is intended to track a pen at a resolution of 100 dots per inch across the whiteboard surface. The pens deposit real ink across the whiteboard surface as diagrams or text is written onto the board, while at the same time ultrasonic transducers built into the pen allow the tracking system to acquire its location on the board. Compared to (say) the Genius tablet [3] with a specified resolution of 2540 dpi (and accuracy of ± 5 mm), the Mimio Xi is a low-resolution device, though completely adequate for its stated purpose. The Mimio Xi is one of a number of acoustic tracking devices that demonstrate the feasibility of tracking by ultrasound.

Ultrasound is an acoustic pressure wave and thus obviously immune to EM interference. Sound travels slowly - approximately $331.4 + (0.6 \times T)$ m/s with T the temperature in degrees Celsius in dry air - when compared to electromagnetic waves, travelling at the speed of light. This is advantageous to design of a graphics tablet, because the slower speed means that a simple timer arrangement can be used to measure distance (refer to Section 4.2) It should however be noted that the speed of sound is not constant, and varies slightly depending on pressure (and, hence, ambient temperature) and relative humidity of the air. The speed of sound could be considered a constant, because the changes are small, but to make a system more accurate (automatic) calibration is required. Ultrasound itself has the useful advantage that it does not distract an artist while drawing. The typical upper limit of human hearing is 20 kHz, while audio signals at (say) 40 kHz are not detectable by an artist operating the device. There are few sources in nature that can produce signals at 40 kHz, and, hence, affect any range measurements taken. Artificial sources, such as simply jangling keys, may be present.

4.1 Ultrasound transducers

Typical ultrasonic transmitter and receiver pair devices operate at around 40 kHz, as this is the resonance frequency of the quartz crystals producing the tone. These devices are widely available and designed primarily for general-purpose range finding or short-range directional communications. The ‘Sensitivity / Sound pressure’ plot of Figure 3 shows the frequency response of a standard ultrasonic transducer [8] and illustrates its high sensitivity to a signal at 40 kHz. The ‘Beam Angle’ plot shows that the device is highly directional, with the greatest gains achieved when the viewing angle is within ± 30 degrees.

When considering the design of an ultrasonic graphics tablet tracking system, a signal must be sent from the stylus, an ultrasonic source. The signal emerges from the drawing tip, travels through the air an unknown distance and some time later arrives at a fixed receiving transducers. If the stylus contains a transmitting source with the characteristics shown in Figure 3, the quality of the signal degrades, as the angle between the stylus and the four receiving points increases.

Radiating ultrasonic transducers are not standard components, as most applications for ultrasound require a directional source. However, a partially radiating device is available. The 400ET180 [9] is a standard ceramic ultrasound transducer but is contained in an unusual[1], sealed-aluminium housing, so that the device can be used outside without letting moisture come into contact with the transducer. The 400ET180's sealed diaphragm, which allows the device to be used outdoors, is a solid aluminium can containing the whole device. A side effect of sealing the transducer is that the whole protective cover has to be free to resonate, giving it a high viewing-angle, as shown in Figure 4.

The 400ET180 is not an ideal candidate due to its large size – over 1 cm in diameter – and poor response between 90 and 270 degrees. The forward lobe of the response – between ± 30 degrees – gives the greatest gain as the internal transducer is directed forward. The side lobes – between 30 and 90 degrees and between 270 and 330 degrees – have a much lower gain, but a signal radiates from the sides of the aluminium can, allowing it to be used at angles up to ± 90 degrees, which is a significant advantage over standard ultrasonic transducers.

4.2 Measuring distance with ultrasonic transducers

In Figure 5, once a trigger signal arrives at the timer, it starts a counter and transmits a signal from the acoustic source 'TX'. The signal then travels an unknown distance, 'Dx', while the counter is clocked at a known rate. The signal then arrives at the acoustic receiver 'Rx', where it stops the counter. The counter result with respect to the frequency of the clock used to increment the counter can be used to calculate the distance 'Dx'. Given the clock frequency of the clock, the approximate resolution of the range measurement and the maximum range can be calculated using Equations (1) and (2) with variables given in Table 1, in which a worst-case estimate of the speed of sound is utilized. The offset compensates for the delay introduced by the 40 kHz modulator / demodulator stages, as well as any other stages that are placed between the 'Start' and 'Stop counter' signals. Providing the counter with a 340 kHz

[1] Most ultrasound transducers are exposed directly to the air, with a mesh grill placed over the front of the housing to protect the delicate transducer from being touched.

clock gives a resolution of exactly 0.1 cm if the speed of sound is 34000 cm/s. If the counter has a 9-bit resolution, then the maximum range of the rangefinder is 51.2 cm, adjusted by the offset.

$$\text{Resolution} = \left[\frac{Vsnd}{Fc}\right] \tag{1}$$

$$\text{MaximumRange} = \left[\left[\frac{Vsnd}{Fc}\right]2^{\text{Cn}}\right] - \text{Offset} \tag{2}$$

Figure 6, shows the geometry of the tracking system. For the offset value, an ultrasonic source is placed at a fixed point over one of the four receivers to find the fixed distance ‘Df’. The location of the stylus is found by the well-known triangulation method. For completeness, these equations are summarized as (3) to (6), which are a redundant set to account for any one receiver being obscured. A second ultrasonic transmitter at the other end of the stylus, with fixed length of the stylus, transmitting at alternate times, may be used to further improve the robustness of the measurements.

$$X(1)_s = \frac{D_2{}^2 - D_3{}^2 + D_f{}^2}{2D_f} \quad Y(1)_s = \frac{D_1{}^2 - D_2{}^2 + D_f{}^2}{2D_f} \quad Z(1)_s = \pm\sqrt{D_1{}^2 - X(1)_s{}^2 - Y(1)_s{}^2} \tag{3}$$

$$X(2)_s = \frac{D_1{}^2 - D_4{}^2 + D_f{}^2}{2D_f} \quad Y(2)_s = \frac{D_1{}^2 - D_2{}^2 + D_f{}^2}{2D_f} \quad Z(2)_s = \pm\sqrt{D_2{}^2 - X(2)_s{}^2 - Y(2)_s{}^2} \tag{4}$$

$$X(3)_s = \frac{D_1{}^2 - D_4{}^2 + D_f{}^2}{2D_f} \quad Y(3)_s = \frac{D_4{}^2 - D_3{}^2 + D_f{}^2}{2D_f} \quad Z(3)_s = \pm\sqrt{D_3{}^2 - X(3)_s{}^2 - Y(3)_s{}^2} \tag{5}$$

$$X(4)_s = \frac{D_2{}^2 - D_3{}^2 + D_f{}^2}{2D_f} \quad Y(4)_s = \frac{D_4{}^2 - D_3{}^2 + D_f{}^2}{2D_f} \quad Z(4)_s = \pm\sqrt{D_4{}^2 - X(4)_s{}^2 - Y(4)_s{}^2} \tag{6}$$

5. Stylus tracking hardware design.

Figure 7 is a top-level design of the tracking system. In practice, specialised hardware is required to send a signal from stylus to receivers, which in turn is connected to a series of timer units to determine the four distances D1-D4. The four distances are then passed to the PC by a controller, while software running on the PC performs the triangulation calculations and determines the coordinates of the stylus. The software then passes the position data to the operating system, so that any application can make use of it.

Figure 8 shows an implementation of the design with four distance-capture units running in parallel to reduce processing time. The main function of the local bus is to allow rapid transfer of data from each of the four timers to the Central Processing Unit (CPU), once a timing event is completed. The secondary function is to allow the CPU to access software registers programmed into each of the key devices in the system, allowing their behaviour to be modified. By deliberately building programmable registers into each of the devices, the CPU is able to transmit a command across the bus to change the decoding method or update the modulation frequency the stylus uses to transmit a signal. These variables are able, in turn, to be updated from a graphical user interface running on the PC and are relayed to the relevant device by the CPU. Using microcontrollers where possible allows the system to be highly flexible and also reduces development time. Blocks like the decoders and timers are only developed once and then their software is copied to the other devices.

5.1 Stylus

Figure 9 shows the dimensions and layout of the prototype stylus. The layout of components is important for the stylus, because it has to be held like a pencil. 400ET180 transducers are mounted at either end of the stylus with tactile switches mounted slightly further in, to allow them to be pressed easily by someone holding the stylus either side of the switches. There are three LEDs for power (PWR), communications, and status. A low-cost microcontroller [10], PIC-16F877 from Microchip Inc., runs from a 20 MHz clock. To ensure the PIC starts correctly when power is first applied, a DS1813 5v microprocessor monitor device is included and attached to the PIC's reset line. The bus has only four active lines, Table 2, to reduce the 'umbilical' width in the prototype. Of course, a final implementation is likely to use a wireless connection.

Figure 10 is a complete circuit diagram of the stylus. The ultrasonic transmitters are attached to the first four bits of Port-A on the PIC microcontroller. The first two bits of Port-B are attached to the Status and COM LEDs, and the last four bits form the COM channel. The last four bits of Port-C are attached to four tactile switches, which leaves 4-bits available on Port-C, and 2 on Port-B. These bits are available for possible use in the future by an electronic compass, which is one way to gauge the stylus' rotation. Referring to 'Conn-H6' in Figure 10, the communications port is defined as a 4-wire bus, with two additional lines for power and ground. By creating a narrow bus, the number of conductors connecting the stylus with the rest of the system is reduced but the speed at which data can be transferred across the bus is also reduced, as compared to a multi-wire parallel bus. As other devices in the system require high-speed access to the CPU, a wide local bus (Section 5.2) is used to transfer more data between those devices in a short period of time. This means that the stylus bus is not compatible with the system bus and must interface to the CPU through an I/O bridge, which translates data between the two bus types.

In Table 2, The ‘DAT’ line is a serial data line, synchronised by ‘CLK’. IRQ is a handshaking line, which allows the stylus to inform the stylus IO that it has data pending. Data is transferred over the bus in fixed length packets, which include a destination register address, followed by the data to be stored at the specified address. The stylus is programmed to treat ‘CLK’ and ‘DAT’ as inputs under normal circumstances and poll the clock line regularly. IRQ is a handshaking line that allows the stylus to inform the stylus IO that it has data pending.

5.2 Local bus

In Figure 8, the CPU and the timer/decode units are conveniently implemented by PIC microcontrollers and, hence, the design of the local board bus evolved from that fact. The prototype’s bus design is capable of transferring 32-bits of data in eight clock cycles, at speeds tested up to 32 MHz and adopts a customised master / slave approach. Table 3 illustrates the line allocation. Four of the eight I/O lines are dedicated to data transfer and are configured to transfer four bytes serially. The four remaining bits are used to synchronise the data transfer and for handshaking between devices. The bus has three lines designed to allow a slave device to temporarily become bus master. However, since the system has a central processor, which controls the behaviour of every other device, the central processor always resumes its role as bus master, once another device has finished writing to the bus.

Figure 11 is a timing diagram showing a 64-bit transfer across the bus. To make communication between devices as simple as possible, a protocol was developed in which each device uses standardised packets of 32-bits to relay data. Each packet contains an 8-bit destination address: ‘D0’ and 24-bits of data: ‘D1-D3’. D4 is the bus clock and indicates that a nibble has been loaded onto D0-D4, and must be read. Each slave device monitors the clock line, treating it as an interrupt that starts a ‘receive data’ routine, which then collects the remaining seven-nibbles of data that follow. ‘Ta’ through to ‘Tb’ represents a 32-bit packet being transferred from the bus master. The central processor is the bus master by default and has three handshaking lines – D5, D6, and D7 - which allow other devices to temporarily become the bus master. ‘D7’ is an interrupt line that allows a slave device to indicate that requires master status. Slave devices test the IRQ line before setting it and wait for the master to send an ‘acknowledge’ on ‘D6’. The master then releases control of the bus and indicates the change in bus ‘direction’ by setting ‘D5’ high. ‘Tc’ to ‘Te’ shows the handshaking process and ‘Te’ to ‘Tf’ show the transfer from the new bus master. At ‘Tf’ the temporary master releases the bus and the central processor resumes control, indicated by ‘D5’ going low.

5.3 Decoders

Each decoder is an 18-pin PIC16F84A attached directly to the local bus. Each device also has a dedicated input, where the ultrasound signal is received, and a dedicated output, which is set high if the ultrasonic signal is valid or remains low if not. A trigger event window, with duration set by the CPU, is used to control event timing. The windowing operation grants the central processor a high level of control and ensures that data is ready for collection when it requires it. If the trigger event window were not present, then a situation may arise in which the decoder does not receive a valid signal and remains in a loop analyzing the incoming signal, failing to respond to data sent across the local bus. While the trigger event window is open, the central processor ensures that there is no local bus activity directed to those devices that are busy. Once a trigger occurs, the decoder begins analyzing the incoming signal by measuring the width of pulse arrivals. The analyzer begins counting once a pulse arrives and halts the count when the following pulse arrives. This is an extremely simple method of testing the incoming signal but it is fast and the result is immediately passed in the PIC’s software to another block of code that compares the result with a ‘valid signal register’ containing the value indicating a valid signal.

5.3 Timers

Each timer, also implemented as an 8-bit PIC microcontroller, is attached directly to the local bus, with an additional line to receive the valid signal data sent by its companion decoder. Each timer also has a special ‘ready’ signal line, which is set high once the timer has finished range finding. The ‘ready’ lines have a path directly to the central processor. There is also an external clock input which allows the timers to make use of a common fixed clock for use in precision range finding but, by default, the timers use fixed-length delays built into the software to provide a virtual clock. As the PIC processor is an 8-bit device, while the system requires range measurements up to 10 bits in length, a 16-bit timer is implemented by combining the results from two separate 8-bit counters.

Finally in Figure 12, the complete decoder/timer circuitry design is shown. JA and JB connect the decoder timer module to the central processor board. JC is the ‘signal in’ connector, where the decoders receive the ultrasound signals from the four receivers and amplifiers. JD is a connector to the local bus where the stylus IO can be attached.

5.4 Amplifiers and A/D converter

A set of amplifiers, marked 'A' in Figure 8, are needed. One of these amplifiers has a gain of around 100 and provides analogue signals sufficient in strength to a range of approximately 15 cm, when the transmitter and receivers have a direct view of each other. Adding an Schmitt Trigger to the output of the amplifier further improves the performance up to approximately 20 cm. The design is further enhanced by connecting the output of the transducer amplifier to the input of a comparator with high gain. The circuit diagram for the transducer amplifier (U1) and comparator (U2) series is shown in Figure 13.

Creating such sensitive analogue electronics proved slightly problematic, because the comparator stage amplifies any noise present on the power supply rails. The digital electronics of the Decoder timer board together with the central processor stylus IO and stylus creates a large amount of high frequency noise on the power supply, especially during data transfers, so that the analogue electronics are isolated by providing a separate filtered power supply. The Schmitt triggers are also kept on the analogue supply and LEDs are added to the output of each to show the signal status of each amplifier, as shown in Figure 14.

5.5 CPU

Figure 15 shows the CPU board circuit. The CPU is responsible for controlling all the external devices that make up the tracking system and acts as a bridge to link the external devices to the software environment running on the PC. The device chosen to act as the CPU was a PIC16F877, because it has a large program memory, a large number of I/O connectors, and an internal Universal Asynchronous Receiver/Transmitter (UART). The CPU essentially connects directly to the local bus of the decoder/timer module, with a number of additional lines to allow the timers to indicate their readiness, without having to transfer data across the bus. The PIC16F877 has three standard 8-bit IO ports, and a 4-bit port capable of analogue sampling. The local bus requires 14-bits with the addition of the timer ready lines, so that two 8-bit ports are used for that bus, with the remaining 8-bit port reserved for controlling a debugging LCD terminal. The 4-bit port is used for RS232 serial bus communication with the PC. At the prototype stage, use of Universal Serial Bus (USB) communication would involve unnecessary complexity, diverting from the main task.

5.6 Hardware operation

The software running on the central processor begins by establishing a link with the host PC and running communications tests to ensure that high-speed serial communication has been properly established. A potential bottleneck for the system is the data link between the external hardware and the PC, especially using RS232, so a serial data transfer speed of 115.2

kb/s is used to minimise any delays. Once communication is fully established with the host PC, the CPU then tests the local bus for errors, before allowing the devices attached to the bus to come out of a reset mode. The processor subsequently polls through a range of device addresses to identity which devices are available.

A key feature of the processor is its trigger scheduler. The user can command the external hardware to initiate a single trigger event, which collects range-finding data and transfers it back to the PC in a single sequence of events. Alternatively, a more efficient transfer mechanism is established by scheduling multiple trigger events. When multiple events are scheduled, the CPU pipelines timing events with transfer of data to the PC host, resulting in twice the data processing rate.

When multiple events are scheduled, the CPU starts a timing event and waits for the range finding operation to complete. It then collects data from the timers, and immediately triggers a new range finding event. While the other hardware is busy carrying out the trigger event the CPU then sends the data it collected for the previous event to the PC. By the time the transfer is complete, the decoders and timers should have completed their work, and have data available. The CPU can then collect the new set of data, and repeat the whole process. The multiple-scheduling method effectively doubles the rate at which results can be sent to the PC by making more efficient use of parallel processors. The host PC sets the scheduling, like every other feature of the external hardware, by loading appropriate register values from. The PICs also have EEPROM memory, so that each device remembers the last configuration that was used.

6. Results

Figure 16 shows a prototype graphics tablet undergoing tests.

6.1 Calibration tests

Preliminary calibration experiments with the directional transducer of Section 4.1, the 250ST/R160, established that a linear response is achievable up to a range of 25 cm with transmitter placed directly opposite each other. However, when the stylus transmitter is inclined at 45^o to the tablet (and 1 cm above) the response fluctuates from about 10 cm and beyond, as the signal arriving at a receiver passes out of the main lobe. The fluctuations are marked if the transmitter is placed directly above the tablet.

The radiating source, the 400ET/R180 device of Section 4.1, was substituted for later tests. All readings were repeated ten times for to verify their reliability. As with the previous tests a single receiver is used. Figure 17 shows a linear response with transmitter and receiver placed directly opposite. There are small departures from linearity at 3 cm and 22 cm, which could not be accounted for either by an error in the timer software or by the presence of reflections. The results for a transmitter inclined at 45° to the tablet (and 1 cm above) and the results for the transmitter facing directly at the table are similar. The results with the single receiver are not ideal, as the transducer does not have an omni-directional response. Nevertheless, the results show that the system is able to deliver a resolution of approximately 0.7 mm with a range up to 25 cm and an average error of 2 mm.

6.2 General tests

To allow comprehensive tests to be conducted on the system with all four receivers in use, a sheet of clear plastic was obtained and a 22 by 22 cm grid was marked on its surface using permanent ink markers. The four receiving transducers were then placed at the four corners of the square grid facing the centre. Mounting holes were drilled into the Perspex sheet at each of the corners, which allowed the ultrasound receivers to be mounted between 1 and 5 cm from the grid perimeter. The stylus was then placed in a clamp, which held it vertically 1 cm from the drawing surface, and was then moved so that the centre of the 400ET transducer was over the 1 cm by 1 cm grid intersections.

Space does not permit a report of all experiments. In a typical experiment, the receiving transducers were moved to 2 cm from the grid perimeter. The tracking system was then reconfigured so that the stylus would emit a shorter ping of 10 cycles, to reduce the chances of a ping from the previous cycle being received as an echo in the next cycle. The 400ET transducer is 15 mm in diameter so that placing the centre of the transducer precisely over the grid intersection at each of the 484 locations was difficult when performed visually. To improve the accuracy with which the stylus is placed on the grid, a piece of wire was glued to the case of the stylus and bent into a triangular shape over the front of the transducer, so that the point of the triangle was directly over the centre of the transducer.

Figure 18 shows the results as a scattergram around each grid intersection, with the display colour coded to indicate the extent of any deviation from the correct location. There are 484 intersections and 47,432 results plotted. The majority of results have errors of between 1 and 10 mm. However, there is a ring of weaker results 11-20 mm error in the centre of the tablet. This is accounted for by the effect of using all four receivers, as any non-linearity is accentuated when the triangulation equations are applied.

Tests were conducted with a simple moving averaging filter. Figure 19 shows the result of tracing a figure 'S' with different sized filters, with a visible improvement when the longer four-point filter was applied, though there are errors at the start and end of the plots.

6.3 Summary of results.

The results show that the prototype tracking system is capable of tracking the stylus to resolution of 0.8 mm with 48 sample/s on a Pentium III host running at a nominal clock speed of 1 GHz. The average error was 4 mm but there is a worst case error of almost 9 mm. Applying an averaging filter improves the drawing results but decreases the rate at which data can be passed to a drawing application.

7. Discussion

The experimental results show that further improvement to the tracking system lies with improved transducers. The 400ET transducer was shown to be significantly better than a standard ultrasound transducer (typically used in broken beam alarm systems) but its larger beam width comes about accidentally by virtue of its weatherproof casing. The 400ET does not have a useful response beyond 90 degrees. The four receiving transducers, also 400ETs, introduce the most significant error due to their directional response. The high-gain of the amplifiers is not quite high enough to compensate for the angular response of the receivers, which results in an annular region in which relatively larger errors occurred. The prototype system did, however, show that in the central region of the test grid, where the gain of the receivers is at their highest, the system is able to track the stylus to a resolution of a minimal 0.8 mm error. Therefore, with further development, an acoustic system can be used to track an object with a high degree of precision.

Since completing the experimental work, an improved type of ultrasound transducer became available, based on a flexible piezoelectric film [11], which enables the devices to be formed into cylinders, which provide a true omni-directional response. Figure 20 shows the typical horizontal and vertical beam directivity response of the US20KT-01 Omni-Directional Ultrasound transmitter [11]. The US20KT-01 transducer radiates a 360 degrees signal at 80 dB, when oriented at 90 degrees. The receiving US40KR-01 transducer is slightly more directional that the transmitter but the gain is still more than 80 dB between 0, 90, and 270 degrees. The operating voltage is 150 V, which requires modifications to the current prototype at 5 V.

8. Conclusions

The central problem that prompted this study was the need to support a graphics tablet that would not lose hand-to-eye coordination in moving from tablet to screen and back. In other words, to allow graphics tablet and display to be fused so that artists could draw or 'paint' in a traditional manner. This led to design, construction, and testing of a tablet which established the position of the stylus through ultrasonic transducers. A study of practising artists allowed the formation of an ideal specification of a graphics tablet, with tracking resolution of 1 mm or better; tracking error of more than 1 mm. system range of 300 mm square; and response time of less than 50 ms to provide 20 or more samples per second. The ultrasonic interface is placed beneath a digital flat panel of 17 inches diagonal or below, thus, allowing direct drawing while viewing the image on the display.

The experimental work of the paper has mainly established the feasibility of meeting the tracking specification in the 2D case for best-case circumstances with current ultrasonic transducers. Certainly in the authors' experience the prototype already allows drawing and painting to a satisfactory degree. Other aspects of the specification such as rotation and tactile response are dependent on sensor technology. Therefore, this paper's final conclusion is that a new generation of low-cost graphics tablet are possible and could well be based on an ultrasonic interface.

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Vsnd	Velocity of sound (approximately 34000 cm/s).	**cm/s**
Fc	Frequency of the reference clock.	**Hz**
Cn	Counter resolution	**bits**
Offset	Processing delay factor of modulator / demodulator	**cm**

Table 1: Variables in Equations (1) and (2)

Line	**Description**
1	Power supply (+5V)
2	Ground
3	**DAT** - Serial Data *(I/O Line)*
4	**CLK** – Serial Data Clock *(I/O Line)*
5	**IRQ** - Stylus Interrupt Request *(Output)*
6	**TRG** – Transmit an ultrasonic signal *(Input)*

Table 2: Details of the stylus bus lines.

Line	**Description**	**Line**	**Description**
1	System CLK	**9**	D1 *(Data)*
2	GND	**10**	D2 *(Data)*
3	Reset	**11**	D3 *(Data)*
4	GND	**12**	D4 *(CLK)*
5	Trigger	**13**	D5 *(DIR)*
6	+5v	**14**	D6 *(ACK)*
7	GND	**15**	D7 *(IRQ)*
8	D0 *(Data)*		

Table 3: Details of the local bus lines.

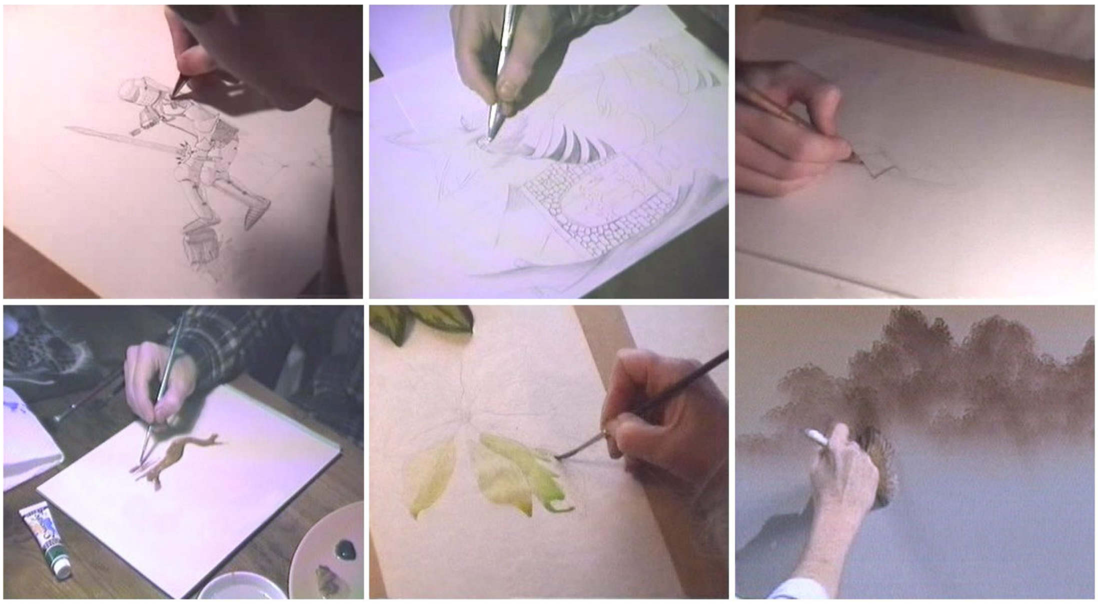
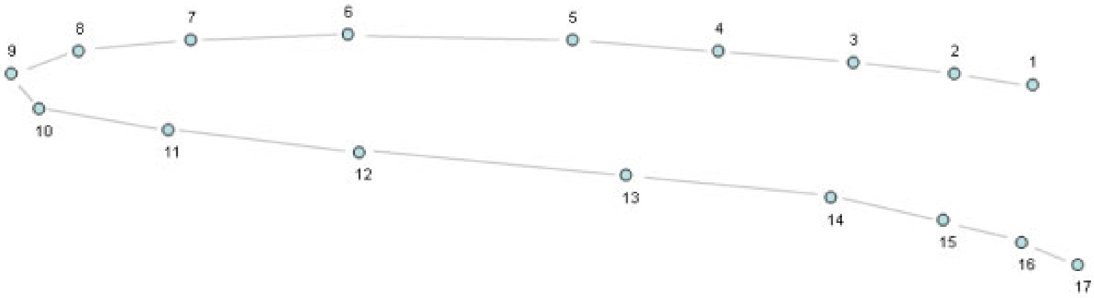
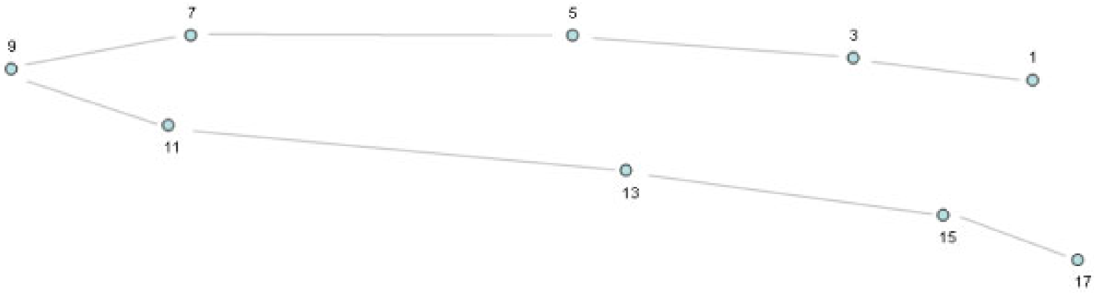


Figure 1: Stills of six artists filmed at work.

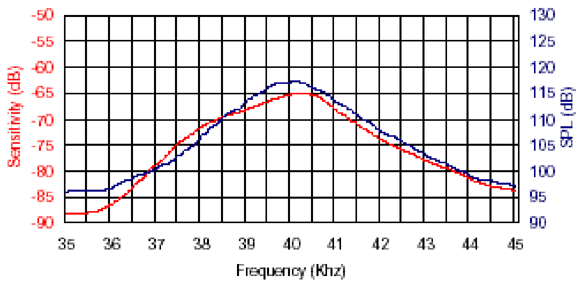


(a)

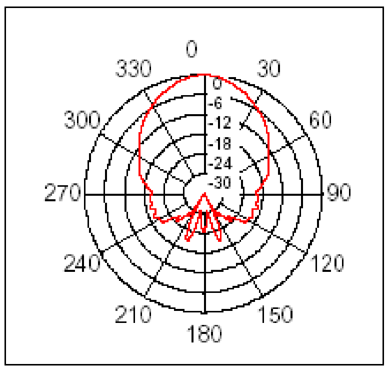


(b)

Figure 2: Line sampled at (a) frame rate (every 40 ms) (b) half frame rate (every 80 ms).



Sensitivity/Sound Pressure Level
Tested under 10Vrms @30cm



Beam Angle: Tested at 40.0Khz frequency

Figure 3: Response of ultrasonic device after [8].

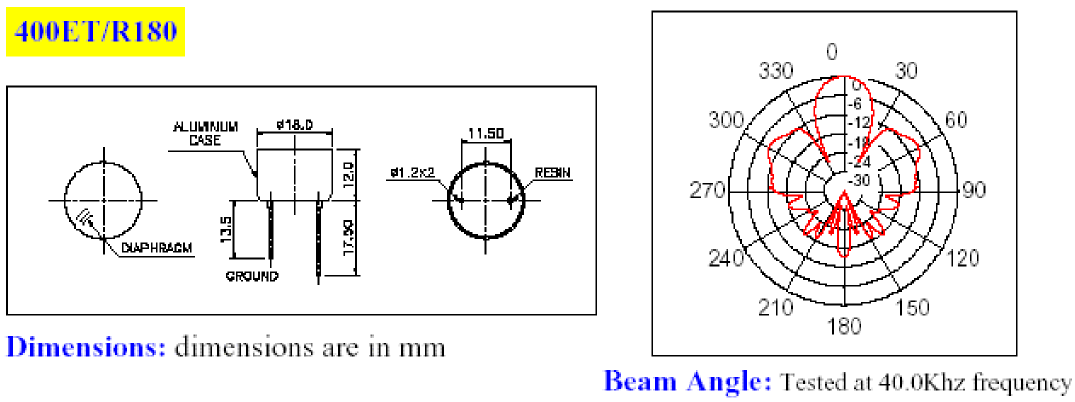


Figure 4: 400ET180 dimensions and viewing angle plot after [9].

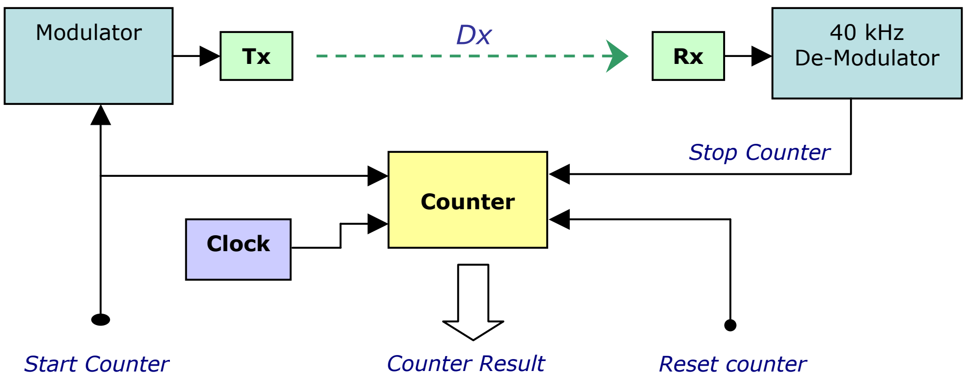


Figure 5: Measuring distance with ultrasound by means of a timer.

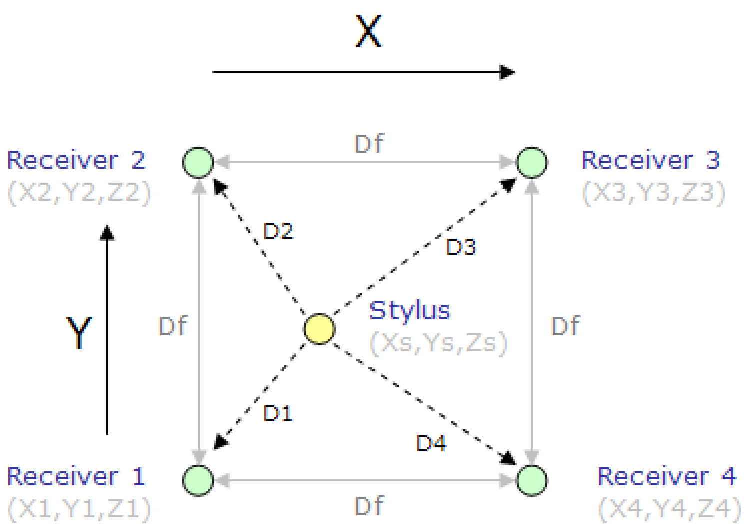


Figure 6: Tracking system geometry.

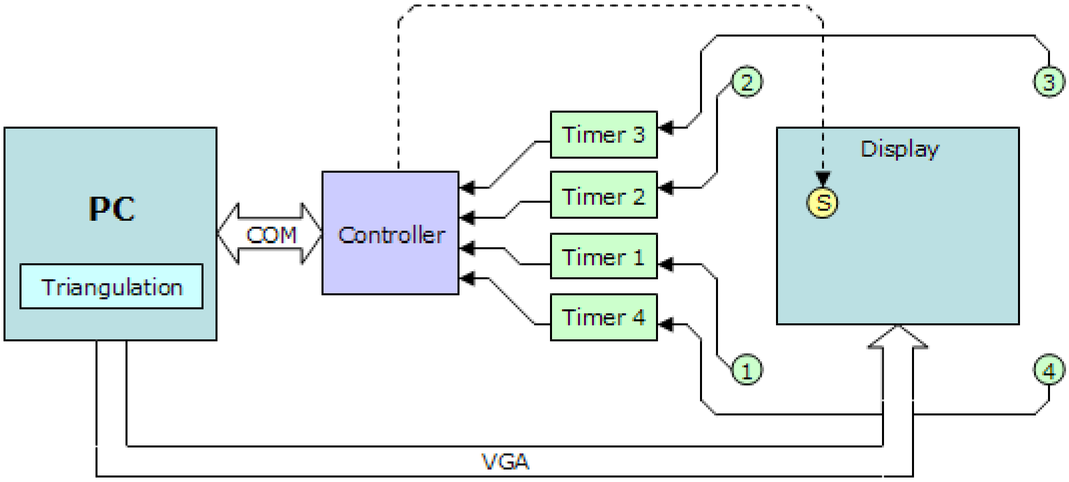


Figure 7: Top-level tracking system design.

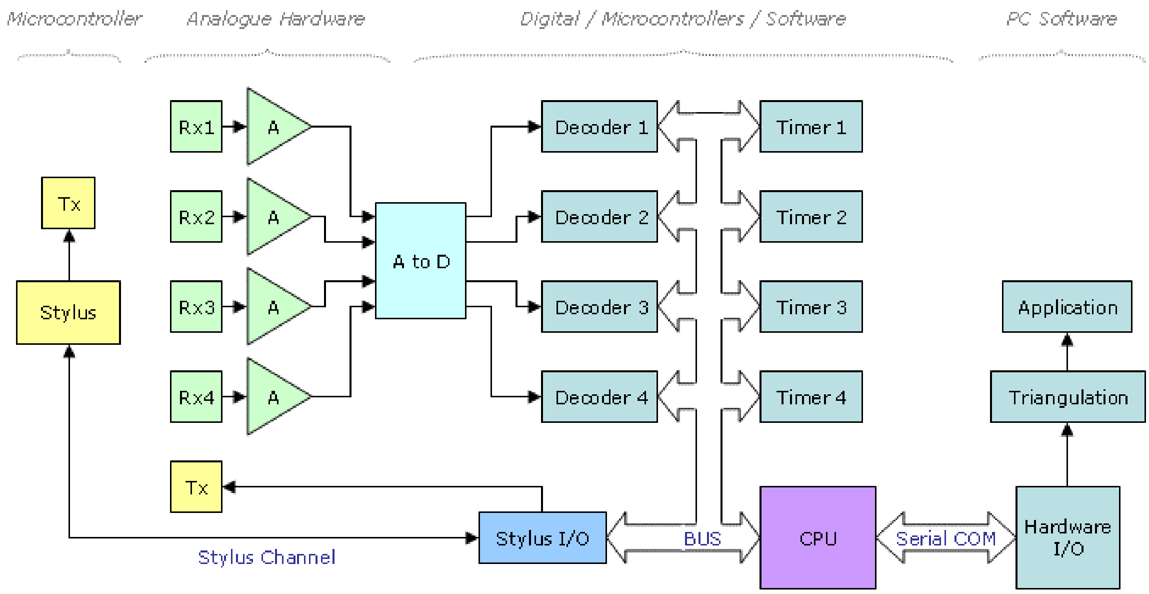


Figure 8: Mid-level design tracking system design.

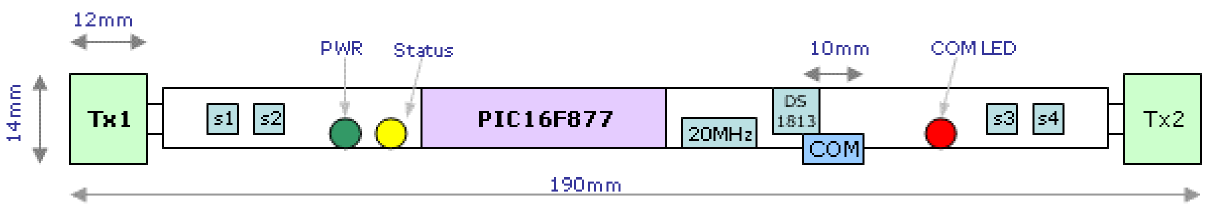


Figure 9: Stylus layout.

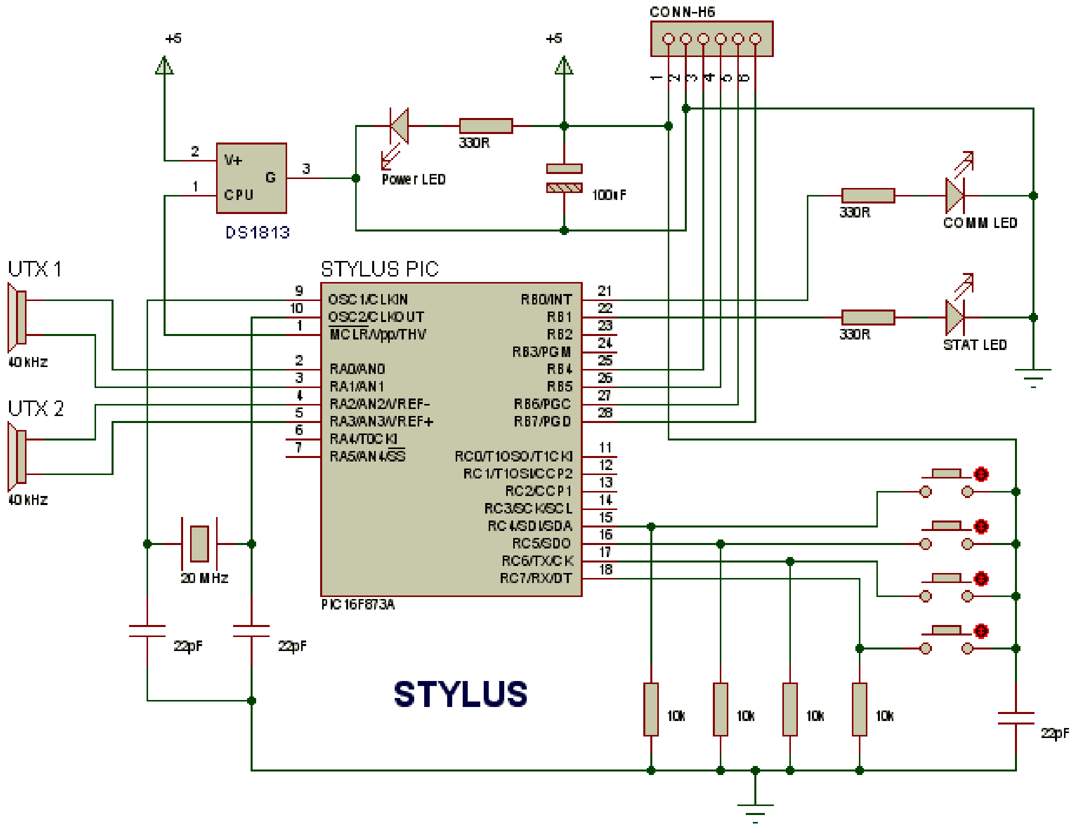


Figure 10: Circuit diagram for the stylus.

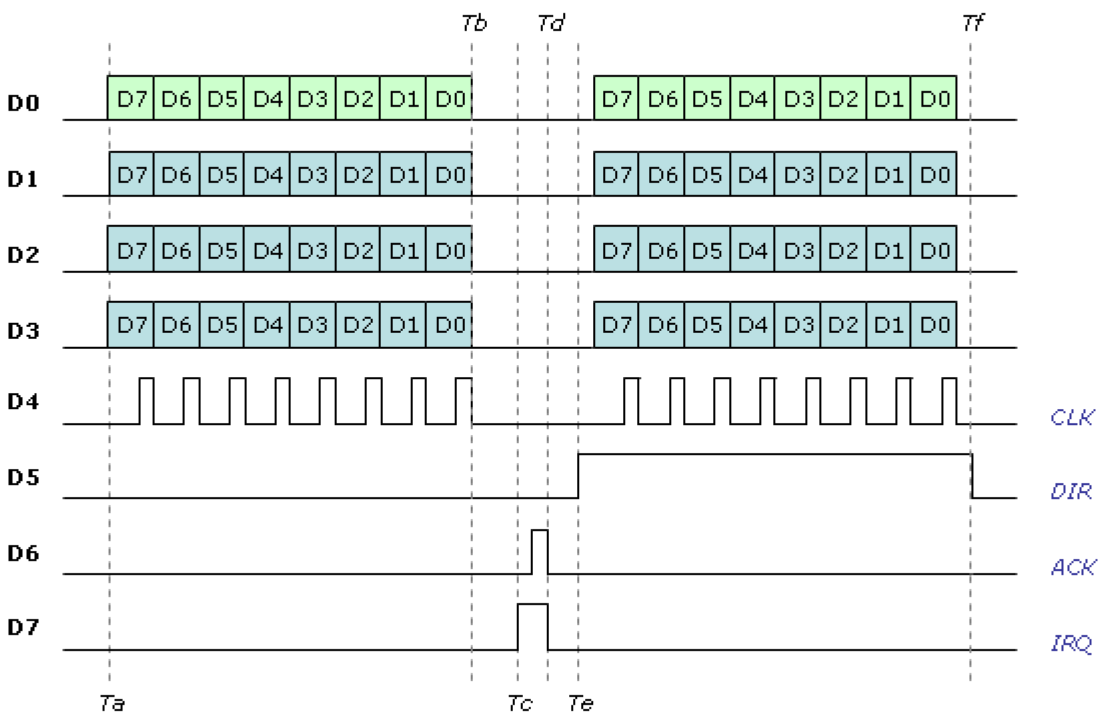


Figure 11: Timing diagram for the local bus.

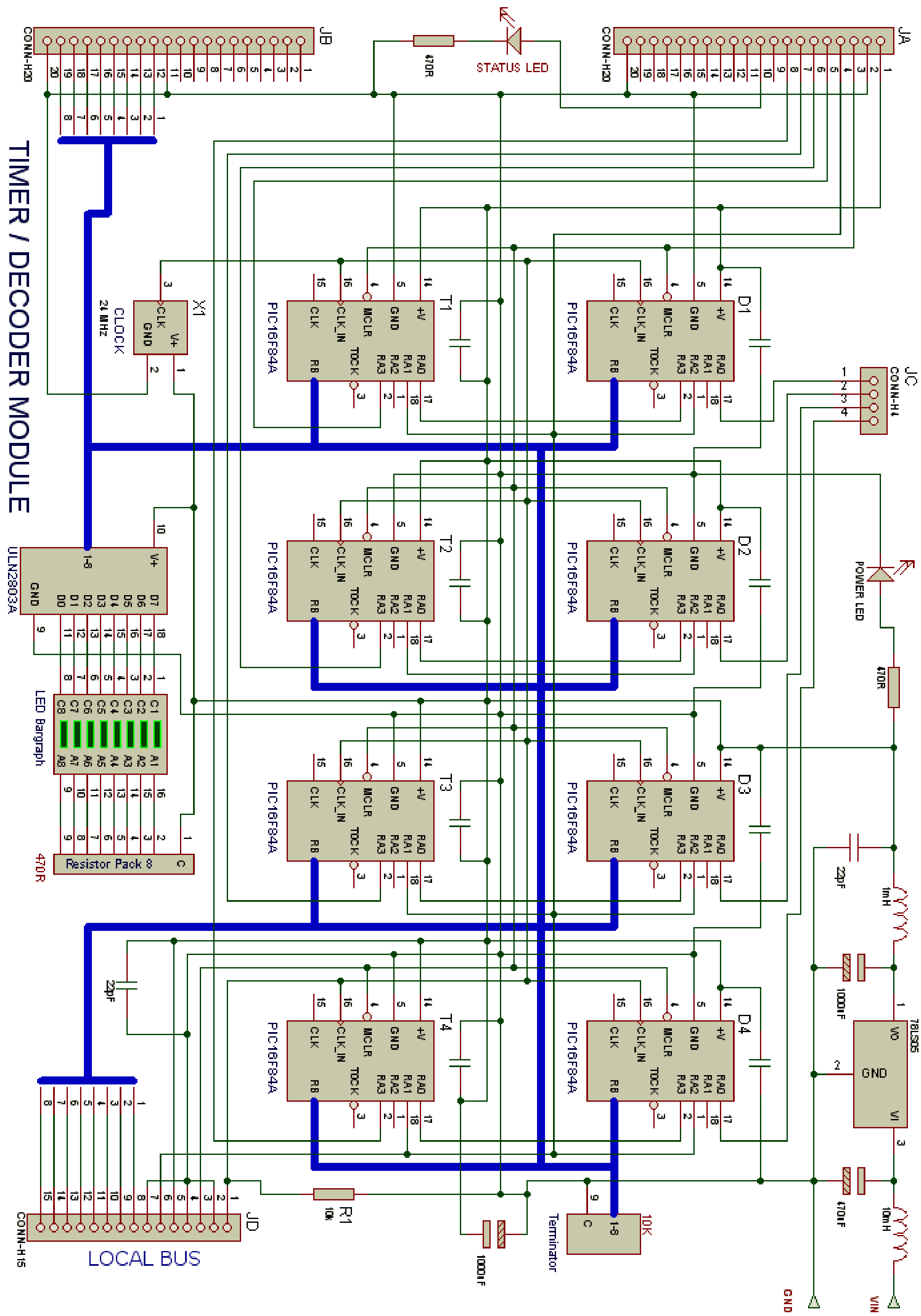


Figure 12: Circuit diagram for the decoder/timer board.

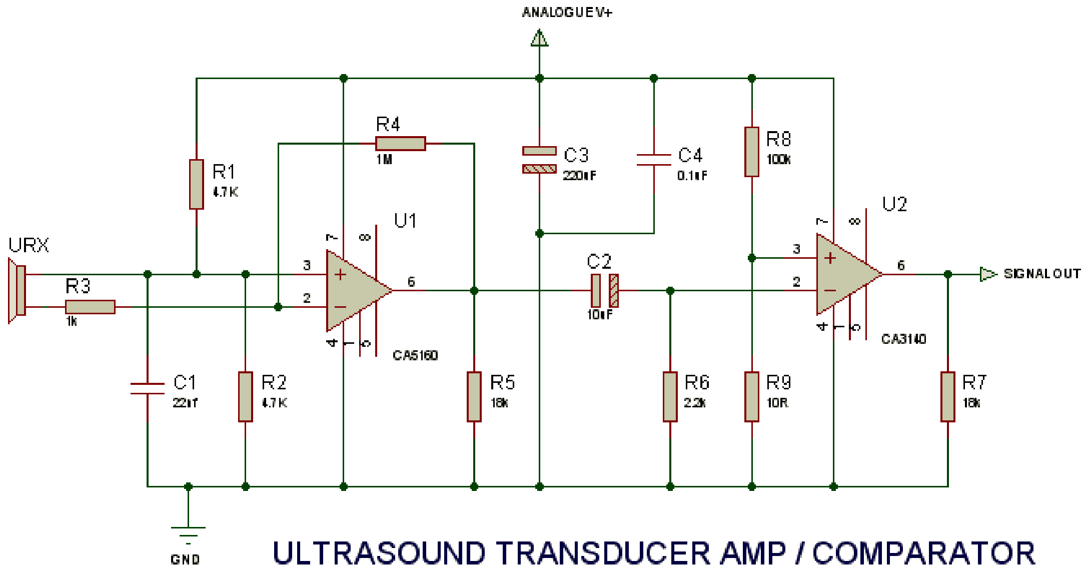


Figure 13: Amplifier series.

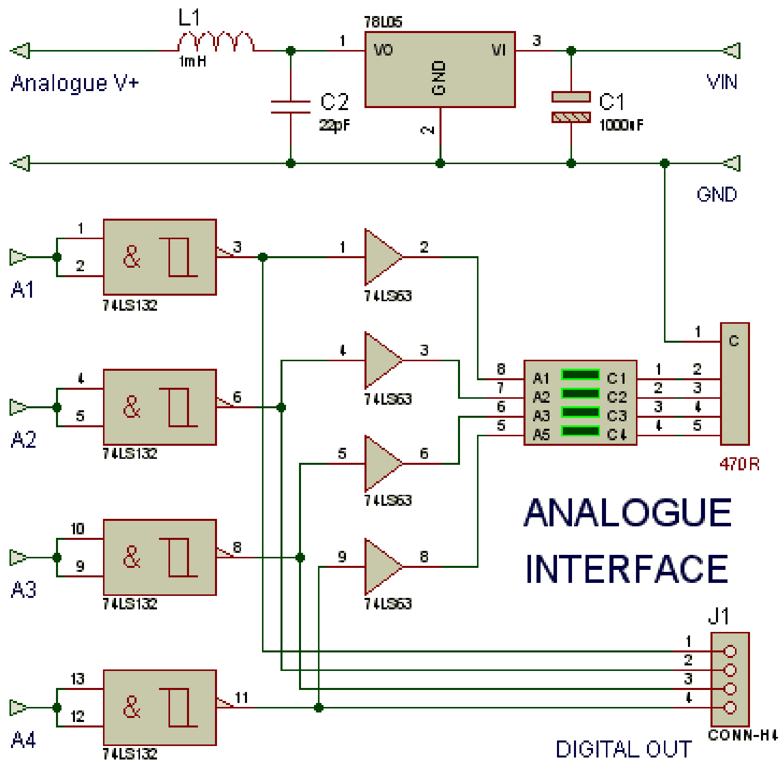


Figure 14: Analogue-to-digital signal interface.

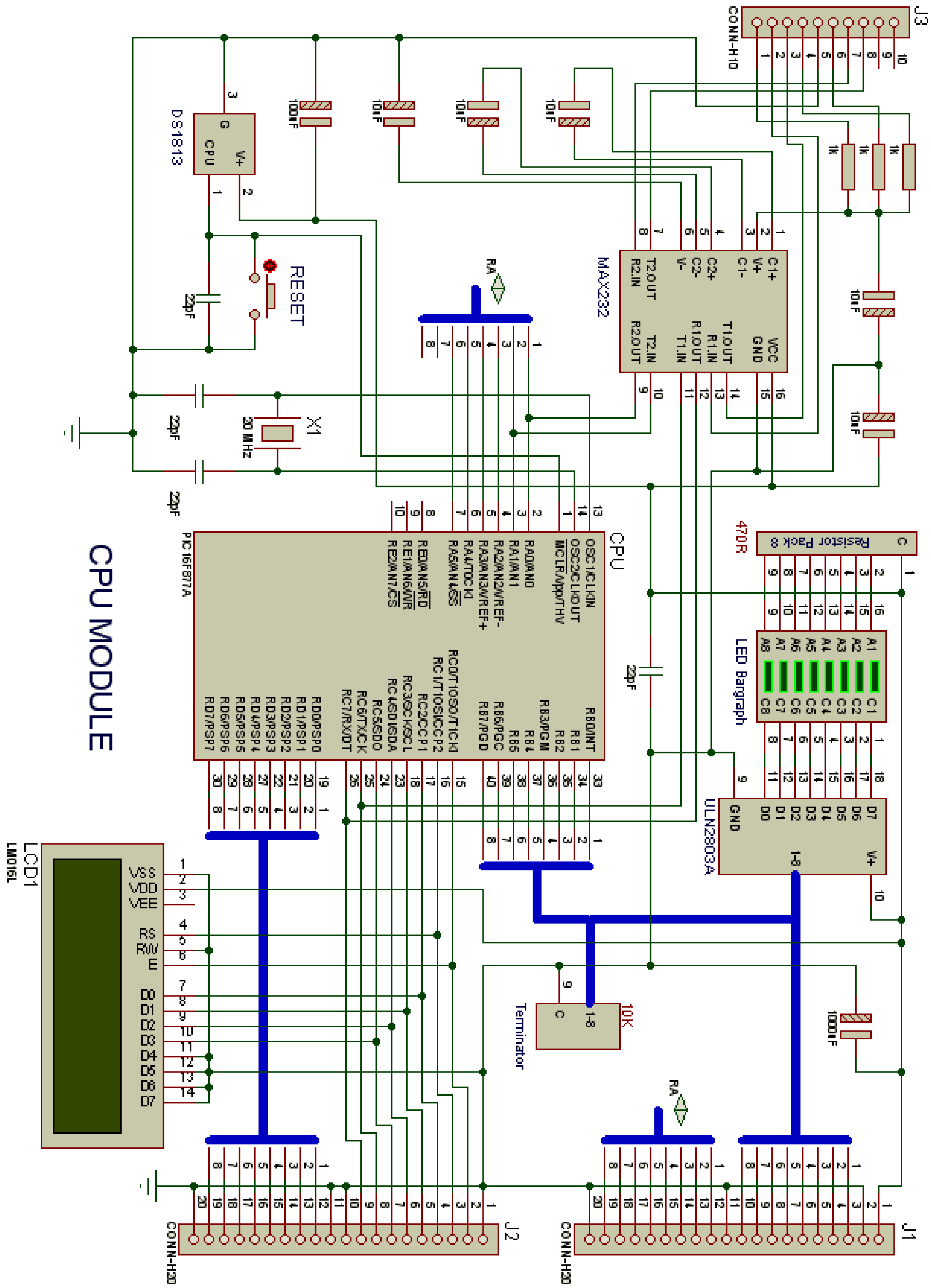


Figure 15: CPU board circuit diagram.

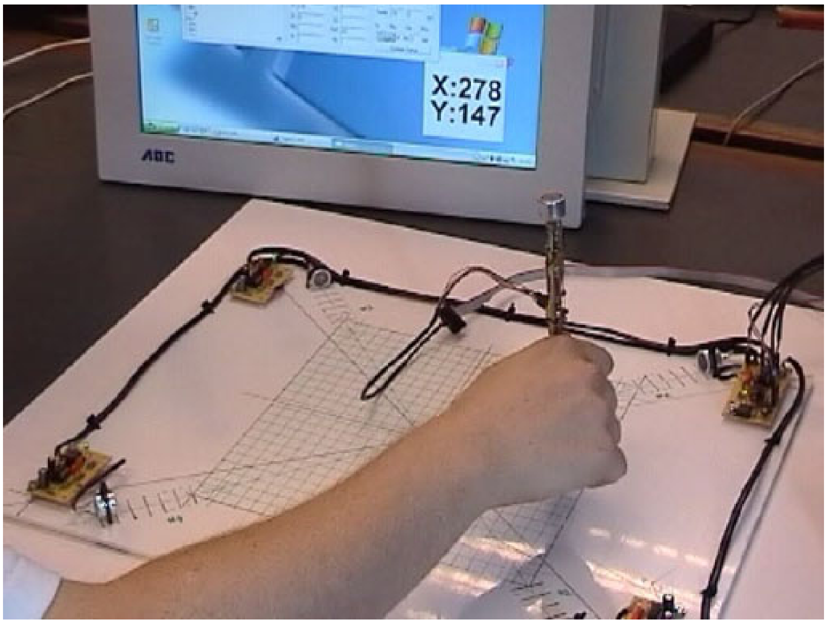


Figure 16: Prototype system in use.

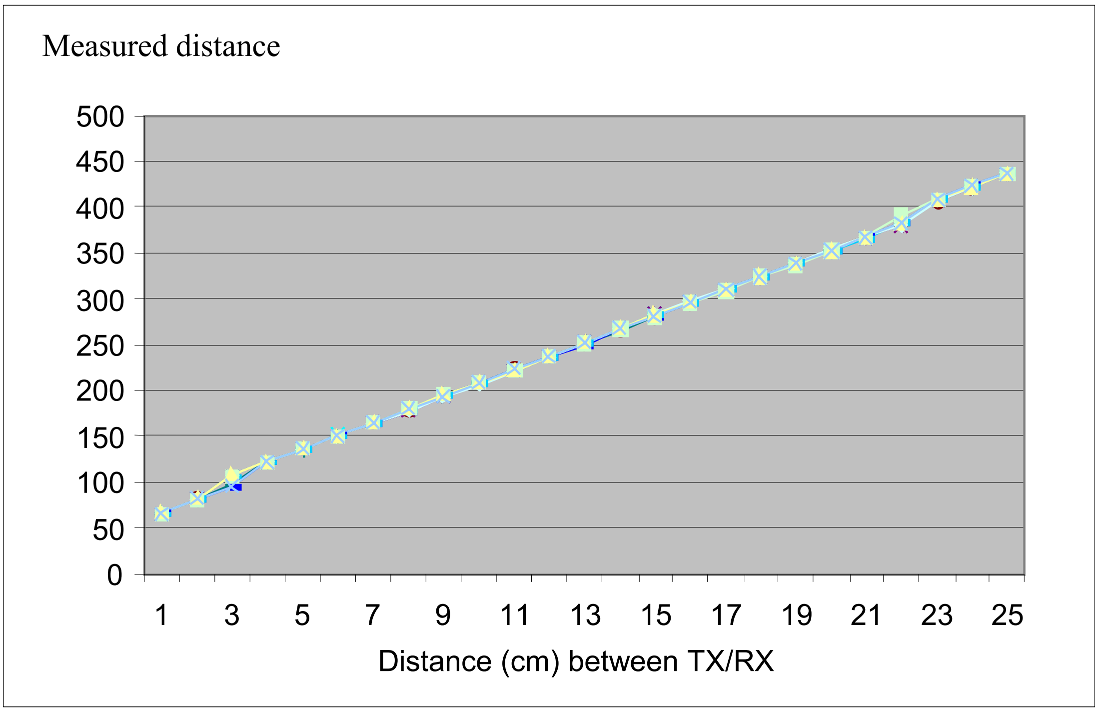


Figure 17: Calibration between measured distance units and known distance for horizontal test (TX and RX directly in line).

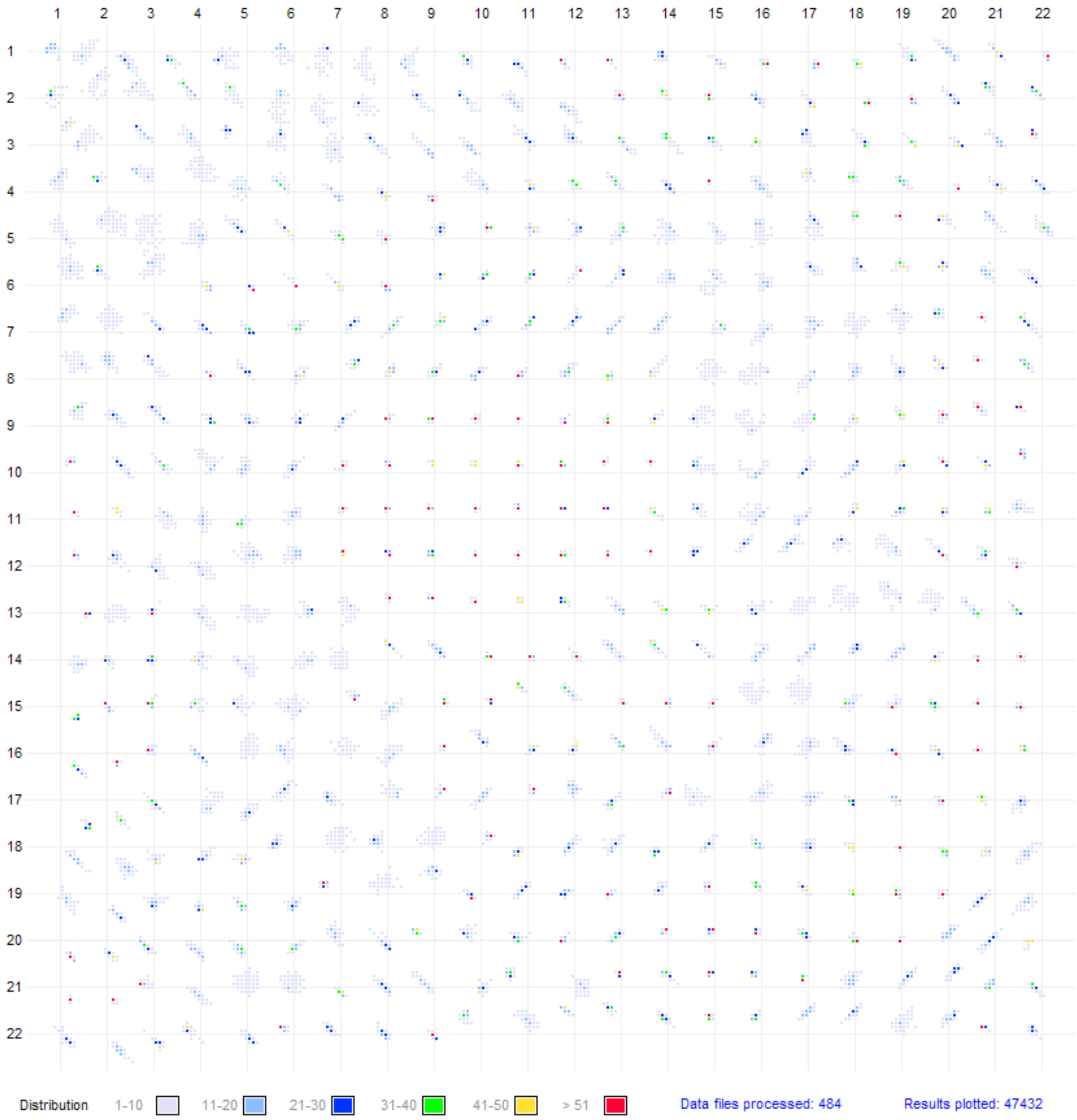
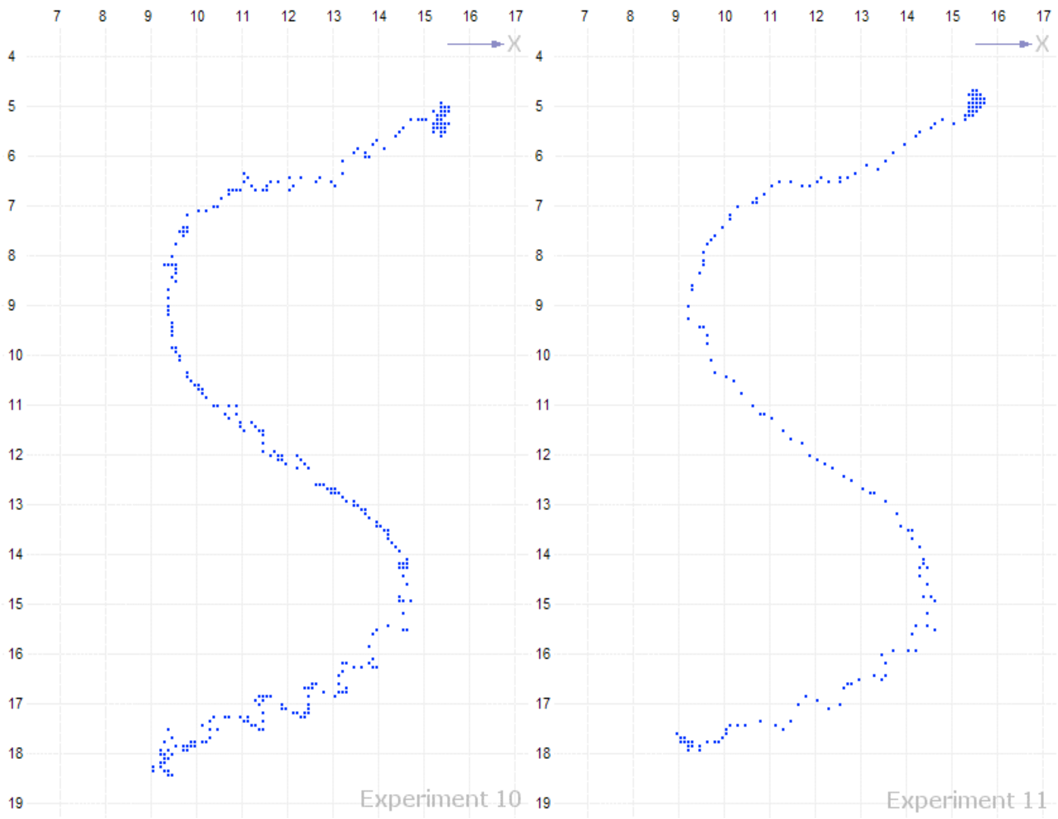


Figure 18: Scattergram showing results of repeated measurements at grid intersections.



(a) **(b)**

Figure 19: Tracing an ‘S’ with (a) 2-point (b) 4-point moving average filter.

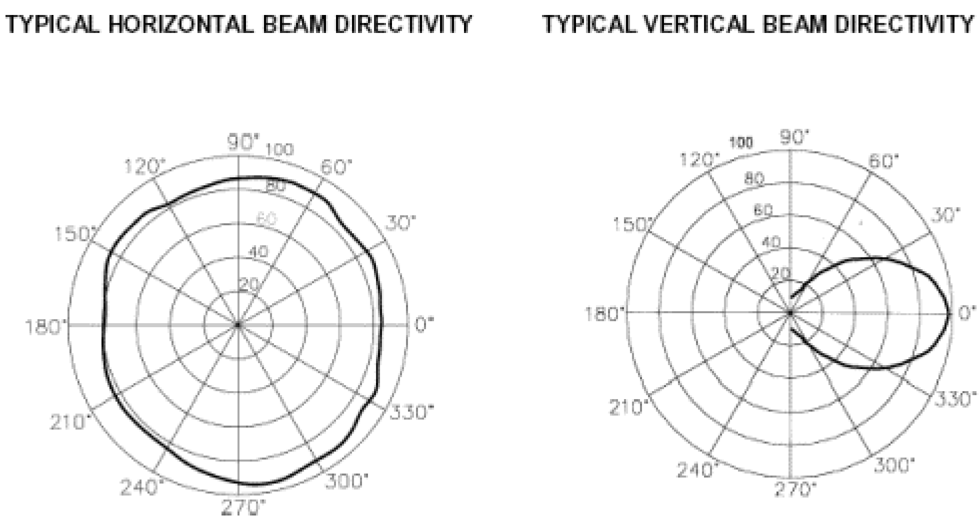


Figure 20: Angular response of US40KT-01, after [12].