A distributive method to increase the analogic output (D/A) resolution of a microcomputer

L. DIONNE, L. LAURENCELLE, and F. TREMBLAY
Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada

This paper describes a simple and efficient method to increase the D/A output resolution of an 8-bit microcomputer, as exemplified on the Apple II. The "distributive method" can increase the final output resolution up to 32K with two 8-bit analogic channels. A simple interface based on balanced sets of resistors and driver software are described. Some applications are also reported.

Computers are indispensable tools in the modern laboratory, especially for electrophysiology studies in which computers are used to collect large amounts of data and to generate a variety of stimulations with ease, rapidity, and efficiency. The first generation of microcomputers congruous with bioscience laboratories was in the 8-bit class (e.g., the Apple II or its versions and copies), and they were built to meet a wide range of applications. These computers still do their job quite well, but their usefulness in particular applications is somewhat impeded by the 8-bit limitation. For example, neurologists and neurophysiologists may need to collect, cumulate, and view electrophysiological signals recorded with sufficient precision. The coarseness of the display based on a 256-step scale is often annoying. The same limitation appears when one wants to generate a graphic pattern, linear or otherwise, on an analogic screen. The analogic output of the Apple II, normally implemented with 8 bits, has a definition that is aesthetically and sometimes critically insufficient and that needs improvement.

Of the many alternatives for circumventing the problem, the one described here involves dispatching a 9- to 16-bit word of definition over two 8-bit channels. This is brought about by making a minor hardware modification to a multichannel 8-bit D/A converter and by writing a short driver routine in assembler language. We propose this as a fair solution, particularly in the short term, for improving the resolution of the analogic output of a microcomputer; it also can serve to pretest application programs before transferring them to a bigger computer, if the need still exists to do so.

WORKING PRINCIPLE

Each channel of an 8-bit D/A card can provide 256 voltage increments distributed, for example, on a -5 V, $+5$ V range. A natural way to increase this precision is to add voltage levels by joining two channels, making up a 16-bit data word. The first channel (low-byte channel)

will be used to transmit the lower 7 bits of information, running progressively over the positive part of its range (0 V, $+5$ V) through 128 increments. The second channel (high-byte channel) operates as a multiplier and determines the overall range. Each increment produces a voltage that is equivalent to the total output range of the lower channel (refer to Figure 1). This is brought about by using resistors that adjust the voltage range of the two channels in the proper ratio, and then by adding the two outputs.

For example, suppose one needs a 1K resolution, or 1024 gradations, for the analogic output of an Apple II. First, one must build an interface for combining properly two channels of an 8-bit D/A card. To obtain 1K of resolution, the lower channel is used to produce the 128 finer levels of voltage, which in turn must be stepped up 8 times through the high-byte channel in order to produce the desired number of levels ($128 \times 8 = 1024$). The high-byte channel output must then be divided into 8 levels of 1.25 V each. The overall range, for instance, would be 10 V, and the 8-level variation would be programmed in the 3 higher bits, 5-7, of the high-byte channel. By using appropriate resistors, the (0 V, $+5$ V) variation on the low-byte channel can be reduced to a 0 V, $+1.25$ V range; the two voltage outputs can then be mixed. One then inserts in the main program a short routine handling the numeric dispatching and D/A triggering. An output with 1K levels, ranging from -5 V to $+5$ V, has thus been created by "distributing" a 10-bit value over two 8-bit D/A channels.

Hardware

The hardware part of this system is simple to build and requires common parts easily found in electronic stores. The attenuators must follow a ratio given by the formula $A_H/A_L = \text{Res}/128$, where A_H and A_L represent the attenuator values associated with the high- and low-byte channels, respectively, and Res is the total resolution needed. The value 128 is the number of levels produced in the low-byte channel; the expected quotient $\text{Res}/256$ is multiplied by 2 because the low-byte channel uses only half the total range of voltage (0 , $+5$ V) of the high-byte channel. Whatever the value of this ratio, the resistors may

Address correspondence to Louis Dionne, Groupe de recherche en Neuropsychologie, Université du Québec à Trois-Rivières, C.P. 500, Trois-Rivières, Québec G9A 5H7, Canada.

Figure 1. Working principle of the distributive method. Two channels of the D/A converter are used in conjunction to simulate a continuous output ranging between 128K and 32K of final resolution, depending on the number of steps one creates in the high-byte channel (S_N ; right graph). The low-byte channel varies from 128 to 255 (0–5 V), looping inside each step of the higher channel. (That correspondence is shown by the shadowed surface.) These two outputs pass through two resistors and are then mixed to produce a higher resolution output within a –5 V to +5 V range. See Figure 2 for details of the electronic circuit.

be in the range from 1 k Ω to 100 k Ω to comply with most peripheral equipment.

The user should buy resistors with the finest tolerance available. In fact, it is still better to couple a resistor of fixed value with a potentiometer, which could compensate for the tolerance error. Moreover, with a potentiometer it is possible to alter the ratio, and, if minor changes

are made in the software, the user can quite easily increase or decrease the final resolution of his system.

Software

Listing 1 shows an assembler routine for the 6502 processor that fits the example developed in the preceding section. Executing this routine will produce a signal

Figure 2. Details of the electronic circuit needed to produce an output of -1 V to $+1$ V from an input of -5 V to $+5$ V with a resolution of 1024. The first potentiometer (100 k Ω) permits a fine adjustment for AH:AL ratio, and the second (2 k Ω) allows for the positioning of the final output level.

on an X-Y-Z oscilloscope; the horizontal definition is 1024 points while the vertical is kept at 256 points. The distribution parameters can be found between lines 16 and 19. Lines 23-28 fix initial values for controlling the output channels ($X_L=128$; $X_H=0$; $Y=0$). Lines 29-48 include instructions defining two loops: the inner one increments the lower channel from 128 to 255, while the outer loop adds an increment of value 32, or $256/8$, in the higher channel. If the card used entails a delay covering conversion time, the user should insert as many <nop> instructions as are needed at appropriate locations in the program. (Note that each <nop> burns out 2 μ sec.)

Such an assembler routine is requisite when the signal is to be displayed (and regenerated) on an analogic oscil-

loscope, whose remanence is low. On the other hand, an equivalent BASIC program, for instance in Applesoft, runs conveniently to drive an analogic X-Y plotter for producing a hard copy of the graphic. Such a program, outlined in Listing 2, corresponds to the preceding one and thus requires no further comment.

DOMAINS OF APPLICATION

The concept of this method, which we call "distributive," can be used in a variety of applications, each time the analogic output capacity of a microcomputer is involved. We have developed and tested this method by including it in software that averages evoked EEG poten-

Listing 1
Example of a 6502 Routine to Obtain 1K of Resolution with the <DISTRIBUTIVE> Method

```

1  ;EXAMPLE
2  ;
3  ;MULTIPLEXING PROCEDURES
4  ;WITH D/A MOUNTAIN
5  ;FOR USE WITH X,Y,Z ANALOGIC SCOPE
6  ;RESULTING RESOLUTION
7  ;X = 1024
8  ;Y = 256
9  ;    LD85
10 ;
11 ;
12     ORG $5A00
13     OBJ $0800
14 ;
15 ;

16 OUT0 EQU $C0B0      ;LOW CHANNEL OUTPUT, J1 PIN 17
17 OUT1 EQU $C0B1      ;HIGH CHANNEL OUTPUT,J1 PIN 16
18 OUT2 EQU $C0B2      ;Z, J1 PIN 15
19 OUT3 EQU $C0B3      ;Y, J1 PIN 13
20 ;
21 ;UTILITY PROGRAM
22 ;
A280 23 AFFICH LDX #128      ;LOAD X REG. FOR LOW CHANNEL
A000 24     LDY #0          ;LOAD Y REG. WITH STARTING VALUE 0
8408 25     STY $08         ;HIGH BYTE LOOP COUNTER
8409 26     STY $09         ;AND HIGH BYTE REFERENCE
A980 27     LDA #128       ;Z VALUE
8DB2C0 28     STA OUT2     ;Z CHANNEL OUTPUT

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Listing 1 (Continued)

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890060 29 AFF LDA $0000,Y ;BANK BUFFER, ENTERING IN MASTER LOOP
EA 30 NOP ;WASTE TIME (OPTIONAL)
8EB0C0 31 STX OUT0 ;X LOW (LOW CHANNEL) OUTPUT
8DB3C0 32 STA OUT3 ;Y CHANNEL OUTPUT
E8 33 INX ;NEXT BIN
D00E 34 BNE NEXTY ;IF NOT 0 STAY IN FIRST STEP OF HIGH BYTE
A280 35 LDX #128 ;LOAD X REG FOR LOW CHANNEL VALUE
A509 36 LDA #09 ;HIGH BYTE REFERENCE
6920 37 ADC #32 ;NEXT STEP IN HIGH BYTE
8509 38 STA #09 ;PROTECT NEW REFERENCE
8DB1C0 39 STA OUT1 ;OUTPUT NEW HIGH BYTE VALUE
4C315A 40 JMP ICI
C8 41 NEXTY INY ;NEXT BYTE IN BANK BUFFER
D0E2 42 BNE AFF ;TO MASTER LOOP
EE0F5A 43 INC AFF+2 ;ADD 256 TO BANK BUFFER POINTER
4C0D5A 44 JMP AFF ;TO MASTER LOOP
E608 45 ICI INC $08 ;INCREMENT HIGH BYTE LOOP COUNTER
A508 46 LDA $08 ;AND CHECK
C908 47 CMP #08 ;IF LAST PASS
D0EF 48 BNE NEXTY ;IF NOT
60 49 ; RTS
50 ; UTILITY PROGRAM
51 ;
52 END

```

Listing 2
BASIC Version of the Same Routine

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1000 VI = 24576 : REM FIRST VALUE IN MEMORY
1010 XB = 49341 : REM LOW CHANNEL OUTPUT CHANNEL 13, PIN 3
1020 XH = 49342 : REM HIGH CHANNEL OUTPUT CHANNEL 14, PIN 2
1030 YD = 49343 : REM Y CHANNEL OUTPUT CHANNEL 15, PIN 1
1040 PL = 49340 : REM PEN LIFT CONTROL CHANNEL 12, PIN 4
1050 POKE PL, 255 : REM PEN UP
1060 POKE XB, 128 : REM LOAD X AXIS FOR LOW CHANNEL WITH 0 V
1070 POKE XH, 0 : REM LOAD X AXIS HIGH CHANNEL WITH -5 V
1080 POKE YD, 128 : REM MIDRANGE VALUE FOR Y AXIS
1090 GET AS : REM SET YOUR PRINTER AND GO
1100 POKE PL, 0 : REM PEN DOWN
1110 FOR I = 0 TO 224 STEP 32 : REM LOOP FOR HIGHER BYTE
1120 FOR B = 128 TO 255 : REM LOOP FOR LOWER BYTE
1130 Y = Y + 1 : REM COUNTER
1140 DY = PEEK (VI + Y) : REM VALUE IN MEMORY
1150 POKE XB, B : POKE XH, I : REM SELECT THE CORRECT BIN
                                (X AXIS)
1160 POKE YD, DY : REM PLACE THE VALUE IN CHANNEL Y
1170 NEXT B : REM IF B = > 255 THEN RESET AND ...
1180 NEXT I : REM ADD 32 UNITS (TO OBTAIN 1 K)
                                IN HIGHER BYTE
1190 POKE PL, 255 : REM PEN UP
1200 STOP

```

tials. Besides increasing the quality of the visual output, particularly on a large screen, the system makes it possible to scrutinize a small portion of the curve directly on the screen without having to edit the signal, expand the display, or otherwise complicate the signal processing software. Also, when plotted on the *X-Y* recorder, the curve appears smoother, without a staircase effect often seen in hard-copy illustrations; it looks as if it were continuous.

The distributive method may also be useful for displaying histograms or other kinds of graphs, by increasing the resolution of the *X* (or time) axis. In comparison with histograms obtained with an 8-bit D/A card, it becomes feasible to display more bars so that a higher resolution is obtained by reducing the bin-width, or alternatively a signal of longer duration by keeping the bin-width and adding more bins.

The method has also been adapted to an apparatus that controls moving parts, such as a (continuous) motor. Through an increase in the resolution, all movements be-

come smoother, without backlash due to coarse settling, thus reducing wearing down of moving parts and obviating in some cases the need for a feedback-controlled positioning.

CONCLUSION

The possibilities for using the distributive method are numerous. The concept and the application of the system are quite simple, and it allows the use of available or cheap microcomputer equipment for applications requiring a performance typical of costlier or unavailable hardware. The user is also able to take advantage of the availability of well-known programs with an Apple II, instead of having to start anew with a more sophisticated, but more complicated, hardware and with nonexistent or unproven software.

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