The Evolution of Digital Signal Processors

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***Abstract* – Digital Signal Processors (DSP) are high-speed dedicated processors designed to perform arithmetic operations on their input signal, and then output the processed signals. They are currently used in many applications, such as telecommunications, video and audio signal processing, flight control systems, spacecraft, missiles, etc. DSP processors have evolved through several generations over the last few decades. This paper outlines the evolution of some of the DSP processors from early days of 1970s to the present.**

***Keywords*—digital signal processor, DSP, microcontroller, microprocessor, digital processing.**

I. INTRODUCTION

Real-time Signal processing dates back several decades. Prior to 1970s, signal processing was mainly performed using analog electronics. The main application areas of analog signal processing were in the field of telecommunications, in radio receivers and radio transmitters, multiplexed radio and line communications for telephony, and in radar.. Analog signal processing mainly included the design of analog filters and matching circuitry. Some other applications of analog signal processing were with sensors, such as reading and processing the analog outputs of temperature, humidity, pressure, distance, and similar sensors, these normally being at sub-audio rates.

In the second half of 1970s, a new era of signal processing started with the introduction of low-cost microprocessors and microcontrollers. This established digital signal processing (DSP) as a new core discipline in electrical engineering. Although DSP is much more complex compared to analog processing, it offers several important benefits:

- DSP offers very high accuracy. For example, filters designed in DSP have very accurate cut-off frequencies compared to analog filters.
- Analog components are bulky, especially at low frequencies. For example, designing low frequency filters require bulky inductors and capacitors. Active RC filters were the subject of much research, but until the availability of cheap op-amps, were seldom cost effective or practicable. Switched-capacitor filters unexpectedly provided a bridge between fully analog signal processing and DSP, and which could be implemented in microelectronic form.
- The values and tolerances of analog components vary over time and with the ambient temperature, thus affecting their performance. DSP does not suffer from such problems.
- It is very easy to reconfigure and change the response of DSP processors since all that is required is re-programming. On the other hand, reconfiguring analog processors is usually costly.
- DSP offers the advantage that the signal can be interfaced to protocols such as UART, SPI, I2C and so on.

Compared to analog processors, the DSP processors have some disadvantages:

- Designing a DSP system is much more complex than designing an analog processor as it requires knowledge of both hardware and software of the DSP chip used.
- The use of DSP requires antialiasing filters which add to the complexity and increases the cost.
- DSP processors were initially more costly compared to analog processors.
- DSP processors dissipate more power than equivalent analog processors, especially at high frequencies.
- Testing DSP processors usually require specialized and more expensive equipment.

DSP processing is normally carried out by receiving continuous analog physical variables in the form of voltage, converting them into digital form, processing using a digital computer, and then outputting the processed signal in analog form.
Fig. 1 shows a typical DSP application [1] where it is implied that separate components are used in the design. Here, a sample-and-hold device (S&H) is used to capture samples of the analog input signal. The analog-to-digital converter (ADC) converts the signal into a digital time-series, most often at a constant sampling rate which must at least comply with the sampling theorems and be at least twice the highest signal frequency. The ADC is chosen to provide the required precision and handle the highest frequency of the input signal. The higher the frequency, the smaller must be the ADC conversion time. The digital signal is then fed to the digital processor (MCU), which is usually a fast microcontroller with additional dedicated hardware, optimized to carry out the common DSP operations as accurately and quickly as needed. The processor is chosen to meet the required precision and highest frequency of the discretized signal. After digital processing, the signal must be converted into analog format using a digital-to-analog (DAC) converter. Although separate components are shown in Fig. 1, most present day DSP processors can incorporate the S&H, ADC, MCU, and DAC modules into a single chip.

II. EARLY MICROPROCESSORS AS DSP PROCESSORS

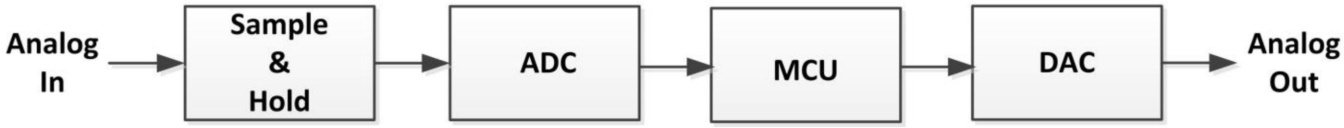

Fig. 1 Typical DSP system

DSP processors evolved through several generations.

In the first generation in the 1970s, attempts were made to use general purpose microprocessors in digital signal processing applications. A microprocessor system consisted of several chips, such as the RAM and EPROM memory, input-output, timing, interrupt etc. For example, the 8-bit Fairchild F8 (Fig. 2) consisted of at least three 40-pin chips, with maximum clock frequency of only 2MHz, very low by today's standards. With four clock pulses per machine cycle, the basic instruction time was 2µs. It was also necessary to add external ADC and DAC chips to complete the design. DSP algorithms mainly consist of multiply and accumulate (MAC) operations as shown by equation (1) below:

$$y[n]=\sum h[k]*x[n-k] \qquad (1)$$

for $k = 0$ *to* $N-1$, where, $h[k]$ are the fixed coefficients. A typical DSP instruction then requires:

- One program memory fetch
- Two data memory reads $h[k]$, $x[n-k]$
- One data memory write $y(n)$

Hence, the main component in signal processing can be viewed as a dot product of two vectors requiring just fast but simple multiply and add operations. In effect that is all that a non-recursive digital filter does. The multiplication consumes many processor cycle times and had to be done in software in the early microprocessors. Because of this and the long cycle time of the microprocessor system, it was only possible to process very low frequency input signals. The accuracy was also very poor since the processor data width was only 8 bits. It was however possible to increase the performance by several factors by using an external multiplier chip or by using table look-up techniques [3]. Software multiplication on the F8 microprocessor took over 500µs, while the same multiplication using an 8x8 bit hardware multiplier (e.g. 8807A) required only 9 bytes of program memory and took only 36µs [4].

Higher performance was available with the introduction of the 8-bit Z80 microprocessor family by Zilog in the late 1970s. This has reduced the chip count, a more powerful instruction set, and also increased processor speed to 2.5MHz and later (e.g Z80A) a clock frequency of 4MHz, 6MHz (e.g. Z80B), and 8MHz (e.g. Z80H). Z80 based DSP systems still required the addition of several support chips and external ADC and DAC chips and also an external multiplier chip for improved performance. Other 8-bit general purpose processors during this time were 8080, 6800, 6502, CDP1802, 6801, 2650 and others. None were really suited to DSP.

- Several external support chips to operate as a complete DSP system.
- External S&H, ADC and DAC support chips were required.
- Processor speed was too low for many applications.
- Multiplication was a slow process and an expensive external multiplier chip was required for medium audio frequency processing
- Power dissipation was high
- To achieve the maximum processing speed possible, high-level languages could not be used, and so assembly language with some clever ways was needed and could be hard to learn and the software was hard to maintain and update.

In early 1980s bit-slice microprocessors became popular. This was a technique of constructing a digital processor from modules having fixed word lengths. For example, two 4-bit modules could be arranged to form an 8-bit processor. This was necessary because processors with wide data lengths were not available at the time. With bit-slice processors, all the control circuitry, timing, memory, etc. had to be designed from the first principles in order to form a complete processor. Such bit-slice processors were used in signal processing applications [5]. The Advanced Micro devices AM2900 series was one of the popular bit-slice processors during the 1980s and was supported by a large number of bit-slice modules [6]. The advantages of a bit-slice processor were:

- Any required word length could be constructed using smaller modules- just requiring increased cost.
- Bit-slice processors made use of bipolar technology which at that time provided very fast throughput compared to MOS technology..
- Bit-slice processors could be programmed using microprogramming techniques with dedicated signal processing instructions for faster throughput. For example, many DSP operations could be performed by a single instructions with only one fetch cycle.

Bit-slice design had the major disadvantage that the overall cost of the design was extremely high compared to the cost of a general purpose microprocessor. Design of a bit-slice processor also required much more hardware and software knowledge and experience, and so applications were mainly in the military area.

III. CURRENT MICROPROCESSORS AS DSP PROCESSORS

Microprocessors are nowadays in the form of microcontrollers where many support functions have been incorporated onto a single chip. These microcontrollers are also known as single-chip microcomputers. The advantages of the present day microcontrollers over the microprocessors are as follows:

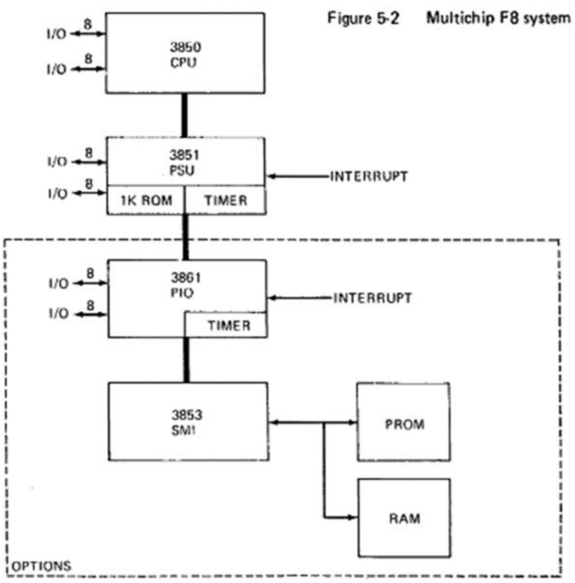

Fig. 2 F8 microprocessor system

- Several previously needed support chips, such as the memory, timing, interrupt, input-output, and others are now all on the same chip.
- The processors have built-in multiplier hardware modules
- Most microcontrollers have built-in multi-channel ADC and DAC ports.
- The power dissipation is considerably lower.
- The processors can be programmed using high-level languages which makes the programming and maintenance easier.

Currently, there are many types of microcontrollers available in the market place. In this section we describe just one popular microcontroller family, the *PIC microcontroller family*.

PIC is a general purpose microcontroller family consisting of over several hundred models of 8,16, and 32-bit microcontrollers with different specifications. Of particular interest for DSP are the PIC18F family, PIC24, dsPIC33F, and the 32-bit family of processors. PIC18F family consists of a large number of 8-bit general purpose microcontrollers with built-in ADC ports and hardware multipliers. The family members can operate from 20MHz to up to 64MHz, and they can all be programmed using high-level languages. Although these are general purpose microcontrollers, they can be adapted for use in low to medium end DSP applications with the addition of an external DAC. While operating at 20MHz, the typical member of the family, PIC18F4520 is reported to take only 0.8µs for 8x8 unsigned multiplication using the standard C language, and 0.92µs for signed 8x8 multiplication [7].

dsPIC33F is a family of 16-bit general purpose microcontrollers with enhanced features for digital signal processing, such as two simultaneous reads from the memory, single-cycle 17x17 bit hardware multiply and divider, 32-bit multiply support, two 40-bit accumulators, ADC and S&H modules. The MAC instruction and other associated instructions can concurrently fetch two data operands from memory while multiplying and accumulating in two W registers. dsPIB33F is supported by high-level DSP libraries including FIR and IIR filter library, FFT and vector library, matrix library and so on [8].

PIC32 is a 32-bit general purpose microcontroller family, based on the M4K 32-bit core, and offering up to 120MHz clock speeds with high throughput multi-channel ADC ports. These processors are also supported by high-level DSP libraries [8] and can be used as DSP processors.

IV. EARLY DEDICATED DSP PROCESSORS

In 1973, TRW produced parallel multiplier chip designs and soon after, bit-slice ALUs but these were too expensive for anything other than the military uses. By 1978, AMI produced the S2811, a 12 bit MOS DSP chip, which might be considered the first single chip DSP. However it was not widely used and so not a commercial success. At about that time, Bell Laboratories produced the DSP-1, for internal uses within AT&T, and at about the same time there was the NEC µPD5770, which could just about handle the audio frequency range. Shortly after, the Intel 2920 (Fig. 3) was one of the early dedicated DSP chips introduced. It incorporated both ADC and DAC, therefore the inputs and outputs were analog signals and was marketed as a 'drop-in' processor (e.g. analogue in, analogue out). The ADC had 4 input channels and a resolution of 9 bits. The DAC had 8 output channels. The ALU consisted of 40 word by 25-bit random access memory. User program was stored in a 4608 bit EPROM. The instruction set of the processor was very basic and there was no multiplication or division. Filter coefficients were approximated using powers of 2 and addition was carried out to simulate multiplication. There were only 16 instructions with no branching. Overall it cannot be said to have been a marketing success.

Although general purpose microcontrollers were used in DSP applications, it was recognized that higher throughput could have been obtained by using dedicated processor architectures. Existing general purpose microprocessors were based on the Von Neumann architecture where instructions and data were stored in the same memory and then delivered to the processor on the same single bus. Of course, 8-bit data or even 16 bit data was not adequate for accurate DSP operations and even 16 bit arithmetic took many extra machine cycles so lowering the useful frequency range. Although bit-slice design solved some of the DSP problems, it was too expensive and required specialized design knowledge. The eventual move was towards the 'Harvard' architecture, where 'multiply-accumulate' is the main operation. With three memory registers, (for two operands and a result all concurrently available), the operation $C := A \text{ op } B$ can be done in a single machine cycle, and having a long enough wordlength is conceptually simple just by having a processor with wide enough data buses (able to be integrated as chip technology advanced). Using floating point arithmetic offered avoidance of overflow problems with large signals at the expense of much greater complexity, and so most designs continue to use fixed point arithmetic for DSP.

The Texas Instruments TMS32010 (Fig. 4) was the first generation of TI's dedicated DSP processors, although its architecture looked like a conventional microcontroller. This was a fast and also an expensive processor that could compute multiplication in 200ns and having an initial cost

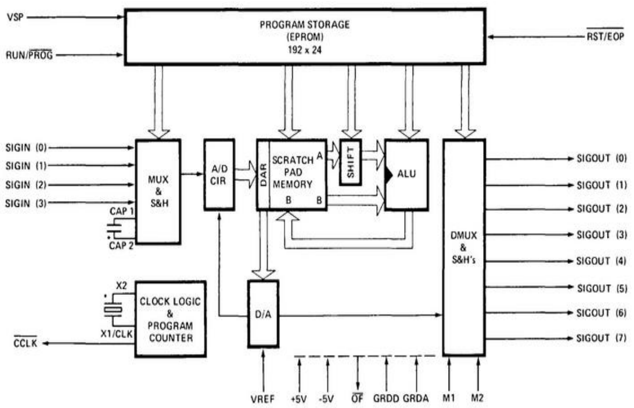

Fig. 3 Intel 2920 processor architecture

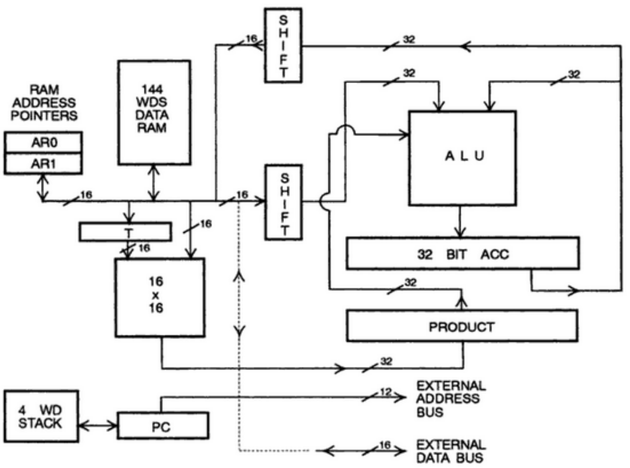

Fig. 4 Simplified architecture of the TMS32010

of $500 a piece.
The TMS32010 was a 16-bit processor having only 144 words of data memory and 1536 words of program memory. The processor had 60 instructions, supporting both DSP specific and general purpose instructions. Nevertheless it represented the start of widespread DSP using microelectronics in many commercial and consumer applications (for example the 'speak and spell' product for children [9]).

In later years we see the development of other DSP from Texas Instruments such as TMS320C1x, C25, C5X and so on where the clock speed and the memory capacity increased steadily.

Motorola DSP 56000 followed by DSP96002 was one of the most advanced DSP chips of late 1980s. The speed increased from 5 million instructions per second (MIPS) of the TMS32010 to 16.5 MIPS with the DSP56002 with a 33MHz clock. This chip had single-cycle 32x32 bit multiplier, floating point mathematical operations, on-chip ROM and RAM data and program memories, and highly parallel instruction set dedicated for DSP processing.

ADSP-21XX from Analog Devices is a 16-bit DSP with on-chip multiplier and accumulator (5). The processor operates at 25MHz with a 40ns instruction cycle. The ALU of this processor consists of three independent computational units: the ALU, multiplier accumulator (MAC), and the shifter. Five internal busses are used for efficient data transfer between various parts of the processor. The program memory can store both instructions and data, permitting the processor to fetch two operands in a single cycle, one from program memory and one from data memory. External support modules such as S&H, ADC and DAC must be added to make a complete DSP system.

ARM is a leading company designing core processors for the mobile market. The company offers low-cost, high-performance and low power consumption processors for the mobile consumer market. The company has also entered the DSP market in early 2000s with the Piccolo processor. This was designed as a 16-bit co-processor to be interfaced to company's other standard ARM processors.

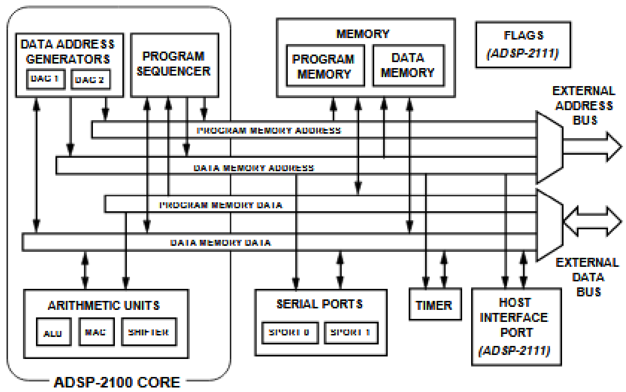

Fig. 5 Functional block diagram of ADSP-21XX

V. CURRENT DEDICATED DSP PROCESSORS

Currently there are many DSP processors available in the market place. DSPs are nowadays used in mobile devices, such as in game players, smart mobile phones, modems, pagers, cordless phones, base stations and so on. As a result of this many manufacturers are now offering mobile DSPs.

Very high performance, large memory, high-level programmability, wide data width, highly parallel core architecture, and support for both fixed-point and floating-point operations are among the features of present day

DSPs. For example, Texas Instruments TMS320C64x+ is a 32-bit processor that supports DDR data rates up to 2GB per second and operates at around 700MHz clock.

The ARM Cortex-M4 family [2] was the first popular DSP processor developed by ARM in the year 2010. This processor was similar to the company's earlier Cortex-M3processors, but it had a 32-bit dedicated MAC DSP engine added to the chip. Cortex-M7, Cortex-M33,and Cortex-M35P are among the other popular DSP based processors from the company. All DSP based processors of the company are supported by the CMSIS—DSP library which is a suite of functions common to signal processing and mathematical operations, optimized for the Cortex family of processors. This library is freely available as part of the CMSIS release from ARM where all the source code is included.

Curiously, Intel used the same number 2920 for its 1979 early DSP chip as it now uses for the Celeron® processor N2920, which has a 2MB cache, 2 GHz CPU, up to 8 GB memory, using 22nm lithography. This shows decisively how the technology has advanced over 40 years [10].

VI. CONCLUSIONS

In this paper the evolution of digital signal processors using microelectronics has been briefly reviewed.

Early DSP applications were developed using the available general purpose microcontrollers. Because of performance limitations, realistic applications were very limited and only covered at most the low end of the audio spectrum. Additionally, those DSP applications had accuracy problems because of the small data width of the processors.

Nowadays, with the availability of fast general purpose microcontrollers, the high throughput high precision ADC and DAC modules and dedicated DSP processors, it is possible to develop highly accurate DSP applications that also cover relatively high frequencies, and complex processes can be done in real time, making possible the modern world of fast digital communications now almost 'taken for granted'.

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