Computer Organization and Architecture

Chapter: Control Unit Design Issue

Study Notes for Engineering Students

The control unit is one of the most important components of the Central Processing Unit (CPU). It is responsible for directing the operation of the processor by generating the timing and control signals needed to fetch, decode, and execute machine instructions. It coordinates the activities of the ALU, registers, memory, and input/output devices so that every instruction is executed in the correct sequence. There are two fundamental approaches used to design a control unit — the hardwired approach and the microprogrammed approach. This chapter discusses both design methods in detail, the concept of horizontal and vertical microprogramming, and a comparison between the two design philosophies.

5.1 Hardwired Control Unit Design

A hardwired control unit is a control unit in which the control signals required to execute instructions are generated using fixed logic circuits, built from combinational and sequential elements such as logic gates, flip-flops, decoders, and counters. The design is called "hardwired" because the control logic is physically wired into the circuit and cannot be changed without redesigning the hardware.

The inputs to the hardwired control unit typically include the opcode from the Instruction Register (after decoding), the current clock/timing signal from the timing generator, and status/flag signals from the CPU (such as carry, zero, overflow). Based on these inputs, the combinational logic circuit produces the exact set of control signals needed at that instant to drive the registers, ALU, memory, and buses.

Working steps of a hardwired control unit:

- The instruction is fetched from memory and placed in the Instruction Register (IR).
- The instruction decoder decodes the opcode part of the instruction.
- The decoded output, along with timing signals from the clock and status flags, is fed into the combinational logic circuit.
- The combinational logic circuit generates the precise sequence of control signals required for that instruction in that particular clock cycle.
- These control signals activate the appropriate registers, ALU operations, memory read/write lines, and bus transfers.

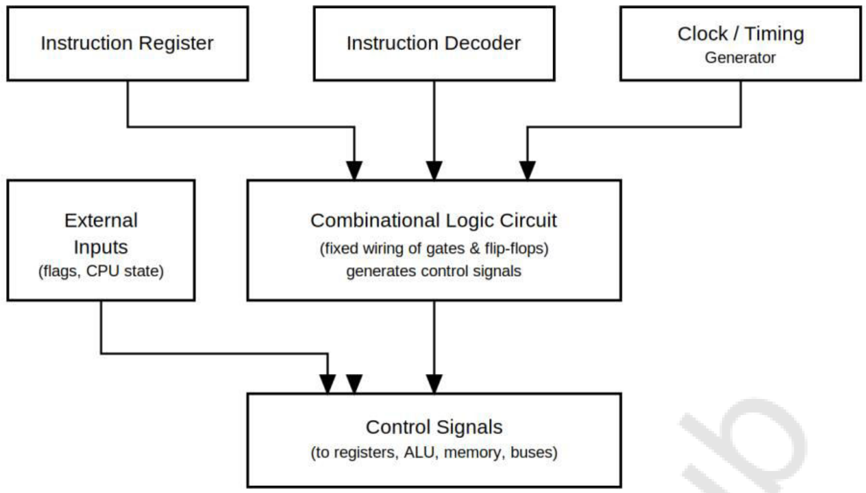

Fig. 5.1 — Block diagram of a hardwired control unit

Advantages:

- Very fast, since control signals are generated directly by logic circuits without any memory access delay.
- Suitable for simple, fixed instruction sets (commonly used in RISC processors).

Disadvantages:

- Difficult to design, test, and modify, since any change in the instruction set requires redesigning the wiring/logic.
- Not flexible — not suitable for processors with large and frequently changing instruction sets.

5.2 Microprogrammed Control Unit Design

A microprogrammed control unit generates control signals with the help of a program known as a microprogram, which is stored in a special high-speed memory called the control memory (or control store). Each machine-level instruction is implemented as a sequence of microinstructions, and each microinstruction specifies one or more micro-operations to be carried out in a given clock cycle.

The concept was introduced by Maurice Wilkes as a systematic alternative to hardwired control, treating control-signal generation as a small stored program (firmware) rather than as fixed hardware wiring.

Key components of a microprogrammed control unit:

- Control Memory (Control Store): A ROM or writable memory that stores all the microinstructions of every microprogram.
- Control Address Register (CAR): Holds the address of the next microinstruction to be fetched from control memory.
- Control Buffer Register (CBR) / Microinstruction Register: Holds the microinstruction currently being executed; its bits directly or indirectly generate the control signals.
- Sequencing Logic (Next Address Generator): Determines the address of the next microinstruction, based on the current microinstruction, status flags, and mapping of the opcode.

Working steps of a microprogrammed control unit:

- The opcode of the machine instruction is mapped to the starting address of its corresponding microroutine in control memory.
- This address is loaded into the CAR.
- The microinstruction at that address is fetched from control memory into the CBR.
- The bits of the CBR generate the control signals for that micro-step (directly, or after decoding).
- The sequencing logic computes the address of the next microinstruction, and the cycle repeats until the microroutine for the instruction is complete.

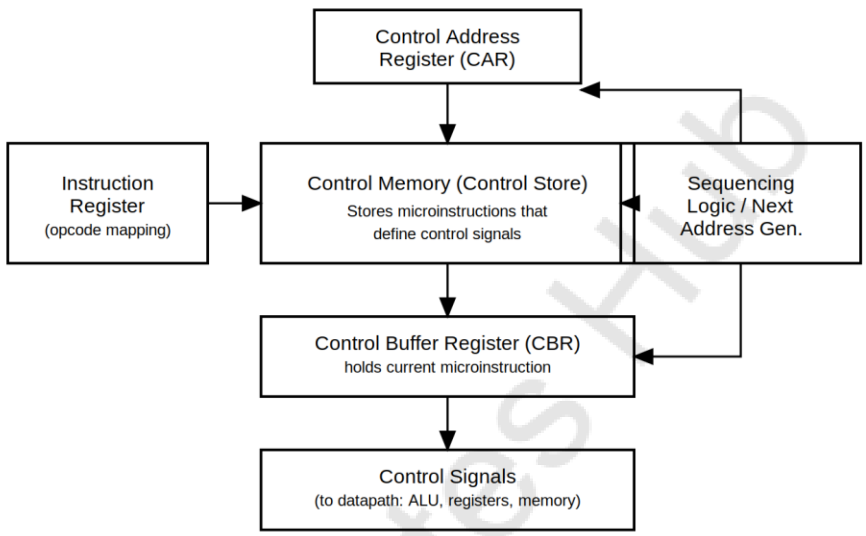

Fig. 5.2 — Block diagram of a microprogrammed control unit

Advantages:

- Flexible — the instruction set can be modified or extended by simply changing the microprogram, without redesigning hardware.
- Easier to design, debug, and maintain, especially for large and complex instruction sets.
- Systematic and well suited to CISC-type processors with many, often complex, instructions.

Disadvantages:

- Slower than hardwired control, since every micro-operation requires a control memory access.
- Requires additional hardware (control memory) which increases cost.

5.3 Concept of Horizontal and Vertical Microprogramming

The manner in which control signals are encoded within a microinstruction word is called the microinstruction format. Depending on how the bits of a microinstruction are organised, microprogramming is broadly classified into two types: horizontal microprogramming and vertical microprogramming.

Horizontal Microprogramming

In horizontal microprogramming, each bit (or field) of the microinstruction is directly associated with one control signal or one micro-operation. There is little or no encoding, so a large number of control lines can be activated simultaneously in the same clock cycle, giving a high degree of parallelism.

- Microinstruction word length is long, since one bit is required for every possible control signal.

- Little or no decoding is required, so it is faster in execution.
- Offers a high degree of parallel operation, since many control signals can be set to 1 at the same time.
- Requires a larger control memory because of the long word length.

Vertical Microprogramming

In vertical microprogramming, control signals are encoded into compact fields (similar to an opcode) rather than being represented bit-by-bit. A decoder is required to interpret the encoded field and generate the actual control signals.

- Microinstruction word length is short and compact, since control information is encoded.
- Requires a decoder to translate the encoded field into control signals, which adds a small delay.
- Supports less parallelism per microinstruction compared to the horizontal format, since only a limited set of operations can be encoded together.
- Requires a smaller control memory, since the microinstruction word is shorter.

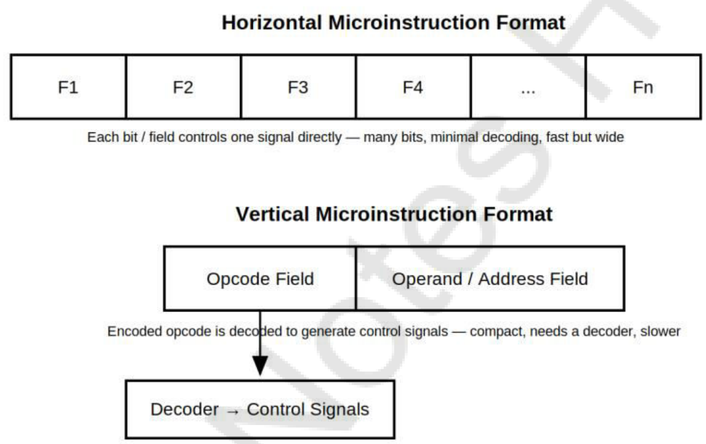

Fig. 5.3 — Horizontal versus vertical microinstruction format

5.4 Comparison Between Hardwired Control Unit and Microprogrammed Control Unit

Both hardwired and microprogrammed approaches achieve the same goal — generating control signals to execute instructions — but they differ significantly in speed, flexibility, cost, and design complexity, as summarised below.

Basis of Comparison	Hardwired Control Unit	Microprogrammed Control Unit
Control signal generation	Using fixed combinational/sequential logic circuits	Using microinstructions stored in control memory
Speed	Faster, no memory access needed	Slower, requires control memory access for each micro-step
Flexibility	Inflexible — changes require hardware redesign	Highly flexible — changes made by editing the microprogram
Design complexity	Complex and difficult to design/debug	Simpler, systematic design approach

Basis of Comparison	Hardwired Control Unit	Microprogrammed Control Unit
Cost	Lower hardware cost for simple instruction sets	Higher cost due to control memory requirement
Suitability	Best suited for RISC processors with small, fixed instruction sets	Best suited for CISC processors with large, complex instruction sets
Ease of modification	Very difficult; requires rewiring/redesigning circuits	Easy; only the microprogram in control memory needs to change

Multiple Choice Questions (MCQs)

Answer the following multiple choice questions. The answer key is provided at the end of this section.

1. In a hardwired control unit, the control signals are generated by:

(a) A stored microprogram
(b) A combinational/sequential logic circuit built from gates and flip-flops
(c) A ROM based control memory
(d) An interpreter program

2. Which control unit design approach is generally faster in operation?

(a) Microprogrammed control unit
(b) Hardwired control unit
(c) Both are equally fast
(d) Depends only on clock speed

3. The memory used to store microinstructions in a microprogrammed control unit is called:

(a) Cache memory
(b) Control memory / control store
(c) Virtual memory
(d) Register file

4. Which register holds the address of the next microinstruction to be fetched from control memory?

(a) Control Buffer Register (CBR)
(b) Control Address Register (CAR)
(c) Instruction Register (IR)
(d) Program Counter (PC)

5. In horizontal microinstruction format, each bit of the microinstruction:

(a) Must be decoded before use
(b) Directly controls one control line/signal
(c) Represents an encoded opcode
(d) Is shared among multiple control units

6. Vertical microinstructions are also known as:

(a) Unencoded format
(b) Encoded/packed format
(c) Wide format
(d) Direct format

7. Which of the following requires a decoder to generate the actual control signals?

(a) Horizontal microinstruction
(b) Vertical microinstruction
(c) Hardwired control unit
(d) None of these

8. Hardwired control units are more suitable for:

(a) CISC processors with large instruction sets
(b) RISC processors with a small, fixed instruction set
(c) Processors that need frequent instruction set changes
(d) Emulator-based systems

9. One major advantage of a microprogrammed control unit over a hardwired one is:

(a) Higher speed
(b) Lower cost of control memory
(c) Flexibility and ease of modification/debugging
(d) No need for control memory

10. In a microprogrammed control unit, a set of microinstructions that implement one machine instruction is called a:

(a) Macro-program
(b) Microprogram / microroutine
(c) Firmware loader
(d) Instruction pipeline

11. Horizontal microinstructions generally result in:

(a) Shorter word length and slower execution
(b) Longer word length and faster execution (more parallelism)
(c) No effect on word length
(d) Elimination of control memory

12. Which component maps the opcode of a machine instruction to the starting address of its microroutine?

(a) ALU
(b) Mapping logic in the sequencing unit
(c) Cache controller
(d) Data bus

13. Modifying the control logic of a hardwired control unit after fabrication is:

(a) Very easy, done through software
(b) Difficult, as it requires redesigning the physical circuit/wiring
(c) Done by changing the control memory content
(d) Not required at all

14. Vertical microprogramming, compared to horizontal microprogramming, offers:

(a) More parallelism but larger control store
(b) Less parallelism but smaller, more compact microinstructions
(c) No decoding requirement
(d) Identical control word length

15. Which type of control unit design is generally preferred when the instruction set is large, complex, and likely to change?

(a) Hardwired control unit
(b) Microprogrammed control unit
(c) Combinational-only control
(d) No control unit is needed

Answer Key

Q.No	Ans	Q.No	Ans	Q.No	Ans
1	(b)	6	(b)	11	(b)
2	(b)	7	(b)	12	(b)
3	(b)	8	(b)	13	(b)
4	(b)	9	(c)	14	(b)
5	(b)	10	(b)	15	(b)

Broad / Long Answer Questions

1. Define control unit. Explain the basic function of a control unit in a digital computer, and list the two fundamental approaches used to design it.

2. With the help of a neat block diagram, explain the working of a hardwired control unit.

3. Explain the working principle of a microprogrammed control unit with the help of a suitable block diagram. Describe the role of the Control Address Register (CAR) and Control Buffer Register (CBR).

4. What is a microinstruction? Explain the concept of horizontal and vertical microprogramming with suitable examples/diagrams.

5. Differentiate between horizontal and vertical microinstruction formats on the basis of word length, speed, degree of parallelism, and need for decoding.

6. Compare hardwired control unit and microprogrammed control unit on the basis of speed, cost, flexibility, and design complexity.

7. Explain, with reasons, why hardwired control units are typically used in RISC processors while microprogrammed control units are typically used in CISC processors.

8. What are the advantages and disadvantages of a microprogrammed control unit over a hardwired control unit?

9. Explain the concept of a microprogram and a microroutine. How does the sequencing logic determine the address of the next microinstruction?

10. Discuss the design issues that must be considered while designing a control unit for a digital computer.