Mechanical Logic Devices and Circuits

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Abstract

In this work an attempt has been made to explore the realm of Mechanical logic devices with functionalities similar to the electronic digital devices. A few combinatorial and sequential circuits and basic memory elements have been explored. The mechanical designs for several devices, like Analog to Digital Signal Converters, Digital to Analog Signal Converters, Multiplexers, Demultiplexers, X-OR gates and RS Flip-Flops have been described. All these designs are based on linkage mechanisms.

These designs implementable at MESO scales could later be translated into the micro domain using compliant joints and microflexural logic gates.

Keywords: Mechanical Logic, Multiplexer, Demultiplexer, A to D and D to A Converters, Flip-Flops

1 Introduction

Mechanical devices which provide functions similar to electronic digital systems are increasingly being sought for a variety of applications specifically where the operating environment is hazardous or under intense radiation [1]. Development of such mechanical devices have been outlined in [1] & [2] and more recently, attempts have been made to evolve these in the domain of MEMS [3]. Mechanical devices may prove to be advantageous as alternatives to electronic devices that are generally unable to function under extreme conditions of temperatures, radiation and severe vibration.

In this paper we outline the results of explorations made to evolve several devices like A to D and D to A converters, Multiplexers, and Flip-Flops. Several of these are based on bar linkage mechanisms with lower pairs. There are a few like the X-OR gate which are not realizable through use of lower pairs [1] and one has to take recourse to the use of other pairs.

2 Combinatorial Logic Devices

2.1 Analog to Digital Converter

An analog-to-digital converter (abbreviated as ADC) is defined as a device which converts continuous signals to discrete digital numbers. The reverse operation is performed by a digital-to-analog converter. An ADC converts an input analog voltage (or current) to a digital number. In a mechanical ADC the analog input is either the rotation of a shaft or the translation of a slider.

For devices with rotary inputs [4], a series of cams in Fig. (1) engage with followers which provide the output.

There is one cam for each bit as shown in Fig. (1) and motion of the input is transmitted to all the cams through gearing. The lobes in the cam serve to move the followers from 0 to 1.

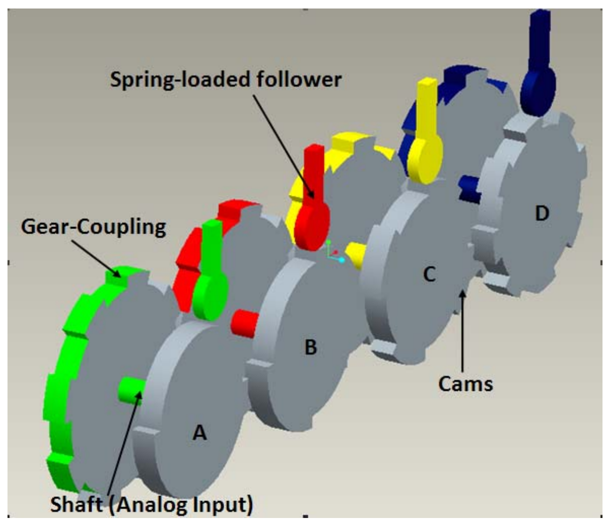

Fig. 1: Mechanical ADC with gear coupling

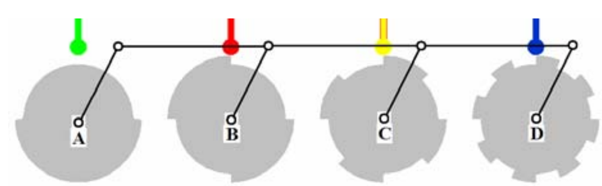

Fig. 2: Mechanical ADC with parallel bar linkage

In the designs of ADC shown in Fig. (1) and Fig. (2), translating followers have been used. However, one can replace translating followers by oscillating ones. The number of lobes differ from cam to cam. The number of lobes, for an N-bit ADC, could be worked out as 2^{N-1} on the cam corresponding to the least significant bit and as one lobe on the cam corresponding to most significant bit. Table 1 shows the number of lobes corresponding to the significance of the bits, for the 4-bit ADC discussed above.

Table 1: Correspondence of the number of lobes to the bit significance

	Most significant bit (Cam A)	Least significant bit (Cam D)
No. of lobes	1	8

Designs shown in Fig. (1) and Fig. (2) have all the cams in a single plane with the analog input motion being provided to one of them. Since all the shafts are coupled using either gears or parallel-bar linkages , they all rotate synchronously. Various other arrangements are also possible as discussed in [4]. The cams can be stacked one behind another on a common shaft or one could use face cams.

The devices discussed above can also function as *Mechanical Absolute Encoders*. An absolute encoder performs the function of encoding analog positions into digital values. An N-bit absolute encoder is designed to produce a digital word that distinguishes 2^N distinct positions of the shaft. Optical encoders are typically used to track the position of a rotating shaft and convert it into a binary code, but as stated earlier such encoders may not be able to operate in harsh environments and there is a need for mechanical devices.

2.2 Digital to Analog Converter

The function of a Digital to Analog converter is to convert digital signal input into analog signal output. When a set of bits are fed into the device, it is expected to output the desired analog signal (for instance, decimal equivalent of the input). Fig. (3) shows the Summing Amplifier based design of a DAC [5], where there is a provision for feeding in the digital input, which fetches the decimal equivalent output of the fed-in binary input.

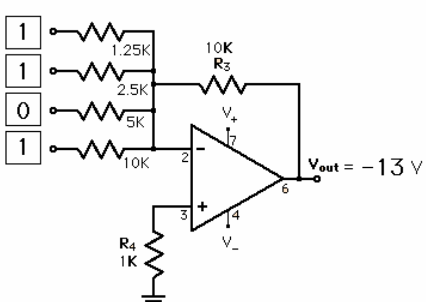

Fig. 3: Summing Amplifier Circuit

A mechanical DAC can be viewed as a sequence of two operations namely, **Amplification** (bitwise, depending on bit weight) and **Addition** of amplified inputs.

Addition could be executed by the seven bar mechanical linkage [shown in Fig. (4)] and gears serve to amplify the motion. This design shown in Fig. (5) uses gear-pairs as the amplifiers and seven bar mechanical linkages as adders to realize a 3 bit A to D converter. Gear ratios of the three gear-pairs are accordingly varied as each bit needs to be amplified by a different factor.

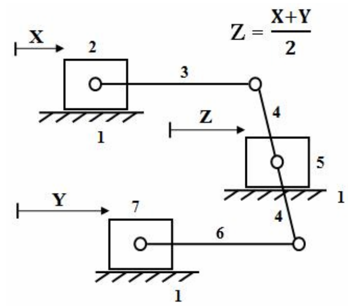

Fig. 4: Seven bar mechanism based adder [2]

Instead of using a gear-based amplification technique, we may also use lever-based amplification [4]. In addition, one could use other mechanical adders viz. bar-roller adder, spur-gear differential and bevel-gear differential. [6]

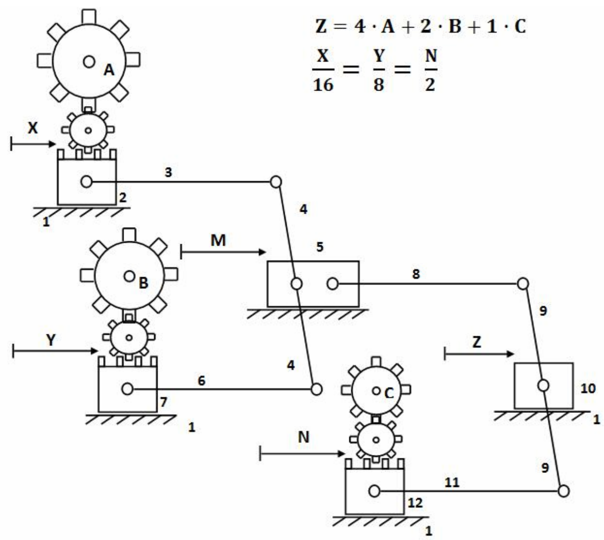

Fig. 5: Three-bit Mechanical D to A Converter

2.3 Multiplexer

A multiplexer [5] is a device that selects amongst a number of input signals and forwards the selected input to the single output line. A 2-to-1 multiplexer has two signal inputs, one control input and one output. However this concept can easily be extended to more than two inputs by increasing the number of control inputs. For every 2^N inputs, a multiplexer requires N control inputs.

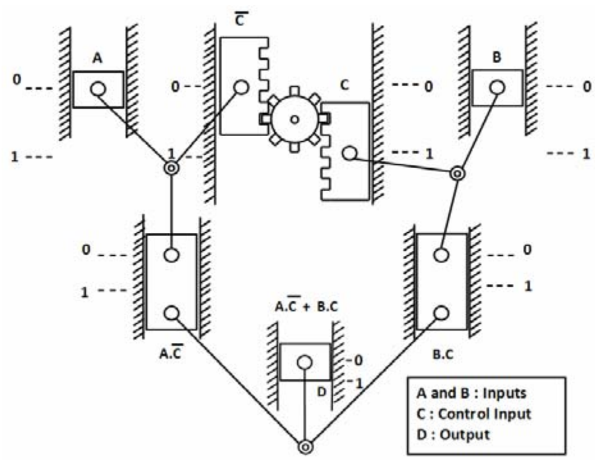

Fig. 6: Mechanical 2-to-1 Multiplexer

The device in Fig. (6) has been arrived at by replacing electronic AND, NOT, OR gates in the electronic multiplexer circuit [7] by form-closed mechanical gates reported in [1]. The voltage signal inputs A and B have been correspondingly replaced by the translational inputs of slider A and B. Similar emulation holds good for control input C as well. The input is given at A and B while the output is given by slider D. One could potentially obtain two designs of mechanical multiplexers, one by incorporating the NOT gate with gear-pair as shown in Fig. (6), or by using the NOT gate based on bar-linkage mechanisms.

2.4 Demultiplexer

In electronics, a demultiplexer [5] is a device that takes in a single input signal and selects one of many data-output-lines, which is then connected to the single input. While designing the mechanical demultiplexer, we again replaced the electronic logic gates by form-closed mechanical logic gates and obtained the mechanical demultiplexer shown in Fig. (7). Note that bar linkage mechanisms, instead of gear pairs, have been used in this instance as NOT gates.

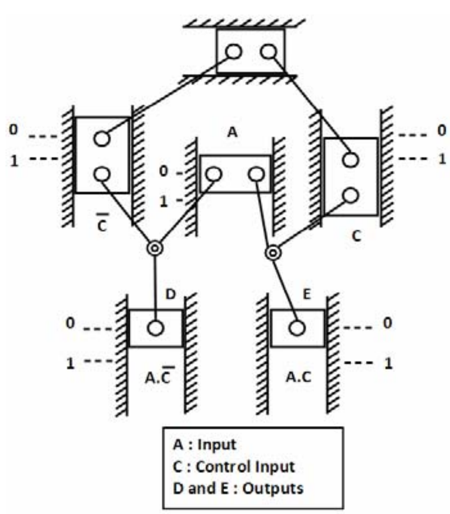

Fig. 7: Mechanical 1-to-2 Demultiplexer

3 Mechanical Ex-OR Gate

The logical operation exclusive OR (XOR or Ex-OR or EOR), results in a value of true when and only when one of the operands has a value of true. [5]

Fig. (8) shows the symbol for Ex-OR gate and Table 2 shows the corresponding truth table.

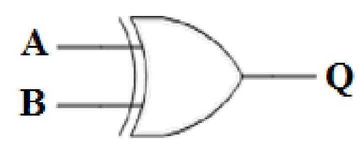

Fig. 5: Symbol for Ex-OR Gate [5]

Table 2: Truth table of Ex-OR Gate [5]

Input A	Input B	Output Q
0	0	0
0	1	1
1	0	1
1	1	0

3.1 Implementation

The mechanical Ex-OR gate can be arrived at, using the basic mechanical NAND or NOR gates [1], in the circuit shown in Fig. (9).

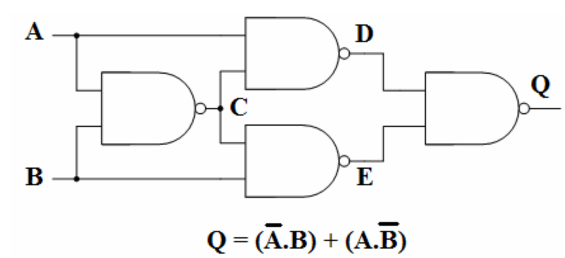

Fig. 9: Ex-OR Gate using NAND Gates

A mechanical NAND gate [1] is a seven link mechanism and so the corresponding circuit will consist of a large number of moving links and the device would be bulky. The design shown in Fig. (10) is an alternative as described first in [8].

This design makes use of higher pairs (shown here as a flat faces and pins) as connection between inputs A and B and a quaternary link (shown here as a disc) pivoted at Q. The disc can be pushed in only one direction by the pin. Slider C is connected to the disc by a binary link PC with two revolute pairs. When input A=1, as shown in Fig. (10) the pin moves the disc, and it rotates and output C=1. The spring at C stores the energy for the return motion of slider C. Note that when both inputs A and B are equal the spring does not store any energy and output C is 0.

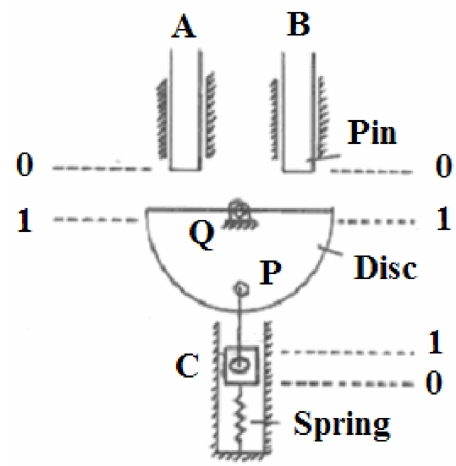

Fig. 10: Mechanical Ex-OR Gate (State 1: A = 0; B = 0; C = 0)

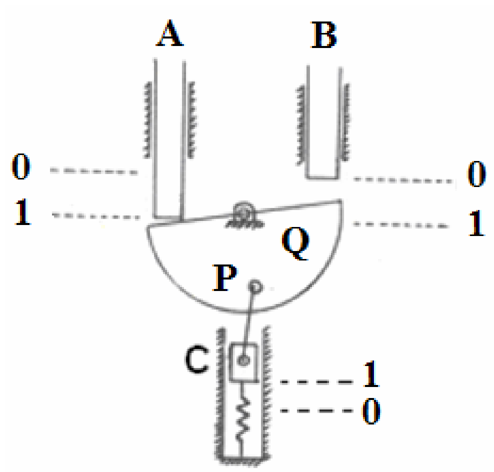

Fig. 11: State 2: A = 1; B = 0; C = 1

4 Mechanical RS Flip-Flop

The Flip-Flop is used in sequential circuits as a memory element. It has two stable states and hence serves as one bit of memory. The Truth table of a RS Flip-Flop is shown in Table 3 [7].

Table 3: Truth table of RS Flip-Flop [5]

R	**S**	**Q(t+1)**	**Q'(t+1)**
0	0	No Change	No Change
0	1	0	1
1	0	1	0
1	1	Forbidden	Forbidden

4.1 Design Implementation

The RS Flip-Flop using NOR gates is shown in Fig. (12). We know that a mechanical NOR gate is a seven link mechanism [1] and when a circuit is built around these, the number of links would increase. In what follows we describe one out of the several devices evolved in [8].

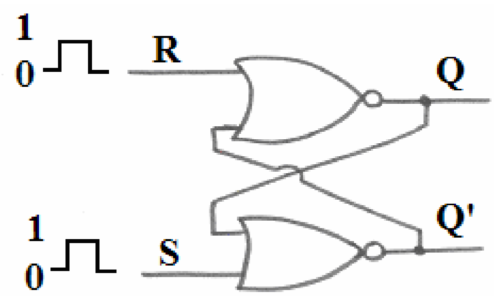

Fig. 12: RS Flip-Flop using NOR gates [5]

4.2 Rack and Pinion - RS Flip-Flop

A device with fewer moving elements is shown in Fig. (13), and consists of two racks engaging a single pinion as shown. The input to one rack is S (set) and the other rack has R (reset) as it input. The pinion provides the requisite output. The racks are pushed forward by pins the connection between the racks and pins being a planar pair.

4.3 Stability of Outputs

The Flip-Flop should be a bi-stable device, we notice that it is not so in the devices described here. Slight disturbances can displace the output from its current position.

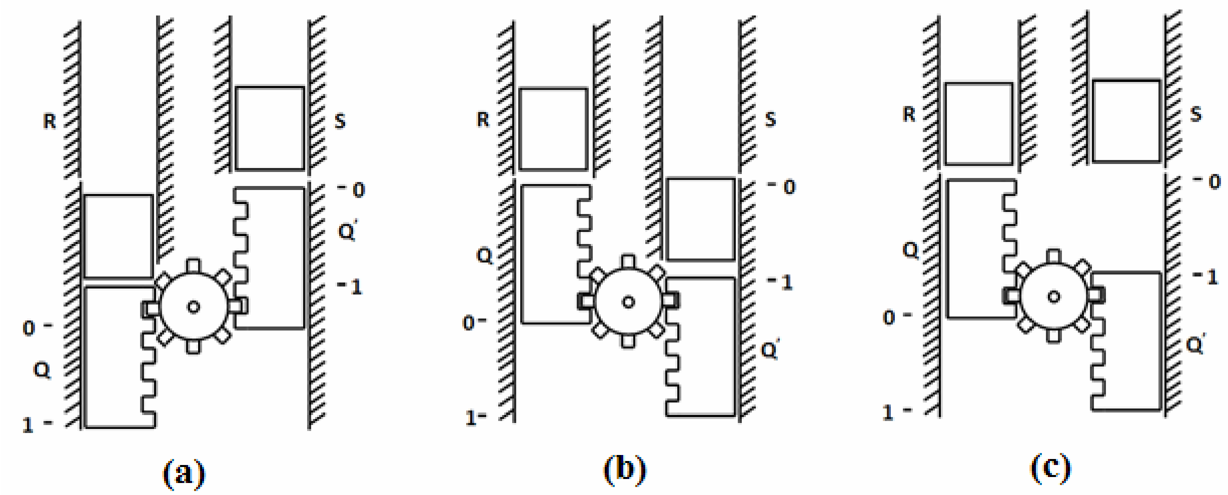

Fig. 13: RS Flip-Flop based on Rack and Pinion [8]

This could be prevented by having one of the links in the chain overcome an energy barrier as the link moves from one stable position to the other.

Frictional forces at the joints may not always suffice and hence use of magnets [9] could be resorted to. This could lead to a rise in the input effort but the design would be robust against the disturbances.

5 Conclusions

Several mechanical logic devices based on bar linkage mechanisms have been presented. These utilize both lower pairs and higher pairs and could be utilized at upto MESO scales. A bigger challenge that lies ahead is to evolve devices suitable for MEMS. Flexural pivots have the limitation that the rotation provided is not adequately large [3] and as the number of devices in a circuit grow one has to resort to use of intermediate amplification devices, and these demand energy inputs.

References

[1] C.Amarnath, Hrishikesh V. Deo, "Logic Gates Based on Bar Link Mechanisms", *Proceedings of the 11th World Congress in Mechanism and Machine Science, August 18~21, 2003, Tianjin, China*

[2] Dewey, G. H, Soni, A. H, "Design of logic systems consisting of mechanical elements", *In proceedings of the second OSU Applied Mechanics Conference*, Stillwater, Oklahoma, U.S.A., 1971

[3] Abhishek Modi, Prasanna S. Gandhi, C. Amarnath, Himani Shah "Design, Analysis and Fabrication of Micro-flexural AND Gate", *13th National Conference on Mechanisms and Machines (NaCoMM07)*, IISc, Bangalore, India, 12-13 Dec. 2007

[4] Abhishek Sharma, "Mechanical Digital Circuits and Devices", *Dual Degree Dissertation, IIT Bombay, 2009*

[5] M.Mano, *Digital Logic and Computer Design*, Prentice Hall India, 2002

[6] John J. Uicker, Gordon R. Pennock, Joseph E. Shigley, *Theory of Machines and Mechanisms, 3rd Edition*, Oxford University Press, Inc., 2003

[7] Paul Horowitz, Winfield Hill, *The Art of Electronics*, 2nd Edition, Cambridge University Press, 1989

[8] Waichale Swapnil Ram, "Mechanical Logic Devices", *Dual Degree Dissertation, IIT Bombay, 2009*

[9] Gowthaman, B Manujunath Prasad, G. N. Srinivasa Prasanna, "Electrical mechanisms: A merger of mechanisms and electrical machines", *Proceedings, NaCoMM07*, IISc Bangalore, 12-13 Dec. 2007