Digital vs. Analogue Control Systems

Presented at the 2011 Annual Meeting of the American College of Medical Physics, Chattanooga, TN, May 1, 2011

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Disclosure: Research supported in part by Varian Medical Systems
Accelerator control systems

- **Mechanical** – Analogue or digital
  - Gantry angle
  - Collimator angle
  - Jaw position
  - MLC leaf position
  - Couch positions (angle, vertical, long, lat)
  - Internal devices (target, flattening filter, light field projector)

- **Electronic** – Analogue or digital
  - Beam production
    - Electron gun
    - Rf power
    - Steering coil current
    - Bend magnet current
  - Dosimetry system
  - Ancillary systems (vacuum, temperature control, etc.)
Analogue transducer, analogue readout

10-turn potentiometer

Wiper

Resistance wire

Single-turn potentiometer

Shaft

10-turn potentiometer

Calibrated in deg gantry or collimator angle, cm couch position

Vout

Vout
Resolver: brushless analogue rotation transducer

Analogue signal output

shaft
Resolver - principle of operation

Input signals

\[ V_{in1} = V_0 \cos \phi \]

\[ V_{in2} = V_0 \sin \phi \]

Output signal

\[ V_{out} = V_0 \sin (\phi - \theta) \]

Shaft angle \( \theta \) found from phase angle of \( V_{out} \)
Rack and pinion drive for couch movements

Motor with gear drive with position indicator in back

Rack, attached to couch top

Pinion
Spindle (screw) drive

Geared motor with position readout in back

Rotating spindle

nut
Limitations of analogue devices

- Precision of potentiometer ~ 0.1% linearity
  - 0.4 mm for 40x40cm² field
  - Sensitive to small changes in wire resistance
  - Degraded accuracy by use and age (brush)
  - Sensitive to power supply voltage

- Reading accuracy ~ 0.2%
  - Digital readout - used even in early linacs
Analogue transducer, analogue and digital readouts (potentiometer)
Single-hand clock: purely analogue display
Reading accuracy about 6 minutes ~ 1%
2-hand clock: Hybrid, one digit + analogue
Reading accuracy ½ min (0.1%)
King’s Cross railway station, London
3-hand clock: Hybrid, two digits + analogue
Reading accuracy \( \frac{1}{2} \text{ sec} \sim 0.001\% \)
“Analogue” precision transducers

• Geared potentiometers
  – “Hour hand” pot goes around once
  – “Minute hand” pot goes around many times
  – 0.01% rotational precision readily obtained with 0.2% accuracy pots

• Geared (dual) resolvers – same principle
Digital transducer: 3-bit shaft encoder
Standard binary encoding

<table>
<thead>
<tr>
<th>Sector</th>
<th>Contact 1</th>
<th>Contact 2</th>
<th>Contact 3</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>off</td>
<td>off</td>
<td>off</td>
<td>0° - 45°</td>
</tr>
<tr>
<td>2</td>
<td>off</td>
<td>off</td>
<td>ON</td>
<td>45° - 90°</td>
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<td>ON</td>
<td>off</td>
<td>90° - 135°</td>
</tr>
<tr>
<td>4</td>
<td>off</td>
<td>ON</td>
<td>ON</td>
<td>135° - 180°</td>
</tr>
<tr>
<td>5</td>
<td>ON</td>
<td>off</td>
<td>off</td>
<td>180° - 225°</td>
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<tr>
<td>6</td>
<td>ON</td>
<td>off</td>
<td>ON</td>
<td>225° - 270°</td>
</tr>
<tr>
<td>7</td>
<td>ON</td>
<td>ON</td>
<td>off</td>
<td>270° - 315°</td>
</tr>
<tr>
<td>8</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>315° - 360°</td>
</tr>
</tbody>
</table>
### 3-bit shaft encoder

**Gray encoding**

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13-bit shaft encoder

Precision = \frac{1\text{rev}}{2^{13}} 
\approx 0.01\% \text{ of } 1\text{rev}
13-bit shaft encoder

Shaft

13 tracks

Optical reader
Incremental encoders count pulses

Cannel A leads … clockwise rotation
Cannel B leads … ccw rotation
Stepper motor – driver and encoder

Energizing coils A, B, C .... ccw rotation
Energizing coils A, C, B .... clockwise rotation
Stepper motor in 1-D water tank

Stepper motor
200 pulses/rev

Spindle
6 mm/rev

Nut
Stepper motor in 3-D water tank

Stepper motor with 90° turn gear

spindle

nut
Initialization of Varian MLC

- IR emitting diode
- Origin (zero) when light at detector reduced by 50%
- 16:1 reduction gear (two 1:4 planetary gears in series)
- DC electric motor with permanent magnet
- Incremental encoder, 2 pulses per rev
- Spindle (screw), 1.5 mm/rev pitch
- 60 leaves
- MLC drive assembly
- 4.5 cm
Initialization of Varian x-ray jaws

Origin (zero point) established when Collision block hits Hard stop. Collision detected by sudden surge of DC current when motor stalls.
Control systems: Operational amplifier

- **Input pos**: $V_{S+}$
- **Input inv**: $V_{S-}$
- **Positive and negative power supply voltages**: $V_{s+}$, $V_{s-}$

**Equations:**

- **Input impedance**: $Z_{in} = \infty$, $I_{in} = 0$  
  - Small input current
- **Output impedance**: $Z_{out} = 0$, $I_{out} = \infty$  
  - High output current
- **Output voltage**: $V_{out} = (V_{s+} - V_{s-}) \times A$  
  - High amplification, $A \to \infty$
Analogue mechanical control system

Motor spins until voltage of potentiometer at back of motor matches program voltage

console

+12V
Program voltage

-12V

accelerator

op amp

output

power amp

+12V

motor

-12V

Feedback voltage
Digital mechanical control system

- Console
  - Node (in stand of linac)
  - Controller for gantry motions
  - Encoder (absolute)

- Accelerator
  - Digital to analogue converter
  - Gantry motor

Compares desired gantry position to actual position
Analogue electronic control system for energy

Output current increases until feedback voltage matches program voltage

console

accelerator

+12V Program voltage

-12V

+ Op amp

Power amp

Bend magnet coils

Feedback voltage

Feedback resistor
Analogue electronic control for beam symmetry

Output current adjusts until (processed) signals from both chamber halves become equal, i.e., beam is symmetric.
Computes ratio of inputs and compares to desired ratio sent from node. Sends correction signal to DAC.

Digital electronic control for beam *symmetry*

Ion chamber

Upper half (toward gantry)

Lower half (toward couch)

Analogue to digital converters

Node

Complements ratio of inputs and compares to desired ratio sent from node. Sends correction signal to DAC.

Beam steering coils

Power amp

Digital electronic control for beam symmetry
Dual systems for safety of modern digital accelerators

- **Mechanical systems**
  - Encoder on back of drive motor + encoder on driven object (gantry angle, couch position, etc.), agreement monitored by computer

- **Electronic systems**
  - Ion chamber has multiple segments, outputs monitored by computer
  - Resistance of bend magnet measured
Neutron protection – boron impregnated polyethylene plates protect against single-event upsets
Merits of digital systems

- Less sensitive to noise
- Less sensitive to component drift
- **Easy return to original settings**
- Easy replacement of broken components
- High precision of mechanical systems
  - Flattening filter and field light projector can be remotely adjusted
- Information readily available for processing
  - Monitor machine performance to predict problems
    - Cooling water flow rate monitored at many places
    - Vacuum system leaks
    - SF$_6$ leaks
Merits of digital systems

• Take into account “second order effects”
  – Flexing of image receiver arm

• Automatic tuning
  – Slow changes of components
    • Thyratron aging
    • Waveguide resonant frequency