Active Scanning Beam 2: Controlling Delivery

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Focus of this talk

- General design and implementation issues of control systems for the dose delivery with an actively scanning beam
  - Speed and safety
  - Control system architecture
- Concrete example
  - Discrete spot scanning implementation of the Gantry 1 system
  - Advanced scanning modes in Gantry 2
- Proscan Safety System
The Therapy Control System’s Task

- The TCS
  - Controls the dose delivery
  - Is configured with the Therapy Plan generated by the Therapy Planning System
  - Controls and supervises the facility equipment to deliver the dose to the patient according to the plan
  - Generates a log of what it finally did with the patient
What are the main issues?
Issue 1: The Need for Speed

• Gantry 1 discrete spot scanning:
• Needs to apply 10‘000 spots to cover volume of 1 liter
• Is required to do this in aprox. 3 minutes
• → an increase of dead-time between the application of 2 spots by only 1 ms increases the total irradiation time by about 5 %...
Issue 1: The Need for Speed...

• In safety relevant control system design, the speed requirement is normally put behind safety...

BUT

... A perfectly safe but slow scanning control system will be as useless as an unsafe fast one!
Issue 1: The Need for Speed...

• Our choices for the control systems:
  – The irradiation is controlled by embedded VME systems with Motorola PPC running the VxWorks RTOS
  – Subsystem communication with digital IOs, fast serial links (over optical fibres), reflective memories. Ethernet only when time does not matter
  – Time critical functions directly implemented in custom FPGA or DSP based subsystems
  – Linux PCs as operator workstations
Issue 1: The Need for Speed...
embedded VME Single Board Computer
Issue 1: The Need for Speed...

VME crate (TVS) with connections to sensors, actuators, ...
Issue 2: Safety

• Safety requirements in simple terms...
  – Avoid any overdose to the patient in excess of 3 Gy (5% of total treatment dose of 60 Gy)
    „no accident“
  – Protect the patient from (mechanical and) radiation hazards, i.e. minimize the risk for
  – Avoid any dose delocalization by more than 1mm
    „no wrong dose at wrong location“

→ required action time to reach safe state (= beam off):
  app. 100 μs

• Again, speed is a key factor!
Safety Architecture
Design Patterns
Controls principle

TDS → set → PaSS → supervise → TVS

Therapy Delivery → Therapy Verification

Patient Safety
Safety Architecture Design Patterns

- Protected Single Channel Pattern
  = „safe setting of actuator“

- Actuator control is done by a system including diagnostic features:
  + allows to detect faults
  + simple to implement (low cost when designed in)
  - channel cannot continue in case of faults
Example: Gantry 1 Sweeper Magnet Control (1)

- The sweeper power supply controller receives target values over an optical link from the TCS, checks data integrity, and controls the power supply for the magnet coils.
- At the same time, the current through the coils is measured and compared in realtime with the target value on a DSP inside the controller, without TCS involvement. Any deviation beyond tolerance triggers a safety interlock.
Magnet Power Supply Control Hardware

- VME board with 4 Industry-Pack Slots and onboard DSP
- Industry-Packs with FPGA implementing communication interface to power supply
- VME transition module with optical transceivers for data transmission to power supply
- Digitally controlled power-supplies (developed by PSI)
Magnet Power Supply Control Hardware
Safety Architecture Design Patterns

- **Monitor-Actuator Pattern**

  ![Diagram showing the Monitor-Actuator Pattern]

  - Actuation and Monitoring are separated into independent channels. Effects of the actuator action are verified by the monitoring channel.
Monitoring channel is measuring the magnetic field with a hall-sensor and triggers an interlock if a deviation beyond tolerance is detected.
# Actuation and Monitoring: Implementation

<table>
<thead>
<tr>
<th>Control Function</th>
<th>TDS Actuation Channel</th>
<th>TVS Monitoring Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Position</td>
<td>Sweeper Magnet controlled by DSP based subsystem. Continuous monitoring of power supply setting and state</td>
<td>Hall sensor measuring sweeper magnetic field monitored by TVS. Ionisation strip chamber measuring beam position at exit of nozzle. Monitored by TVS</td>
</tr>
<tr>
<td>Beam Tune</td>
<td>Degrader and beamline control through Machine Control System (MCS). MCS implements full actuator supervision</td>
<td>Degrader position and bending magnet hall sensor data continuously monitored by DSP based subsystem</td>
</tr>
<tr>
<td>Range Modulation</td>
<td>Control of range-shifter with DSP based subsystem. State of single plates measured with optical sensors supervised continuously</td>
<td>Redundant optical sensors for each single plate. Monitored by TVS</td>
</tr>
<tr>
<td>Patient Position</td>
<td>Patient table and Gantry rotation through the Gantry and Patient Positioning System (GPPS). GPPS implements full actuator supervision as well as collision protection</td>
<td>Absolute position encoders and end-switches monitored by TVS</td>
</tr>
</tbody>
</table>
Safety Architecture Design Patterns

- **Heterogeneous Redundancy Pattern**

  - Several channels of equal weight with different implementations
    - allows to detect random and systematic faults
    - expensive (development overhead and cost)

  ```
  Channel Type A
  Sensor Type A
  
  Input Processing → Data Processing → Output Processing
  
  Channel Type B
  Sensor Type B
  
  Input Processing → Data Processing → Output Processing
  
  Combinatory Logic
  
  Actuator
  ```
Example: Gantry 1 Spot Termination

- General method for dose measurement:
  - Ionisation chambers
  - Current converted to frequency, fed into counter module
  - When counter reaches preset value, it triggers beam-off
Example: Gantry 1 Spot Termination

- **TDS**: Beam off
- **TVS**: Interlock
- **Watchdog**: Interlock!

- **Fixed limit**
- **Nominal + offset**
- **Nominal**

**dose**
Example: Gantry 1 Spot Termination

Diagram:

- Dose Monitor 1 (thin and faster)
- Dose Monitor 2 (thick and slower)
- Dose Monitor 3 (grid chamber)

Flowchart:

1. Dose Monitor 1 → Current to Frequency Converter Type 1 → TDS Dose Counter → Beam Off Request when Monitor 1 preset count reached
2. Dose Monitor 2 → Current to Frequency Converter Type 2 → TVS Dose Counter → Interlock when Monitor 2 preset count reached → Safety System Logic → Beam Off Request (Nominal or Interlock)
3. Dose Monitor 3 → Current to Frequency Converter Type 3 → Dose Watchdog → Interlock when Dose Watchdog expires

Legend:

- Triangle: Monitor
- Square: Converter
- Arrow: Signal Flow
Spot Scanning Control Loop

• TDS & TVS walk through therapy plan:
  – TDS sets devices, TVS checks devices
  – when all devices ready: beam on!
  – spot termination by dose counter firmware
  – check correct application after each spot
  – write logs
  – proceed to next spot
Spot Scanning: Operator Tools

Spot 2035 / P08464_C0T0_T0_F0_D45.SCO / WED JAN 07 14:21:18 2009

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<tr>
<th>Check ID</th>
<th>time [s]</th>
<th>OK</th>
<th>TOL</th>
<th>difference</th>
<th>result</th>
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<tr>
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peering into the control loop ...
Spot Scanning: Operator Tools

```
<table>
<thead>
<tr>
<th>Spot</th>
<th>U FWHM</th>
<th>KickerLeak</th>
<th>Mon1/Mon2</th>
<th>dU</th>
<th>dT</th>
<th>T FWHM</th>
<th>dMon2</th>
<th>M1A+</th>
<th>dSweep</th>
<th>dADG3</th>
<th>Mon1Rate</th>
<th>Mon1/Upst</th>
<th>Mon1/Mon3</th>
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</thead>
<tbody>
<tr>
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<td>1.252</td>
<td>51.33</td>
<td>1.300</td>
<td>0.031</td>
<td>0.062</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Mon1/Sgnl ungap-gat</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>
```

Beam position:

- **U [mm]**
- **T [mm]**

Plate 1:

```
plate 1
```

Plate 40:

```
```

Ratio Monitor 1 / Monitor 2:

```
0  10  20  30  40  50  60  70  80  90  100  110  120  130  140  150  160  170  180  190  200  210  220  230  240  250  260  270  280  290  300
1.25
1.3
1.35
```

- **ratio Monitor 1 / Monitor 2**
Gantry 2
Sweeper magnets for position control $x, y$

2 Sweeper magnets beam position control up to 2 cm/ms
Therapy Control System
Control of fast actuators

Precise and synchronous control of fast actuators; timing resolution $\sim 10 \mu s$

- Sweeper magnets (2 dim lateral position)
- Deflector plate (intensity)

Implemented in state-of-the-art hardware to cope with challenging Gantry 2 requirements
Use of FPGA based control system for drawing the dose with the beam

Continuous scanning

– Repainted, homogeneous box 6 x 8 cm$^2$
– 500 iso-energy planes painted in less than 1 minute
Intensity modulation

sensor dose monitor

actuator HV on deflector plate

Intensity

modulation
Functional Safety Approach

- *From IEC 61508 „Functional safety of electrical / electronic / programmable safety-related systems“:*

„A safety function [...] is intended to achieve or maintain a safe state for the EUC (equipment under control), in respect of a specific hazardous event“

- Detect events that might cause a risk
- Take decisions based on sensor information
- Maintain or achieve the safe state
### Proscan Final Elements

#### Action for Beam-Off

<table>
<thead>
<tr>
<th>Actuator / Device</th>
<th>Action for Beam-Off</th>
<th>Reaction Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kicker magnet AMAKI</td>
<td>Fully activate magnetic field</td>
<td>150 µs</td>
</tr>
<tr>
<td>High-frequency Generator</td>
<td>De-energize</td>
<td>300 µs</td>
</tr>
<tr>
<td></td>
<td>Reduce power</td>
<td>300 µs</td>
</tr>
<tr>
<td>Ion source</td>
<td>De-energize</td>
<td>3 ms</td>
</tr>
<tr>
<td>Fast beam stopper BMx2</td>
<td>Insert mechanical beam stopper</td>
<td>60 ... 100 ms</td>
</tr>
<tr>
<td>Beam stopper BMx1</td>
<td>Insert mechanical beam stopper</td>
<td>600 ms</td>
</tr>
</tbody>
</table>
Proscan Logic Subsystem

- Local & central final elements
  → local & central logic subsystems
Logic Subsystems and Switch-Off Functions

<table>
<thead>
<tr>
<th>Interlock Level / Beam Switch-Off Control Function</th>
<th>Measures for Beam-Off</th>
<th>Beam Switch-Off Element Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETOT ATOT ALOK ATOT Beam Off Command</td>
<td>Close local beam blocker BMB2</td>
<td>Local PaSS Logic</td>
</tr>
<tr>
<td></td>
<td>Activate kicker AMAKI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Close beam stopper BMB1</td>
<td>Central PaSS Logic</td>
</tr>
<tr>
<td></td>
<td>Close beam stopper BMA1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduce HF generator power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switch-off HF generator</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switch off ion-source power supply</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

• Speed & Safety as key issues of equal importance
• Redundancy
  – set channels safely
  – check channels independently
  – supervise by safety logic
• Logic and Final Elements
  – local & central subsystems
  – hierarchy of interlock levels