High availability process safety applications enabled by Concurrent Connections

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Abstract

In the Spring 2023 publication of the CIP family of specifications, ODVA announced the addition of an important new technology, Concurrent Connections. This technology enables flexible, zero switchover time, end-to-end redundancy solutions. This presentation briefly introduces the basic terms and concepts related with high availability. This presentation discusses characteristics of process industry systems and points out some of the deficiencies of current high availability solutions. Finally, the presentation explains the Concurrent Connections technology and describes how Concurrent Connections improve high availability and safety systems.
Overview of High Availability

- **Availability**
  - Mean Time To Failure
  - Mean Time To Restore/Repair

- **High Availability**

- **Redundancy**
  - Hot, Warm, or Cold
  - Active or Passive synchronization
  - Switchover or Concurrent

- **Fault Tolerance**

**Availability** = \( \frac{MTTF}{MTTF + MTTR} \)

<table>
<thead>
<tr>
<th>“Number of nines”</th>
<th>Availability %</th>
<th>Possible Downtime per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>99 %</td>
<td>3.65 days</td>
</tr>
<tr>
<td>3</td>
<td>99.9 %</td>
<td>8.76 hours</td>
</tr>
<tr>
<td>4</td>
<td>99.99 %</td>
<td>52.6 minutes</td>
</tr>
<tr>
<td>5</td>
<td>99.999 %</td>
<td>5.26 minutes</td>
</tr>
<tr>
<td>6</td>
<td>99.9999 %</td>
<td>30 seconds</td>
</tr>
</tbody>
</table>
• Large-scale and complex installations
• Processes cannot be easily stopped
• Consequences of failure can be catastrophic
  – Bhopal gas tragedy
  – Piper Alpha oil rig explosion
  – Deepwater Horizon oil spill
  – Tianjin explosions
• High Availability is critical
• Highly regulated
High Availability and Redundancy in the CIP Specification

- CIP Networks Library, Volume 1 Common Industrial Protocol
  - Redundant Owner connection type, Ownership of Outputs (ROO) and Claim Output Ownership (COO) bits
- CIP Networks Library, Volume 2 EtherNet/IP Adaptation of CIP
  - PRP
  - DLR
- CIP Networks Library, Volume 4 ControlNet Adaptation of CIP
  - Media redundancy with ring topologies
Existing Redundancy solutions and their problems

- Vendor specific
- Solution 1: switchover on IP address
  
  ![Diagram of switchover process]

- Solution 2: Delay applying connection fault action
- Solution 3: Redundancy realized at the application level
  
  ![Diagram of redundant devices]

...
Concurrent Connections

- “PRP on the CIP connection level”
- Redundant participants
- Multiple paths for transferring CIP data
- One logical CIP connection from an application perspective
Concurrent Connections – connection management

- New Connection Manager services:
  - `Concurrent_Forward_Open` and `Large_Concurrent_Forward_Open`
    - “Forward_Open + Concurrent Connections Protocol Version field”
  - `Concurrent_Forward_Close`
    - Same format as `Forward_Close`

- New Extended Network Segment
  - `Concurrent Connection Path` (list of Concurrent Connection Hops)

**Hop 1**
- Egress port: Port number on Controller
- Number of Link Addresses: 2
- Link Address 1: Router Participant A
- Link Address 2: Router Participant B

**Hop 2**
- Egress port: Port number on Router
- Number of Link Addresses: 2
- Link Address 1: I/O Device Participant A
- Link Address 2: I/O Device Participant B
Concurrent Connections - Connection Opening Process

Legend:
- Concurrent Forward Open request
- Concurrent Forward Open response
- Open branch of Concurrent Connection

Hop 1
- Egress port: Port number on Controller
- Number of Link Addresses: 2
- Link Address 1: Router Participant A
- Link Address 2: Router Participant B

Hop 2
- Egress port: Port number on Router
- Number of Link Addresses: 2
- Link Address 1: I/O Device Participant A
- Link Address 2: I/O Device Participant B
Concurrent Connections - Connection Closing Process

Legend:
- Open branch of Concurrent Connection
- Concurrent Forward Close request
- Concurrent Forward Close response
Concurrent Connections – Data flow

Legend:
- Open branch of Concurrent Connection
- Last Concurrent Connection Packet (CCSC=1)
- Fresh Concurrent Connection Packet (CCSC=2)
- Discarding the redundant packet

The same process happens in I/O Device to Controller direction.
Concurrent Connections - Fault tolerance

- The connection remains open as long as there is at least one available path between connection endpoints
- Zero switchover time

- Redundant devices are functionally equivalent and participate in the process all the time
- Hot, active, and concurrent redundancy

Legend:
- Open branch of Concurrent Connection
- Failure
Concurrent Connections – Branch recovery

Legend:
- Open branch of Concurrent Connection
- Failure
- Concurrent Forward Open request
- Concurrent Forward Open response

- Local, periodic attempts to reopen failed Concurrent Connection branches
Concurrent Connections - Flexibility

Controller

Participant A

Router 1

Participant B

Router 2

I/O device

Controller

Participant A

Router 1

Participant A

Router 2

Participant B

I/O device

Controller

Participant A

Router 1

Participant A

Router 2

Participant B

I/O device

Controller

Participant A

Router 1

Participant B

Router 2

Participant B

I/O device

Controller

Participant A

Router 1

Participant B

Router 2

Participant C

I/O device
Concurrent Connections will be supported by **Wireshark 4.2** (November 2023 release)
Real example – Concurrent_Forward_Open

<table>
<thead>
<tr>
<th>No.</th>
<th>Time</th>
<th>Source</th>
<th>Destination</th>
<th>Protocol</th>
<th>Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>2320</td>
<td>0.966484</td>
<td>10.192.71.101</td>
<td>10.192.71.103</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2321</td>
<td>0.966579</td>
<td>10.192.71.101</td>
<td>10.192.71.104</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2329</td>
<td>0.982349</td>
<td>10.192.71.102</td>
<td>10.192.71.104</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2331</td>
<td>0.984646</td>
<td>10.192.71.104</td>
<td>10.192.71.101</td>
<td>CIP CM Success: Connection</td>
<td>Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2334</td>
<td>0.984744</td>
<td>10.192.71.104</td>
<td>10.192.71.102</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2347</td>
<td>0.982268</td>
<td>10.192.71.102</td>
<td>10.192.71.103</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2354</td>
<td>0.984334</td>
<td>10.192.71.103</td>
<td>10.192.71.101</td>
<td>CIP CM Success: Connection</td>
<td>Manager - Concurrent Forward Open</td>
</tr>
<tr>
<td>2355</td>
<td>0.984431</td>
<td>10.192.71.103</td>
<td>10.192.71.102</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Open</td>
</tr>
</tbody>
</table>

Controller
- Participant A
- Participant B

Router 1
- Participant A
  IP: 10.192.71.101
- Participant B
  IP: 10.192.71.102

Wireshark

Router 2
- Participant A
  IP: 10.192.71.103
  Slot: 0
- Participant B
  IP: 10.192.71.104
  Slot: 1

I/O Device
- Participant A
  Slot: 2
- Participant B
  Slot: 3
Real example – Concurrent_Forward_Open format

Legend:
- Originators shall use the same values
- Routers and Targets shall check if values are the same for a given Connection Triad
- Difference from Forward_Open
Real example – Concurrent Connection Path

Concurrent Connection Path

Connection Path: [Network], Assembly, Instance: 0xBF, Connection Point: 0xC7, Connection Point: 0x0434

Path Segment: 0x5f (Extended Network Segment)
010. .... = Path Segment Type: Network Segment (2)
...1 1111 = Network Segment Type: Extended Network Segment (31)
Network Segment Length: 4 words
Extended Segment Subtype: 0x8004
Hops Count: 1
Length of Concurrent Connection Path: 4

CC Hop: 1
Egress Port: 1
0000 .... = Link Address Type: 8-bit numeric link addresses (0)
.... 0010 = Number of link addresses: 2
Link address: 2
Link address: 3

Router 2
Participant A
IP: 10.192.71.103
Slot: 0

Participant B
IP: 10.192.71.104
Slot: 1

I/O Device
Participant A
Slot: 2

Participant B
Slot: 3
Real example – Concurrent_Forward_Close

<table>
<thead>
<tr>
<th>No.</th>
<th>Time</th>
<th>Source</th>
<th>Destination</th>
<th>Protocol</th>
<th>Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>76205</td>
<td>31.000231</td>
<td>10.192.71.101</td>
<td>10.192.71.103</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Close</td>
</tr>
<tr>
<td>76214</td>
<td>31.001112</td>
<td>10.192.71.103</td>
<td>10.192.71.101</td>
<td>CIP CM</td>
<td>Success: Connection Manager - Concurrent Forward Close</td>
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<tr>
<td>76221</td>
<td>31.000358</td>
<td>10.192.71.102</td>
<td>10.192.71.104</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Close</td>
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<tr>
<td>76222</td>
<td>31.004084</td>
<td>10.192.71.102</td>
<td>10.192.71.103</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Close</td>
</tr>
<tr>
<td>76229</td>
<td>31.006355</td>
<td>10.192.71.103</td>
<td>10.192.71.102</td>
<td>CIP CM</td>
<td>Success: Connection Manager - Concurrent Forward Close</td>
</tr>
<tr>
<td>76232</td>
<td>31.001255</td>
<td>10.192.71.104</td>
<td>10.192.71.101</td>
<td>CIP CM</td>
<td>Success: Connection Manager - Concurrent Forward Close</td>
</tr>
<tr>
<td>76236</td>
<td>31.004227</td>
<td>10.192.71.102</td>
<td>10.192.71.104</td>
<td>CIP CM</td>
<td>Connection Manager - Concurrent Forward Close</td>
</tr>
<tr>
<td>76241</td>
<td>31.007075</td>
<td>10.192.71.104</td>
<td>10.192.71.102</td>
<td>CIP CM</td>
<td>Success: Connection Manager - Concurrent Forward Close</td>
</tr>
</tbody>
</table>

- **Transmission Control Protocol**: Src Port: 57866, Dst Port: 44018, Seq: 1
- **EtherNet/IP (Industrial Protocol)**: Session: 0x4000000E, Send RR Data
- **Common Industrial Protocol**
- **CIP**: Connection Manager
- **Service**: Concurrent Forward Close (Request)
- **Command Specific Data**
  - ...00000000 = Priority: 0
  - ...00000200 = tick time: 4
  - Time-out ticks: 187
  - Actual Time Out: 2992ms
  - Connection Serial Number: 0xcccc
  - Originator Vendor ID: Rockwell Automation/Allen-Bradley (0x0001)
  - Originator Serial Number: 0x41465c4
  - Connection Path Size: 7 words
  - Reserved: 0x00

**Concurrent Connection Path**

- **Path Segment**: 0x3F (Extended Network Segment)
  - 010 ... = Path Segment Type: Network Segment (2)
  - ...1111 = Network Segment Type: Extended Network Segment (31)
  - Network Segment Length: 4 words
  - Extended Segment Subtype: 0x0004
  - Hops Count: 1
  - Length of Concurrent Connection Path: 4
- **CC Hop**: 1
  - Egress Port: 0
  - 0000 ... = Link Address Type: 8-bit numeric link addresses (0)
  - 0010 = Number of link addresses: 2
  - Link address: 2
  - Link address: 3

- **Path Segment**: 0x20 (8-Bit Class Segment)
  - Path Segment: 0x24 (8-Bit Instance Segment)
Real example – Real-Time data O->T

<table>
<thead>
<tr>
<th>No.</th>
<th>Time</th>
<th>Source</th>
<th>Destination</th>
<th>Protocol</th>
<th>Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>124</td>
<td>1.105903</td>
<td>10.192.71.101</td>
<td>10.192.71.104</td>
<td>CIP I/O CC_SEQ=0000031900</td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>1.105912</td>
<td>10.192.71.101</td>
<td>10.192.71.103</td>
<td>CIP I/O CC_SEQ=0000031900</td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>1.105465</td>
<td>10.192.71.102</td>
<td>10.192.71.104</td>
<td>CIP I/O CC_SEQ=0000031900</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>1.105486</td>
<td>10.192.71.102</td>
<td>10.192.71.103</td>
<td>CIP I/O CC_SEQ=0000031900</td>
<td></td>
</tr>
</tbody>
</table>

User Datagram Protocol, Src Port: 2222, Dst Port: 2222
EtherNet/IP (Industrial Protocol)
Concurrent Connection Packet

Packet Type and Keep-alive: 0x8001, Packet Type: Concurrent Connection Packet Format

... ... 0 0001 = Packet Type: Concurrent Connection Packet Format (1)
... ... 0 00 00 00 00 = Keep-alive Flag: 0x0
... ... 0 00 00 00 00 = Keep-alive Hop Count: 0
0000 0000 0000 0000 = Reserved: 0x00
Packet Length: 10
Concurrent Connection Sequence Count: 31900
CRC: 0xcede1fe4fd

Common Industrial Protocol, I/O
Concurrent Connections implementaiton hints

Concurrent Connections extend existing CIP connections

<table>
<thead>
<tr>
<th>Concurrent Connections functionality</th>
<th>ODVA CIP Specification Vol 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concurrent Connection Path Extended Network Segment</td>
<td>C-1.4.3.6.2, 3-7.1</td>
</tr>
<tr>
<td>Concurrent Forward_Open Connection Manager service</td>
<td>3-5.6.5, 3-7.2</td>
</tr>
<tr>
<td>Concurrent Forward_Close Connection Manager service</td>
<td>3-5.6.6, 3-7.3</td>
</tr>
<tr>
<td>Concurrent Connection Packet production and consumption</td>
<td>3-7.4.1.1, 3-7.4.3, 3-7.4.4</td>
</tr>
<tr>
<td>Branch recovery</td>
<td>3-7.5</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>3-5.3.1.10, 3-5.3.1.11, 3-5.3.1.12</td>
</tr>
<tr>
<td>Originators synchronization of Concurrent Connection parameters</td>
<td>3-7.2</td>
</tr>
<tr>
<td>Endpoints synchronization of produced connection data</td>
<td>3-7.4.2</td>
</tr>
</tbody>
</table>
Concurrent Connections Summary

**Pros**

- **Standardized end-to-end solution for redundant device communication across a system with devices from multiple vendors**
- Enable high availability systems, maximize system MTTF
- Flexible
- Eliminate switchover solution deficiencies
- Relatively easy to implement (extension of existing CIP connections)

**Cons**

- Higher use of network bandwidth
- Additional packet processing steps
- Require active synchronization of the redundant endpoints (vendor-specific)