Flexible Fault Tolerance In Configurable Middleware For Embedded Systems

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Acknowledgment

- Dr. Bakken—advisor
- Committee members
- MicroQoSCORBA team
- My Family—Angie, KJ, and Ethan

Presentation Outline

- Introduction
- Architectural Taxonomy
- MicroQoSCORBA Base Architecture
- Configurable Fault-Tolerant Mechanisms for MicroQoSCORBA
- Implementation and Integration
- Results and Analysis
- Related Work
- Conclusion

Introduction—1

- Explosion of embedded systems
  - Advancements in computing technology
  - 11 billion parts per year
  - Ubiquitous networking (soon all will be interconnected)
  - Provide a better and more integrated level of service
- Opportunities and difficulties associated with embedded system development
  - Restricted resources of devices
  - Reliance on proprietary, low-level mechanisms
  - Rapid evolution of computing technologies
Introduction—2

• Middleware technologies
  – Overcome difficulties in distributed systems (not specifically embedded systems)
  – “Plumbing” of an information system
  – Manage complexity and heterogeneity
  – Common Object Request Broker Architecture (CORBA)

• Middleware applied to embedded systems
  – General purpose frameworks fail to scale down
  – Do not have the flexibility to cover the wide space of the embedded systems market
  – Overlook the fundamental problems of partial failures and consistent ordering of distributed events (fault tolerance)

Introduction—3

• MicroQoSCORBA (MQC)
  – Configurable middleware framework for embedded systems
  – Tailorable to hardware and application requirements
  – Improved taxonomy of terms / orthogonal components
  – CASE toolkit to easily configure system / application constraints

Introduction—4

• Focus of this thesis
  – Integrate fault tolerance into MQC

• Contributions
  – Analysis, design, implementation of several fault-tolerant mechanisms into the MQC framework
  – Analysis, design, implementation of a highly configurable fault-tolerant group communication system (stand alone / integrated into MQC)

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Architectural Taxonomy—1

- Embedded system applications and hardware characteristics (wide space)
- Need to categorize this wide space (completely and orthogonally) for MQC
- We divided the properties of embedded systems and middleware architecture into a more fine-grained definition

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Architectural Taxonomy—2

<table>
<thead>
<tr>
<th>Embedded H/W</th>
<th>Roles (Client/Server/Peer)</th>
<th>SW I/O</th>
<th>IDL Subsetting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control Flow</td>
<td>Data Flow</td>
<td>Interaction Style</td>
</tr>
<tr>
<td></td>
<td>Connection Setup</td>
<td></td>
<td>Data Direction</td>
</tr>
<tr>
<td></td>
<td>Receive Setup</td>
<td></td>
<td>In (Out)</td>
</tr>
<tr>
<td></td>
<td>Request</td>
<td></td>
<td>In (Out)</td>
</tr>
<tr>
<td></td>
<td><em>Network Logic</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Application Service</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Error Service</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Other</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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MicroQoSCORBA Base Architecture—1

- Lifecycle Epochs
  - Important characteristics / constraints are provided in each epoch
  - MQC architecture and toolkit span epochs to capture as much of these characteristics as possible
  - Lifetime of an MQC project divided into 5 epochs:
    - Design, IDL Compilation, Application Compilation, System / Application Startup, and Run Time
  - Each epoch provides opportunities to refine key facets of the application
MicroQoSCORBA Base Architecture—2

<table>
<thead>
<tr>
<th>Lifecycle Epoch</th>
<th>Constraint Bound</th>
<th>Representative Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>HW Heterogeneity</td>
<td>Symmetric, asymmetric</td>
</tr>
<tr>
<td></td>
<td>HW Choice</td>
<td>X86, TINY, ColdFire</td>
</tr>
<tr>
<td></td>
<td>Communications HW</td>
<td>Ethernet, Serial, Infrared</td>
</tr>
<tr>
<td></td>
<td>Processing Capability</td>
<td>50 Mhz, 1 Ghz, 8bit, 32bit</td>
</tr>
<tr>
<td></td>
<td>System size</td>
<td>small, medium, large (e.g., transducers to jets)</td>
</tr>
<tr>
<td></td>
<td>Power Usage</td>
<td>line, battery, and/or parasitic power</td>
</tr>
<tr>
<td>IDL Compilation</td>
<td>Communication Style</td>
<td>Passive, Pro-active, Push, Pull</td>
</tr>
<tr>
<td></td>
<td>State/Proxy Generation</td>
<td>Inline vs. library usage</td>
</tr>
<tr>
<td></td>
<td>Message Lengths</td>
<td>Fixed, variable-length messages</td>
</tr>
<tr>
<td></td>
<td>Parameter Marshalling</td>
<td>Fixed Formats</td>
</tr>
<tr>
<td>Application Compilation</td>
<td>Space/Time Optimizations</td>
<td>Loop unrolling, code migration, function and proxy inlining</td>
</tr>
<tr>
<td>System/Application Startup</td>
<td>Library Usage</td>
<td>Static vs. dynamic library linkage</td>
</tr>
<tr>
<td>Run Time</td>
<td>Minor QoS adaptation</td>
<td>Adjust QoS parameters</td>
</tr>
</tbody>
</table>

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Configurable Fault-Tolerant Mechanisms for MQC—1

- Most embedded applications require some level of dependability
- Dependability—The measure in which reliance can be justifiably be placed on the service delivered by a system
- Need for dependability (fly-by-wire systems, anti-lock brake systems, remote banking systems)
- Because of this need it is important that MQC have fault tolerance mechanisms

Configurable Fault-Tolerant Mechanisms for MQC—2

<table>
<thead>
<tr>
<th>Redundancy</th>
<th>Reliability</th>
<th>Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal</td>
<td>Group Communication</td>
<td>Sender FIFO</td>
</tr>
<tr>
<td>Spatial</td>
<td>• Best Effort</td>
<td>Causal</td>
</tr>
<tr>
<td>Value</td>
<td>• Reliable</td>
<td>Logical Timestamping</td>
</tr>
<tr>
<td></td>
<td>• Uniform</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>• Atomic</td>
<td>Moving-Sequencer based</td>
</tr>
</tbody>
</table>

Configurable Fault-Tolerant Mechanisms for MQC—3

- Temporal Redundancy
  - Doing the same thing more than once
- Spatial Redundancy
  - Having several copies of the same component
- Value Redundancy
  - Adding extra information about the value of data being stored or sent
Configurable Fault-Tolerant Mechanisms for MQC—5

• Reliability
  – Group Communication
    • Multi-point to multi-point communication through groups
    • Reliability aspects and ordering aspects
    • Fundamental building block of fault-tolerant distributed systems
  – Failure Detection
    • Detect and diagnose failed components in a system

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Implementation and Integration—1

• Temporal Redundancy
  – Communication Channel
  – Tolerate $k$ omission failures by transmitting messages $k+1$ times
  – Number of retransmissions configurable from CASE toolkit
  – Client and Server code modified to handle retransmissions and duplicate filtering

Implementation and Integration—2

• Spatial Redundancy
  – Communications path
  – Provides message omission and channel failure tolerance
  – Communication paths to be supported is configurable from the CASE toolkit
  – Client code modified to filter duplicate messages received
Implementation and Integration—3

• Value Redundancy
  – Checksum included in messages
  – CRC32 checksum selected
  – Selectable from the CASE toolkit

• Group Communication
  – Developed as a stand alone system
  – Integrated into MQC (Server side—replication)

Implementation and Integration—4

• Group Communication (cont.)
  – Nonuniform Failure-Atomic Multicast (2 phase)
  – Dynamically Uniform Failure-Atomic Multicast (3 phase)
  – Ordering
    • FIFO Ordered Multicast (ID based)
    • Causal Ordered Multicast (vector timestamp)
    • Totally Ordered Multicast (moving sequencer)
  – All modes are configurable from the CASE toolkit

Implementation and Integration—5

• Failure Detection
  – Implemented as part of the Group Communications package
  – User can specify a timeout in the CASE toolkit
  – Group Communications package monitors the transmission of messages
  – If a message is late it is assumed that the group member has crashed (removed from group)

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Results and Analysis—1

- Testing Platforms
  - Two desktop systems (1.5Ghz P4, Linux, 100 BaseT network)
  - Two TINI boards (40Mhz Dallas Semiconductor DS80C390 CPU)
  - Two Systronixs SaJe boards (100Mhz ajile CPU)

Results and Analysis—2

- Impact on memory footprint
  - “Simple” application selected for analysis
  - Client and Server class file sizes examined
  - Some numbers for TINI and AJILE not available due to UDP

<table>
<thead>
<tr>
<th>Application: Simple -- (use TCP and GIOP unless stated otherwise)</th>
<th>Linux</th>
<th>TINI</th>
<th>AJILE</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fault Tolerance</td>
<td>68,654</td>
<td>32,882</td>
<td>253,985</td>
</tr>
<tr>
<td>Temporal Redundancy</td>
<td>69,067</td>
<td>33,022</td>
<td>254,161</td>
</tr>
<tr>
<td>Spatial Redundancy (TCP and Unreliable UDP)</td>
<td>88,287</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Group Comm (Non-Uniform)</td>
<td>137,800</td>
<td>63,014</td>
<td>NA</td>
</tr>
<tr>
<td>Group Comm (Uniform)</td>
<td>142,596</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Value Redundancy</td>
<td>70,109</td>
<td>33,506</td>
<td>254,793</td>
</tr>
</tbody>
</table>

Results and Analysis—3

- Impact on Memory Footprint (cont.)
  - Impact to class file size is very small (except for Group Communication options)
  - Group Communication is not optimized for MQC (designed as a stand alone—uses its own transports, etc.)

Results and Analysis—4

- Impact on Execution Times
  - “Timing” application selected (simple program with one method that passes a long from the client to the server and back)
  - Average call time calculated from many iterations
Results and Analysis—5

- Temporal Redundancy
  - Increase in time is due to the retransmitting of the message along with the duplicate filter processing
  - Impact is linear and small on PC, but as CPU power goes down the impact is much more significant

<table>
<thead>
<tr>
<th>Application: Timing (Use TCP and GIOP unless stated otherwise)</th>
<th>Execution Time (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux</td>
<td>TINI</td>
</tr>
<tr>
<td>No Fault Tolerance</td>
<td>307</td>
</tr>
<tr>
<td>Temporal Redundancy (2 retrans)</td>
<td>387</td>
</tr>
<tr>
<td>Temporal Redundancy (4 retrans)</td>
<td>457</td>
</tr>
<tr>
<td>Temporal Redundancy (6 retrans)</td>
<td>519</td>
</tr>
</tbody>
</table>

Results and Analysis—6

- Spatial Redundancy
  - Impact is about double (exactly what would be expected—twice as long to send the message down two paths)
  - Numbers not available on TINI and AJILE due to problems with UDP implementation

<table>
<thead>
<tr>
<th>Application: Timing (Use TCP and GIOP unless stated otherwise)</th>
<th>Execution Time (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux</td>
<td>TINI</td>
</tr>
<tr>
<td>No Fault Tolerance</td>
<td>307</td>
</tr>
<tr>
<td>Spatial Redundancy (TCP and Unreliable UDP)</td>
<td>564</td>
</tr>
</tbody>
</table>

Results and Analysis—7

- Value Redundancy
  - Impact is very dependent on CPU processing power (due to CRC32 calculation)
  - Insertion and extraction of checksum value also has an impact

<table>
<thead>
<tr>
<th>Application: Timing (Use TCP and GIOP unless stated otherwise)</th>
<th>Execution Time (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux</td>
<td>TINI</td>
</tr>
<tr>
<td>No Fault Tolerance</td>
<td>307</td>
</tr>
<tr>
<td>Value Redundancy</td>
<td>388</td>
</tr>
</tbody>
</table>

Results and Analysis—8

- Group Communication
  - Replicated server configuration
  - Impact is significant (expected)
    - Not tightly integrated (uses own transport)
    - Group Communication requires the transmission of a large amount of messages (1 message becomes 10 in the worst case)

<table>
<thead>
<tr>
<th>Application: Timing (Use TCP and GIOP unless stated otherwise)</th>
<th>Execution Time (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux</td>
<td>No Fault Tolerance</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Linux</td>
<td>307</td>
</tr>
<tr>
<td>Linux</td>
<td>502</td>
</tr>
</tbody>
</table>
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Related Work—1

- MQC allows constraints to be chosen at much finer granularity
  - Designed from the device level up
- We have found no middleware framework that allows the hardware and application constraints to be used for tailoring the middleware
- We have found no middleware framework for small embedded devices that supports multiple QoS properties (fault tolerance tends to be completely overlooked)

Related Work—2

- Projects / Products that are starting to address embedded system issues:
  - MinimumCORBA (cut down version of full CORBA)
    - Still too large to be usable on most small embedded devices
  - e*ORB framework by Vertel
    - Smaller, but no flexibility provided
  - LegORB
    - Very few details available—some customizations allowed (much less granularity) and no QoS
  - OMG Smart Transducers Interface RFP
    - Focused on lightweight communications only
  - MMLite
    - Targeted for embedded systems and real time—narrow QoS breadth
  - Aegis Weapon System (AWS)
    - CORBA with custom UDP implementation

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Conclusion—1

• Project was successful!—we were able to identify, design, implement, and integrate several important fault-tolerant mechanisms into MQC

• Areas for Future Work
  – Configurable means of how to deal with duplicate messages that are received due to redundancy (error detection, voting, etc.)
  – Incorporate more sophisticated error correction codes for value redundancy
  – Support for more modes of communication in the group communication package (virtual synchrony, TO with causality)
  – Tighter integration of the group communication package into MQC (use MQC’s existing transport mechanism, message header)
  – Group communication support on the client
  – Failure detection as an independent mechanism

Conclusion—2

• Publications:

Conclusion—3

• Questions / Comments??
• Thanks!!!!