UNIVERSITÀ DI PISA

Master's Degree in Artificial Intelligence and Data Engineering

Distributed Systems and Middleware Technologies

Task Force

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Contents

Chapter 1

Introduction

TaskForce is a distributed job scheduling system. The system demonstrates the practical application of fundamental distributed systems concepts including consensus algorithms, message-oriented middleware, fault tolerance, and distributed coordination.

The project implements a complete job scheduling pipeline with:

- **Erlang/OTP orchestrator** [1] using Raft consensus for leader election
- **RabbitMQ cluster** [2] with priority-based queuing and dead letter handling
- **Java Spring Boot API gateway** [3] with REST endpoints and real-time SSE updates
- **Polyglot worker farm** supporting Python and Java job execution
- **Comprehensive monitoring** with Prometheus and Grafana
- **Multi-node deployment** on Docker containers and Ubuntu VMs

The system successfully handles concurrent jb submissions, automatically recovers from node failures, maintains exactly-once execution semantics, and scales horizontally by adding worker nodes. All course requirements regarding synchronization/coordination, communication, Erlang implementation, and multi-node deployment have been fully satisfied.

1.1 Background

Distributed systems have become the backbone of modern computing infrastructure. From cloud computing platforms to microservices architectures, the ability to coordinate work

across multiple nodes while maintaining consistency and availability is fundamental. Job scheduling - the allocation of computational tasks to worker nodes - represents a classic distributed systems problem that encompasses many core challenges: coordination, communication, fault tolerance, and load balancing.

1.2 Problem Statement

Modern distributed applications require reliable job processing systems that can:

- Handle thousands of concurrent task submissions
- Guarantee exactly-once or at-least-once execution semantics
- Tolerate node failures without data loss
- Scale horizontally as workload increases
- Support heterogeneous execution environments
- Provide real-time visibility into system state

Existing solutions like Apache Airflow, Celery, and AWS Batch are powerful but complex. This project aims to build a simplified yet complete distributed job scheduler from first principles, demonstrating how fundamental distributed systems algorithms and middleware technologies address these challenges.

1.3 Project Scope

The scope of this project includes:

- Design and implementation of a distributed job scheduler
- Implementation of Raft consensus algorithm for leader election
- Integration with RabbitMQ for reliable message queuing
- Development of a polyglot worker execution framework
- REST API for job submission and management

- Real-time status streaming via Server-Sent Events
- Multi-node deployment on both containers and VMs
- Comprehensive monitoring and observability

Chapter 2

System Architecture

2.1 High-Level Architecture

2.2 Data Flow

Job Submission Flow:

1. Client submits job via REST API to API Gateway
2. API Gateway stores job in H2 database, publishers to RabbitMQ
3. RabbitMQ queues job based on priority (High/Medium/Low)
4. Erlang Orchestrator consumes job, assigns to worker via load balancing
5. Worker executes job, sends status updates via REST
6. API Gateway updates job status, notifies clients via SSE

Failure Recovery Flow:

1. Leader orchestrator node fails
2. Remaining nodes detect failure via heartbeat timeout
3. Raft consensus elects new leader
4. New leader resumes job processing
5. Failed node rejoins cluster as follower

2.3 Component Responsabilities

- **Orchestrator** (Erlang/OTP): Leader election, job registry, worker coordination, health monitoring
- **API Gateway** (Java/Spring Boot): REST API, job persistence, SSE streaming, rate limiting
- **Message Broker** (RabbitMQ): Priority queuing, message persistence, dead letter handling
- **Workers** (Python, Java): Job execution (calculation, transformation, validation)
- **Load Balancer** (Nginx): Traffic distribution across APU gateways
- **Database** (H2): Job metadata persistence
- **Cache** (Redis): Session management, rate limiting
- **Monitoring** (Prometheus/Grafana): Metrics collection and visualization

Chapter 3

Distributed Systems Challenges and Solutions

3.1 Synchronization/Coordination Challenges

3.1.1 Challenge 1: Leader Election

Problem: In a distributed system, multiple orchestrator nodes cannot all act as leaders simultaneously. A single leader must be elected to coordinate job assignments and maintain consistency.

Solution: **Raft Consensus Algorithm Implementation**

```
% Simplified Raft state machine (raft_fsm.erl)
-define(ELECTION_TIMEOUT, {150, 150}). % 150-300ms
-define(HEARTBEAT_INTERVAL, 150).      % 150ms

% State: follower, candidate, leader
% Key operations:
% - request_vote/3 : Request votes from peers
% - append_entries/6: Replicate log entries
% - commit/1       : Commit entries to state machine

% Leader election sequence:
% 1. Follower detects election timeout
% 2. Follower     Candidate, increments term
% 3. Candidate requests votes from peers
% 4. Candidate receives majority     Leader
```

```
% 5. Leader sends heartbeats to maintain authority
```

Code 3.1: Raft Consensus Algorithm Implementation

Complexities Addressed:

- **Term management**: Logical clock to detect stale leaders
- **Vote splitting**: Randomized election timeouts
- **Log matching**: Ensure followers have consistent logs
- **Safety**: At most one leader per term

3.1.2 Challenge 2: Distributed State Consistency

Problem: Multiple orchestrator nodes need a consistent view of job states. Simple master-slave replication can lead to inconsistencies during network partitions.

Solution: CRDT-based Job Registry

```
% CRDT implementation using Observed-Remove Set (job_registry.erl)
merge_crdt(State1, State2) ->
    orddict:merge(fun(_Key, {T1, V1}, {T2, V2}) ->
        case T1 > T2 of
            true -> {T1, V1};
            false -> {T2, V2}
        end
    end, State1, State2).

% Each update includes timestamp for conflict resolution
update_job(JobId, Status) ->
    Timestamp = erlang:system_time(microsecond),
    CRDT = orddict:store(JobId, {Timestamp, Status}, State),
    broadcast_crdt_update(CRDT).
```

Code 3.2: CRDT-based Job Registry

Properties Guaranteed:

- **Eventual consistency**: All nodes converge to same state
- **Conflict-free**: Concurrent updates merge deterministically

- **No central coordinator**: Each node operates independently
- **Fault-tolerant**: Network partitions resolve automatically

3.1.3 Challenge 3: Exactly-Once Execution

Problem: Ensuring each job executes exactly once, even in the presence of worker failures, network issues, or system restarts.

Solution: **Multi-layered Approach**

```
% 1. Idempotent job design
process_job(Job) ->
    case job_already_processed(Job#job.id) of
        true -> {ok, already_processed};
        false -> execute_job(Job)
    end.

% 2. Delivery tracking with RabbitMQ
% - Messages not acknowledged until job completes
% - Automatic requeue on worker failure
% - Dead letter queue for failed jobs

% 3. Distributed locking
acquire_job_lock(JobId) ->
    case global:set_lock({job_lock, JobId}, [node()], 5000) of
        true -> {ok, acquired};
        false -> {error, locked}
    end.
```

Code 3.3: Multi-layered Approach

3.1.4 Challenge 4: Worker Coordination

Problem: Dynamically assigning jobs to available workers while respecting capacity limits and job priorities.

Solution: **Worker Pool with Load Balancing**

```
% Least-loaded worker selection (worker_pool.erl)
select_least_loaded(Workers) ->
    lists:foldl(
```

```
        fun(Worker, Acc) ->
            LoadRatio = Worker#worker.current_load / Worker#worker.capacity,
            AccRatio = Acc#worker.current_load / Acc#worker.capacity,
            if LoadRatio ¡ AccRatio -> Worker; true -> Acc end
        end,
        hd(Workers), tl(Workers)
    ).

% Priority-based queue routing (router.erl)
priority_to_queue(Priority) when Priority ≥ 10 -> ≪"job.high"≫;
priority_to_queue(Priority) when Priority ≥ 5 -> ≪"job.medium"≫;
priority_to_queue(_) -> ≪"job.low"≫.
```

Code 3.4: Worker Pool with Load Balancin

3.2 Communication Challenges

3.2.1 Challenge 5: Reliable Message Delivery

Problem: messages can be lost, duplicated, or reordered in distributed systems.

Solution: **RabbitMQ with Confirms and Persistence**

```
% Publisher confirms (RabbitMQ Java client)
rabbitTemplate.setConfirmCallback((correlationData, ack, cause) -> {
    if (ack) {
        log.debug("Message confirmed: {}", correlationData);
    } else {
        log.error("Message rejected: {}", cause);
        // Retry or store for later delivery
    }
});

% Durable queues and persistent messages
channel.queue_declare(queue, true, false, false,
    [{"x-max-priority", 10}, {"x-queue-type", "quorum"}]);

% Consumer acknowledgments
ch.basic_ack(delivery_tag);  // Success - remove from queue
```

```
ch.basic_nack(delivery_tag, false, true);  // Failure - requeue
```

Code 3.5: RabbitMQ with Confirms and Persistence

Delivery Guarantees:

- **At-least-once**: Messages survive broker restarts
- **Exactly-once**: Idempotent consumers + message deduplication
- **Ordered processing**: Per-queue FIFO semantics
- **Dead lettering**: Failed messages routed to DLQ

3.2.2 Challenge 6: Heterogeneoous System Integration

Problem: Different components written in different languages (Erlang, Java, Python) need to communicate seamlessly.

Solution: **Polyglot Communication Strategy**

Communication Pattern	Protocol	Use Case	Components
Synchronous RPC	HTTP/REST	Job submission, status queries	Client ↔ API Gatev
Asynchronous Messaging	AMQP	Job distribution	API Gateway ↔ Wo
Real-time Updates	SSE/WebSocket	Live job monitoring	API Gateway ↔ Cli
Inter-node Coordination	Erlang Messaging	Raft consensus	Orchestrator ↔ Orc
Health Monitoring	HTTP	Worker heartbeats	Workers → Orchest

Example: **Java → Erlang Communication (HTTP)**

```
// Java side
@PostMapping("/api/jobs")
public ResponseEntity¡Job¿ submitJob(@RequestBody JobRequest request) {
    Job job = jobService.createJob(request);

    // HTTP call to Erlang orchestrator
    erlangRestClient.registerJob(job)
        .subscribe(response → log.info("Job registered: {}", response));

    return ResponseEntity.accepted().body(job);
}
```

Code 3.6: Erlang Communication (HTTP) - Java

```erlang
% Erlang side (http_server.erl)
handle_register_job(Req, State) ->
    {ok, Body, Req2} = cowboy_req:read_body(Req),
    Job = jsx:decode(Body, [return_maps]),
    distriqueue:register_job(Job),
    cowboy_req:reply(202, ?CONTENT_JSON,
        jsx:encode(#{status => accepted}), Req2).
```

Code 3.7: Erlang Communication (HTTP) - Erlang

3.2.3 Challenge 7: Real-time Updates

Problem: Clients need immediate visibility into job status changes without polling.

Solution: **Server-Sent Events (SSE)**

```java
// Java side
@GetMapping(value = "/jobs/stream", produces = MediaType.TEXT_EVENT_STREAM_VALUE)
public SseEmitter streamJobUpdates() {
    SseEmitter emitter = new SseEmitter(Long.MAX_VALUE);

    // Register emitter for this client
    sseEmitters.put(clientId, emitter);

    emitter.onCompletion(() -> sseEmitters.remove(clientId));
    emitter.onTimeout(() -> sseEmitters.remove(clientId));

    return emitter;
}

// When job status changes
private void broadcastJobUpdate(Job job) {
    sseEmitters.forEach((id, emitter) -> {
        try {
            emitter.send(SseEmitter.event()
                .name("job-update")
                .data(Map.of(
                    "jobId", job.getId(),
                    "status", job.getStatus(),
                    "timestamp", Instant.now()
                )));
```

```
        } catch (IOException e) {
            sseEmitters.remove(id);
        }
    });
}
```

Code 3.8: Server-Sent Events (SSE)

3.2.4 Challenge 8: Cross-node State Synchronization

Problem: State changes in one orchestrator node must propagate to all other nodes.

Solution: **Gossip Protocol with Vector Clocks**

```
% Broadcast update to all peers (job_registry.erl)
broadcast_job_update(Job) ->
    Nodes = [N || N <- nodes(), N /= node()],
    lists:foreach(
        fun(Node) ->
            gen_server:cast({?MODULE, Node}, {sync_job, Job})
        end, Nodes).

% Merge conflict resolution using vector clocks
merge_job_state(LocalJob, RemoteJob, LocalClock, RemoteClock) ->
    case compare_clocks(LocalClock, RemoteClock) of
        gt -> LocalJob;        % Local is newer
        lt -> RemoteJob;       % Remote is newer
        eq -> LocalJob;        % Concurrent, arbitrary choice
        concurrent -> merge_jobs(LocalJob, RemoteJob)  % CRDT merge
    end.
```

Code 3.9: Gossip Protocol with Vector Clocks

3.3 Fault Tolerance Challenges

3.3.1 Challenge 9: Node Failure Detection

Problem: Quickly detecting failed nodes to trigger recovery.

Solution: **Heartbeat Monitoring**

```
% Health monitor (health_monitor.erl)
handle_info(check_health, State) ->
    Now = erlang:system_time(millisecond),
    Timeout = app:get_env(heartbeat_timeout, 120000),

    lists:foreach(
        fun({Node, LastHeartbeat}) ->
            if Now - LastHeartbeat > Timeout ->
                lager:warning("Node  p unresponsive", [Node]),
                trigger_recovery(Node);
               true -> ok
            end
        end, State#state.last_heartbeats),

    erlang:send_after(30000, self(), check_health),
    {noreply, State}.
```

Code 3.10: Heartbeat Monitoring

3.3.2 Challenge 10: Split-Brain Prevention

Problem: Network partitions can lead to multiple nodes believing they are the leader.

Solution: **Quorum-based Decisions**

```
% Raft requires majority for all decisions
commit_if_majority(LogEntry, State) ->
    Majority = (length(State#state.peers) + 1) div 2 + 1,
    AckCount = length(State#state.match_index),

    if AckCount ≥ Majority ->
        commit_entry(LogEntry),
        State#state{commit_index = State#state.commit_index + 1};
       true ->
        State
    end.
```

Code 3.11: Quorum-based Decisions

Chapter 4

Technology Stack And Implementation Details

4.1 Project Structure

The project consists primarily of these files:

- **orchestrator/**: Erlang/OTP application
- **gateway/**: Java Spring Boot API
- **workers/python-worker/**: Python worker implementation
- **workers/java-worker/**: Java worker implementation
- **deploy/**: Deployment scripts and config

4.2 Erlang/OTP (Orchestrator)

4.2.1 Key Implementation: Raft Consensus

File: ‘orchestrator/src/raft_fsm.erl‘

The Raft implementation consists of 3 state functions and 6 cores operations (simplified version):

```
%%% State 1: Follower (default state)
follower(state_timeout, election_timeout, State) ->
    % No heartbeat from leader, start election
```

```
    NewTerm = State#state.current_term + 1,
    become_candidate(NewTerm, State).

%%% State 2: Candidate
candidate(cast, {request_vote_reply, {vote_granted, _, Term, true}}, State) ->
    Votes = State#state.votes + 1,
    Majority = (length(State#state.peers) + 1) div 2 + 1,
    if Votes ≥ Majority → become_leader(State);
       true → State#state{votes = Votes}
    end.

%%% State 3: Leader
leader({call, From}, {propose, Command}, State) ->
    % Append to local log
    LogEntry = {State#state.current_term, Command},
    NewLog = State#state.log ++ [LogEntry],

    % Replicate to followers (asynchronous)
    replicate_to_followers(NewLog, State),

    {keep_state, State#state{log = NewLog},
     [{reply, From, {ok, length(NewLog)}}]}.
```

Code 4.1: Raft Consensus implementation

Complexity Analysis:

- **Time complexity**: $O(n)$ for log replication, $O(1)$ for leader election
- **Space complexity**: $O(jobs)$ for log storage
- **Message complexity**: $O(n)$ heartbeats per leader, $O(n^2)$

4.2.2 Key Implementation: CRDT Job Registry

File: ‘orchestrator/src/job_registry.erl‘

The job registry uses an Observed-Remove Set (OR-Set) CRDT (simplified version):

```
% CRDT state: {Key, {Timestamp, Value}}
merge(State1, State2) ->
    orddict:merge(
```

```
        fun(_Key, {T1, V1}, {T2, V2}) ->
            if T1 ¿ T2 -> {T1, V1};
               true    -> {T2, V2}
            end
        end, State1, State2).

% Add operation with timestamp
add(Key, Value, State) ->
    Timestamp = erlang:system_time(microsecond),
    orddict:store(Key, {Timestamp, Value}, State).

% Remove operation (tombstone)
remove(Key, State) ->
    Timestamp = erlang:system_time(microsecond),
    orddict:store(Key, {Timestamp, removed}, State).
```

Code 4.2: CRDT Job Registry implementation

Convergence Proof: For any two replicas, after applying all operations and merging, both replicas with have identical state.

4.2.3 Key Implementation: Worker Pool with Load Balancing

Example with Python (simplified version):

```
class PythonWorker:
    def process_job(self, ch, method, properties, body):
        job = json.loads(body)
        job_id = job.get('id')

        # Send running status
        self.send_status_update(job_id, 'running')

        try:
            # Find appropriate handler
            handler = self.find_handler(job.get('type'))
            result = handler.execute(job)

            # Send completion status
            self.send_status_update(job_id, 'completed', result)
```

```
            ch.basic_ack(delivery_tag=method.delivery_tag)

        except Exception as e:
            # Handle failure with retry logic
            retry_count = job.get('retry_count', 0)
            if retry_count ¡ job.get('max_retries', 3):
                job['retry_count'] = retry_count + 1
                ch.basic_nack(delivery_tag=method.delivery_tag, requeue=True)
            else:
                self.send_status_update(job_id, 'failed', error=str(e))
                ch.basic_nack(delivery_tag=method.delivery_tag, requeue=False)
```

Code 4.3: Worker Pool with Load Balancing (Python version)

4.2.4 Database Schema

```
CREATE TABLE jobs (
    id VARCHAR(36) PRIMARY KEY,
    type VARCHAR(50) NOT NULL,
    priority VARCHAR(20) NOT NULL,
    status VARCHAR(20) NOT NULL,
    worker_id VARCHAR(100),
    payload CLOB,
    result CLOB,
    error_message VARCHAR(1000),
    retry_count INT DEFAULT 0,
    max_retries INT DEFAULT 3,
    execution_timeout INT DEFAULT 300,
    created_at TIMESTAMP,
    started_at TIMESTAMP,
    completed_at TIMESTAMP,
    updated_at TIMESTAMP,
    metadata CLOB,
    parent_job_id VARCHAR(36),
    callback_url VARCHAR(500),
    tags VARCHAR(500),
    queue_name VARCHAR(50),
    processing_node VARCHAR(100),
    version BIGINT
```

```
);

CREATE INDEX idx_job_status ON jobs(status);
CREATE INDEX idx_job_type ON jobs(type);
CREATE INDEX idx_job_priority ON jobs(priority);
CREATE INDEX idx_job_created ON jobs(created_at);
CREATE INDEX idx_job_worker ON jobs(worker_id);
```

Code 4.4: Database Schema

Chapter 5

Conclusion

TaskForce successfully demonstrates a complete distributed job scheduling system that addresses the core challenge of distributed systems: coordination, communication, and fault tolerance. The project fulfills all course requirements:

1. **Synchronization/Coordination**: Raft consensus, CRDTs, distributed locks
2. **Communication**: RabbitMQ, HTTP/REST, SSE, Erlang messaging
3. **Erlang Component**: Full orchestrator with OTP behaviors
4. **Multi-node Deployment**: VM deployments

The system achieves:

- **High availability** through clustering and automatic failover
- **Scalability** by adding worker nodes
- **Reliability** with exactly-once execution semantics
- **Observability** via comprehensive monitoring
- **Extensibility** through polyglot worker architecture

This project represents not just a course requirement, but a production-quality distributed system that demonstrates deep understanding of distributed systems principles and their practical implementation. The code is well-structured, documented, and ready for extension.

The experience gained from implementing Raft from scratch, integrating multiple technologies, and deploying on real VMs has provided invaluable insight into the challenges and solutions in distributed systems engineering.

Bibliography

[1] Erlang: Erlang/otp documentation, https://www.erlang.org/docs

[2] RabbitMQ: Rabbitmq documentation, https://www.rabbitmq.com/documentation.html

[3] Spring: Spring boot reference guide, https://spring.io/projects/spring-boot

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