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Adaptive Process Synchronization Based on System Metrics on QEMU-Emulated ARM Cortex-A57

Project Title: Adaptive Process Synchronization Based on System Metrics on QEMU-Emulated ARM Cortex-A57

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Platform: Linux (Ubuntu 22.04)

Architecture: ARM Cortex-A57 (QEMU Emulated)

Tools Used: C, POSIX Threads, QEMU, shm_open, GCC, Mutex, Shared Memory

Introduction

Modern embedded systems, especially in battery-powered devices like smartphones, IoT appliances, and industrial sensors, must operate efficiently under varying system constraints such as CPU usage, temperature, and power levels. These constraints can heavily influence the performance, longevity, and responsiveness of such systems. Effective process synchronization under these dynamic conditions becomes critical to ensure optimal system behavior without overloading any single resource.

This project titled **"Adaptive Process Synchronization Based on System Metrics on QEMU-Emulated ARM Cortex-A57"** aims to emulate such an environment using the QEMU virtualizer configured with an ARM Cortex-A57 processor and Ubuntu Linux. The ARM Cortex-A57 architecture is chosen due to its widespread use in energy-efficient and performance-critical embedded devices. By simulating system metrics such as CPU load (via `/proc/stat`), temperature, and battery level (through synthetic data), the project demonstrates how multiple processes can adapt their behavior and synchronize based on real-time system conditions.

The goal of this implementation is to provide a realistic model of how embedded software could respond in real devices, and to give developers and researchers an inexpensive and accessible platform for testing synchronization logic and inter-process coordination. Using POSIX shared memory (`shm_open`) and mutexes, processes communicate system status and adapt their execution logic accordingly.

This simulation provides a conceptual foundation for building energy-aware, thermally stable, and performance-conscious software systems, and forms a strong use case for systems engineering, embedded OS design, and low-level application development.

Motivation and Inspiration

Embedded systems today are expected to operate reliably in environments with constrained resources—whether it's limited battery power, rising internal temperatures, or fluctuating processor workloads. In real-world deployments such as smartphones, smart home devices, medical wearables, and automotive systems, software processes must intelligently adapt to these changing conditions to ensure smooth operation, safety, and efficiency.

The motivation behind this project stems from the growing need for **adaptive, resource-aware process management** in embedded and edge computing platforms. In traditional systems, processes often run on fixed schedules or priorities, regardless of current system health. This rigidity can lead to overheating, unnecessary battery drain, and degraded performance. On the other hand, by **incorporating system feedback into process behavior**, developers can significantly extend device lifespan and optimize runtime performance.

This project takes inspiration from real embedded operating systems like Android's thermal and power management frameworks, which throttle CPU frequencies and adjust service behaviors based on system temperature and battery levels. Furthermore, modern automotive ECUs (Electronic Control Units) use similar adaptive logic to regulate the execution of safety-critical and auxiliary tasks.

Given the difficulty of working directly on physical embedded devices during development and testing phases, **QEMU's virtual emulation** of ARM Cortex-A57 offers a practical and cost-effective alternative. This architecture is widely used in modern SoCs, including those in Raspberry Pi 3, NVIDIA Jetson platforms, and mobile phones, making it an ideal target for our simulation.

Ultimately, the project is driven by the idea that **process synchronization in embedded systems shouldn't be static**—it should evolve with system status. This approach not only mirrors how actual embedded software works in the field but also provides a foundation for future development in thermal- and energy-aware embedded OS design.

System Architecture

The architecture of this project simulates an **adaptive process synchronization system** designed to operate within an ARM-based embedded environment. The entire system is emulated using **QEMU** with an **ARM Cortex-A57** processor running **Ubuntu Linux**, enabling development and testing in a virtualized but realistic embedded setting.

1. Core Components

The system comprises three key threads (simulating embedded processes):

- **Battery Monitor Thread**: Simulates battery charge/discharge behavior and updates a shared memory region with the current battery percentage.
- **Temperature Monitor Thread**: Mimics a temperature sensor by incrementally adjusting a simulated CPU temperature value, also stored in shared memory.
- **Sensor-Control Thread**: Reads both battery and temperature values from shared memory and adjusts its behavior—such as work cycles, delays, or processing load—based on the metrics.

2. Shared Memory Communication

All threads share a memory segment created using **POSIX shared memory (`shm_open`)**. A global structure is defined in this region, containing:

c

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```
typedef struct {
    int battery;
    int temperature;
    pthread_mutex_t lock;
} SystemStatus;
```

This ensures that all threads read/write to a **single synchronized memory block**, enabling consistent communication.

3. Synchronization

A **POSIX mutex lock** is used to synchronize access to shared memory to avoid race conditions. Each thread locks the shared memory while reading or updating data, ensuring thread-safe operations even under concurrent access.

4. Dynamic Behavior

- When the **battery level is low**, the sensor thread reduces its activity or simulates a power-saving mode.
- When the **temperature is high**, the thread reduces processing intensity or increases delay, mimicking thermal throttling.
- Under **normal conditions**, the thread performs standard operations in real-time.

5. Execution and Emulation Layer

- The project runs entirely on a **QEMU ARM Cortex-A57** setup with a full Ubuntu OS.
- Each thread is a **POSIX-compliant program**, compiled using GCC for ARM architecture.

- The shared memory segment uses `/dev/shm`, and standard Linux IPC tools (`ipcs`, `ps`, etc.) can be used for debugging and introspection.

Implementation Details

The project simulates process synchronization in an embedded ARM system by emulating dynamic system metrics such as **battery level**, **temperature**, and **CPU utilization**, all within a **QEMU-emulated ARM Cortex-A57 environment** running Ubuntu.

Programming Environment

- **Language**: C (POSIX-compliant)
- **Platform**: Ubuntu 22.04 running on QEMU with ARM Cortex-A57
- **Compiler**: `arm-linux-gnueabihf-gcc` for cross-compilation
- **Threading**: POSIX `pthread` library
- **IPC Mechanism**: POSIX Shared Memory using `shm_open`, `mmap`, and `pthread_mutex_t`

Core Modules and Workflow

1. **Shared Memory Setup**
    - A shared memory object `/sys_status` is created using `shm_open`.
    - It contains a `SystemStatus` struct holding simulated `battery`, `temperature`, and a `pthread_mutex_t` lock.
    - `ftruncate` is used to allocate size, and `mmap` maps it to the process address space.
2. **Battery Thread**

    - Simulates battery charging/discharging using a loop with increment/decrement logic.
    - Periodically updates the battery value in shared memory while holding the mutex.

3. **Temperature Thread**
    - Simulates CPU temperature fluctuations (e.g., heating when active, cooling during idle).
    - Also writes to the shared memory under mutex protection.

4. **Sensor Thread (Adaptive Behavior)**
    - Reads both battery and temperature from shared memory.
    - Based on thresholds:
        - If temperature > 75°C → reduce workload, increase sleep time.
        - If battery < 20% → simulate low-power mode (skips cycles or performs partial work).
    - Demonstrates real-time adaptation similar to energy-efficient embedded devices.

Execution Procedure

- All three threads are launched from the `main()` function in `main.c`.
- Each thread runs in an infinite loop, simulating real-time sensors and adaptive system behavior.
- The system can be observed via log statements printed in the terminal.

Safety and Concurrency

- All shared memory accesses are synchronized using `pthread_mutex_lock()` and `pthread_mutex_unlock()`.

- The mutex is initialized with `PTHREAD_PROCESS_SHARED` attribute to allow sharing between threads.

Execution Instructions

This section provides step-by-step guidance to set up, compile, and run the project on a QEMU-emulated ARM Cortex-A57 Ubuntu environment.

Prerequisites

Ensure the following are installed on your host machine:

- **QEMU** with ARM support
  (`sudo apt install qemu qemu-system-arm`)
- **Ubuntu ARM root filesystem** inside QEMU (with development tools installed)
- **GCC cross-compiler for ARM**
  (`sudo apt install gcc-arm-linux-gnueabihf`)
- **Make** and **build-essential** packages inside guest Ubuntu

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Step 1: Transfer Project Files

Unzip the project archive on your host:

bash
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```
unzip arm_sync_project_copy.zip
```

1.
2. Start your QEMU ARM VM.
3. From your host machine, copy the project folder to the guest VM using:

SSH method (if set up):

bash
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```
scp -r arm_sync_project/ user@<guest-ip>:~/arm_sync_project
```

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- **Shared folder** (via QEMU `-virtfs`), or mount ISO image, if applicable.

🔧 Step 2: Compile the Code

1. Open a terminal inside the guest Ubuntu.

Navigate to the project directory:

bash
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```
cd ~/arm_sync_project
```

2.

Compile the code using:

bash
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```
make
```

If there's no `Makefile`, compile manually:

bash
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```
gcc -pthread -o sync_app main.c battery_thread.c temperature_thread.c
sensor_thread.c -lrt
```

3.

Step 3: Run the Program

Run the compiled binary:

bash
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```
./sync_app
```

You will see logs like:

less
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```
[Battery] Charging... Level: 41%
[Temp] Temperature rising: 63°C
[Sensor] Adaptive Mode: Reducing workload (Temp: 80°C)
```

The threads continuously simulate sensor values and adapt behavior in real-time.

Step 4: Clean Up

To clean up the shared memory object after stopping the program:

bash
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```
rm /dev/shm/sys_status
```

Or, include it in your `exit_handler()` inside the code to unlink on shutdown:

c
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```
shm_unlink("/sys_status");
```

This setup and execution flow ensures that you can simulate dynamic behavior of embedded processes on a QEMU-emulated ARM system using POSIX threads and shared memory.

Results

The successful execution of this project on a QEMU-emulated ARM Cortex-A57 environment demonstrates a functional simulation of inter-process synchronization under varying system metrics, akin to real-world embedded platforms. Key observations were gathered through detailed logging and behavioral analysis of each thread's response to simulated battery and temperature levels.

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1. Functional Behavior

- **Battery Thread:**
  Correctly simulates charging and discharging cycles from 0% to 100%, altering its direction of charge dynamically.
  Observation: Charging state triggers conditional behavior in sensor threads (e.g., reduced processing when battery is low).

- **Temperature Thread:**
  Simulates rising and falling CPU temperature in a pattern mimicking real workloads.
  Observation: The system reacts to high temperatures by reducing activity in dependent threads, showing awareness of thermal states.

- **Sensor Threads:**
  Two sensor threads react in real-time to changes in shared metrics, entering energy-saving or thermal-safe modes when appropriate.
  Observation: Threads successfully detect threshold crossings and adapt behavior, demonstrating the working synchronization logic.

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2. Synchronization & Shared Memory

- **Shared Memory:**
  The use of `shm_open` and `mmap` allowed all threads to read/write shared data safely using a `pthread_mutex_t` lock.
  Observation: No data races or segmentation faults occurred during long runs, verifying synchronization integrity.

- **Thread Safety:**
  Proper usage of mutexes ensured mutual exclusion and consistency of battery and temperature values across all threads.

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3. Platform Compatibility

- **QEMU Emulation:**
  The entire project ran reliably within a QEMU virtual machine emulating an ARM Cortex-A57 processor with Ubuntu.
  Observation: This validates that the simulation approach is portable and can be adapted for real ARM SoCs with minor changes.

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4. Performance & Stability

- The system remained stable during extended execution (~30 minutes), consistently updating and synchronizing values.
- Logging proved useful in validating state transitions and process behavior.
- No memory leaks or shared memory leaks were found due to proper cleanup on exit.

These results collectively confirm that the project meets its design goals: simulating process/thread synchronization under system-like conditions with scalability and ARM compatibility. The modular code also provides flexibility for future enhancements such as integrating real sensors or migrating to multi-core synchronization.

Learnings and Takeaways

This project offered a valuable, hands-on experience in designing and simulating a process synchronization model in an embedded-like environment using QEMU and shared memory. The key takeaways span multiple technical domains, deepening our understanding of embedded systems, operating system internals, and inter-process communication.

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1. Understanding Embedded System Behavior

By simulating battery levels and temperature in an ARM Cortex-A57 environment, we learned how real-world embedded systems adapt their process scheduling and execution strategies in response to system resource constraints. This includes throttling, energy-saving modes, and temperature-aware behavior—vital concepts in mobile and IoT device firmware.

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2. Shared Memory and Mutex Synchronization

Implementing shared memory using `shm_open()` and `mmap()` provided a practical understanding of memory sharing between threads or processes in POSIX systems. Integrating `pthread_mutex_t` further reinforced the concept of critical sections and race condition avoidance, which are essential for writing thread-safe code in concurrent applications.

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3. QEMU Virtualization and ARM Emulation

Working with QEMU and setting up a virtual ARM Cortex-A57 system helped us gain confidence in using hardware emulation tools. We explored how software can be prototyped on target architectures without physical access to actual ARM boards, making QEMU a powerful resource for embedded systems research and development.

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4. Multi-threading and Resource Awareness

Writing and managing multiple threads that respond dynamically to system metrics deepened our understanding of process/thread scheduling and responsiveness. This is especially relevant for applications in real-time systems where timing, responsiveness, and resource usage must be carefully balanced.

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5. Debugging and Code Discipline

Managing shared memory and synchronization primitives taught us the importance of clean thread exits, memory deallocation, and error handling. We also experienced how logging and modular code design can greatly enhance traceability and maintainability in complex concurrent systems.

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6. Simulated vs. Real Data Handling

Since actual system calls for battery and thermal metrics weren’t available in the emulated QEMU environment, we simulated them intelligently. This not only taught us how to design

fallback mechanisms but also how to decouple logic from data sources—making the design adaptable for real sensor input in the future.

Future Work

While this project successfully demonstrated synchronization of processes based on simulated system metrics such as battery level and temperature in a QEMU-emulated ARM Cortex-A57 environment, it also opened up several avenues for further enhancement and real-world application. The following directions outline key improvements and extensions that can make the system more robust, realistic, and scalable:

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1. Integration with Real Hardware Sensors

The current simulation uses dummy data to represent battery and temperature values due to limitations of the virtual environment. As future work, this system could be ported to an actual ARM-based development board like Raspberry Pi 4 or BeagleBone Black, using GPIO and I2C interfaces to connect real sensors for live temperature and battery monitoring. This would bring the simulation closer to deployment-ready firmware for embedded applications.

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2. Dynamic Power and Thermal Management Policies

The current implementation uses simple thresholds to control thread synchronization and process execution. More complex and realistic power management strategies—such as Dynamic Voltage and Frequency Scaling (DVFS), task migration, or thermal throttling—can be introduced to mimic how mobile operating systems manage performance under constrained conditions.

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3. Multi-Process Architecture with IPC Mechanisms

Although this project uses threads and shared memory, an extension to fully independent processes using advanced inter-process communication (IPC) like message queues or sockets would better simulate microservice-like designs found in modern embedded and RTOS (Real-Time Operating System) applications.

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4. Visualization Dashboard

Adding a web-based or terminal-based dashboard to visualize the current system state (battery, temperature, thread status, etc.) in real time can greatly enhance the usability and debugging of the system. This can be implemented using lightweight frameworks like Flask for web or ncurses for terminal UI.

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5. AI-based Predictive Scheduling

A long-term enhancement could be incorporating a machine learning model that predicts upcoming system load or thermal spikes based on past patterns, adjusting thread behavior proactively. This would showcase how AI can be embedded in low-power devices to make intelligent scheduling decisions.

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6. System Call Hooking for Realistic Emulation

With more in-depth QEMU customization, it's possible to simulate sensor inputs by intercepting system calls and injecting realistic values. This would allow for testing the same code without modifying the underlying logic, ensuring portability across emulated and real systems.

Conclusion

This project successfully demonstrated the design and implementation of an adaptive process synchronization mechanism in an emulated embedded environment using QEMU with an ARM Cortex-A57 CPU. By simulating key system metrics—namely battery level, temperature, and CPU usage—the system showcased how embedded applications can dynamically adapt to changing runtime conditions. Through the use of POSIX threads, shared memory (via `shm_open`), and mutex synchronization, multiple concurrent processes were controlled in a coordinated manner based on the system's simulated health and performance states.

A core strength of this project lies in its practical emulation of real-world embedded behavior, where power constraints and thermal limitations directly influence system scheduling. The emulated setup not only mirrors many characteristics of real ARM devices but also enables experimentation and learning without the need for physical hardware. The modularity and extensibility of the implementation make it a strong foundation for further development in both academic and industrial contexts.

This work emphasizes the importance of resource-aware system design in embedded environments, particularly where real-time performance and reliability are critical. From implementing shared memory structures to designing a thread scheduling policy based on live

(simulated) metrics, every component of the project reinforces foundational concepts in systems programming, embedded design, and synchronization.

Ultimately, this project served as a hands-on exploration of how embedded systems must respond to environmental constraints, and how such systems can be prototyped and tested effectively in a virtualized environment. The knowledge gained through this endeavor lays a solid groundwork for tackling more complex challenges in embedded computing, real-time operating systems, and intelligent resource management.

References

- QEMU Official Documentation: https://www.qemu.org
- ARM Cortex-A57 Technical Reference Manual
- Linux `man` pages: shm_open, mmap, pthread_mutex
- Embedded Systems Literature on Dynamic Scheduling and Thermal Management