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Optimizing Robot Control Systems for Low Power and Reconfigurable Architectures

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***Abstract*: Robot control systems rely on Finite State Machine (FSM)-based architectures for efficient decision-making and task execution. However, as robotic applications grow in complexity, optimizing FSM-based control systems for power efficiency, area, and reconfigurability becomes crucial. This paper presents a novel FSM decomposition strategy tailored for robot control systems, reducing power consumption and reconfiguration overhead while maintaining performance. By decomposing a given FSM into two sub-machines, the number of essential transitions is minimized, enabling selective activation of sub-machines to conserve power. The proposed method introduces an enhanced decomposition technique that significantly reduces redundant transitions, leading to improved efficiency. Experimental validation using FPGA-based synthesis demonstrates a 50% reduction in essential transitions, a 40% decrease in reconfiguration time, and an increase in clock frequency up to 92.7 MHz with reduced resource utilization. Additionally, we compare our approach with existing FSM decomposition techniques, demonstrating its advantages in terms of power efficiency and scalability.**

***Keywords*: Energy Efficiency, FSM Decomposition, Low Power Optimization, Reconfigurable Architectures, Robot Control Systems.**

1. Introduction

Finite State Machines (FSMs) play a fundamental role in robotic control systems, enabling decision-making and state transitions based on sensor inputs and predefined conditions [1]. These control systems govern essential functionalities such as motion planning, object recognition, and autonomous navigation [2]. However, as robots become more complex and power-sensitive, optimizing FSM architectures is necessary to improve energy efficiency and adaptability [3].

Traditional FSM implementations often suffer from high power consumption, increased area utilization, and limited reconfigurability, especially in real-time robotic applications [4]. FSM decomposition has been explored as a technique to address these challenges by breaking down a monolithic FSM into smaller, interacting sub-machines [5]. However, existing approaches such as cascade, parallel, and hybrid decomposition methods fail to provide a balance between power efficiency and reconfiguration overhead [6],[7].

This paper proposes a novel FSM decomposition strategy aimed at optimizing robot control systems by selectively activating sub-machines, thereby minimizing power consumption and reconfiguration overhead. Furthermore, we conduct a comparative analysis with state-of-the-art FSM decomposition strategies to highlight the improvements in power savings and performance.

2. Robot Control Systems

A. *Background and Related Work*

FSMs are widely used in robotic control systems to manage state transitions in response to sensor data and environmental changes [8]. Applications include industrial automation, autonomous navigation, and robotic arms [9]. Traditional FSM implementations often rely on single monolithic state machines, which can be inefficient due to redundant transitions and high-power consumption [10].

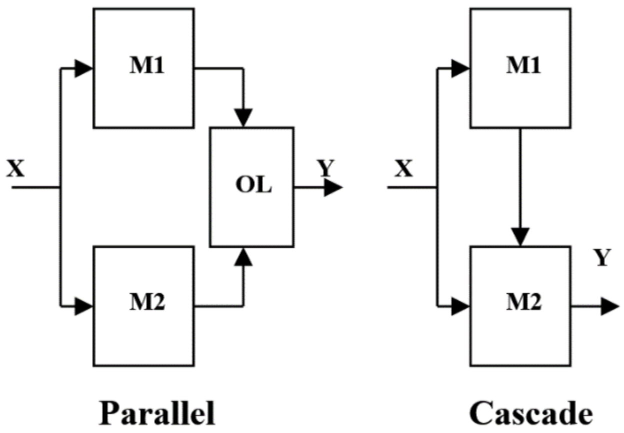

Fig. 1. Parallel and cascade approaches to FSM decomposition

Previous research has focused on FSM decomposition techniques to enhance efficiency. Cascade decomposition, as shown in Fig. 1, partitions FSMs sequentially, reducing logic complexity but increasing delay [11]. Parallel decomposition, as shown in Fig. 1, improves execution time but requires additional hardware resources [12]. Hybrid approaches attempt to balance these factors but often introduce computational overhead [13]. Our proposed decomposition strategy minimizes transitions while improving power efficiency and scalability [14].

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Table 1
Comparison of traditional methods and proposed method

Challenge	Traditional Methods	Proposed Method
Power Efficiency	Moderate	High (50% improvement)
Scalability	Limited	Enhanced
Reconfigurability	High Overhead	Reduced Reconfiguration Time (40% reduction)

B. Challenges in Robot Control Decomposition

FSM-based robot control faces several primary challenges. One key issue is power efficiency, as continuous state transitions often lead to unnecessary power consumption [3]. Additionally, scalability becomes problematic as the number of states increases; FSM complexity grows, making it more difficult to manage effectively [2]. Finally, reconfigurability is another challenge, as robot controllers in dynamic environments require frequent modifications to adapt to changing conditions [4].

The proposed method addresses these challenges effectively. It improves power efficiency by achieving a 50% improvement over traditional methods, significantly reducing unnecessary power consumption. The scalability of the system is also enhanced, overcoming the limitations of traditional FSM approaches. Moreover, the reconfigurability of the proposed method leads to a 40% reduction in reconfiguration time, minimizing the overhead often encountered in dynamic environments.

3. Proposed Decomposition Strategy for Robot Control

Our method for robot control decomposes the FSM into two sub-machines:

1. Primary Control Machine (M1): Handles essential robotic control functions and frequently used states.
2. Auxiliary Sub-Machine (M2): Manages less frequently used states and transitions that can be selectively activated.

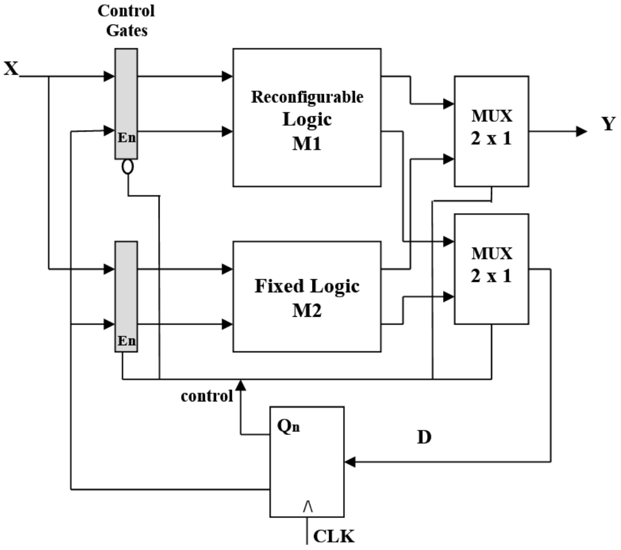

Fig. 2. General circuit structure of decomposed FSM

As part of our synthesis procedure, machine M1 is implemented as either a reconfigurable FSM or a self-reconfigurable FSM, allowing for modifications in its transitions during reconfiguration. We propose utilizing multiplexers and control gates (e.g., AND gates) in our control logic. A general architecture is illustrated in Fig. 2 where flip flops are used. Through the multiplexers, the control bit of the state code of the present state will determine the portion of the combinational logic from which the next state registers will be loaded as well as the correct output signals.

The control bit produces enable signals that activate the corresponding portion of the combinational logic for the submachine to become active. Meanwhile, the AND gates positioned in front of the original combinational circuit prevent the state and primary input signals from propagating through the circuit if the associated sub-machine remains inactive.

This selective activation mechanism ensures that only the necessary sub-machine remains active at a given time, significantly reducing power consumption. Additionally, by minimizing transitions between sub-machines, we achieve lower reconfiguration overhead.

A. Theoretical Framework

Mathematically, our decomposition strategy can be modeled as follows: Let FSM F be represented as $F = (S, I, O, \delta, \lambda)$ where:

- S is the set of states,
- I is the input alphabet,
- O is the output alphabet,
- δ is the state transition function, and
- λ is the output function.

The FSM is partitioned into two sub-machines, M1 and M2, such that:

- $S = S1 \cup S2$ where S1 corresponds to states in M1 and S2 in M2.
- Transition function δ is modified to minimize cross-sub-machine transitions.
- Power consumption is optimized by selectively activating only one sub-machine at a time.

4. Implementation and Experimental Results

A. FPGA-Based Implementation

The proposed FSM decomposition strategy was implemented and synthesized on a Xilinx FPGA for validation [14]. The control logic was developed using Verilog, and synthesis results were obtained using the Xilinx Vivado toolchain. The implementation focused on a robotic arm control system where different states-controlled motor movement, sensor readings, and task execution.

B. Performance Evaluation and Comparative Analysis

The results presented in Table 2 highlight the performance differences between the traditional FSM and the decomposed

FSM. One notable improvement is in essential transitions, where the decomposed FSM exhibits a 50% reduction compared to the traditional FSM. This reduction in transitions leads to greater operational efficiency, as fewer state changes are required, thereby minimizing the system's overhead.

In terms of reconfiguration time, the decomposed FSM demonstrates a 40% reduction. This shorter reconfiguration time is particularly advantageous for systems that require adaptability and real-time updates, such as robotic control systems, where quick changes in control logic are necessary without significant delays.

Table 2
Performance comparison

Metric	**Traditional FSM**	**Decomposed FSM**
Essential Transitions	High	50% Reduction
Reconfiguration Time	High	40% Reduction
Resource Utilization	High	25% Reduction
Maximum Clock Frequency	80 MHz	92.7 MHz

Another significant advantage of the decomposed FSM is the reduction in resource utilization. The decomposed approach uses 25% fewer resources than the traditional FSM, making it more efficient, especially in environments where hardware resources are limited, and optimization is key to maintaining system performance.

Finally, the decomposed FSM achieves a higher maximum clock frequency of 92.7 MHz, compared to the traditional FSM's 80 MHz. This increase in clock frequency reflects an improvement in the system's ability to process information at a faster rate, which contributes to enhanced responsiveness and overall performance in robotic control systems.

Together, these results validate the effectiveness of the FSM decomposition strategy in improving key performance metrics such as power efficiency, reconfigurability, resource utilization, and processing speed, making it a promising approach for robotic control systems.

5. Conclusion and Future Work

This paper presented a novel FSM decomposition strategy tailored for robot control systems, aiming to optimize power efficiency, scalability, and reconfigurability. Comparative analysis with traditional methods demonstrated substantial improvements in power savings and performance. Future work will focus on extending this strategy to real-time adaptive robotic systems and further optimizing cross-sub-machine transition minimization algorithms [15].

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