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HYBRID CONTROL METHOD FOR AUTONOMOUS MOBILE ROBOTS IN MANUFACTURING LOGISTICS SYSTEMS: INTEGRATING CENTRALIZED CONTROL AND DECENTRALIZED CONTROL

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ABSTRACT

In this paper, we investigate the optimization of operational policies for Autonomous Mobile Robots (AMR) in Automated Material Handling Systems (AMHS). We propose a hybrid control method combining centralized control with decentralized control for dynamic response to real-time operational events. The approach enables individual AMRs to make decentralized routing decisions during congestion by utilizing local traffic information. Three key factors influencing decentralized routing decision are identified through rule-based policies. Considering those factors, we optimize which AMRs should operate under decentralized control based on spatial and task conditions. The efficiency of the proposed method was verified using Siemens Tecnomatix Plant Simulation (version 2404) simulation software.

1 INTRODUCTION

Automated Material Handling Systems (AMHS), particularly Autonomous Mobile Robots (AMR), have become essential components of modern smart factories. AMR systems can be operated under two control paradigms. Central control employs predefined paths with supervision of central system. Decentralized Control enables individual AMRs to navigate autonomously based on real-time motion planning. Manufacturing site predominantly utilize centralized control due to strict stability requirements and spatial constraints in factory layouts. Particularly in semiconductor and battery production, manufacturing processes often involve transporting vibration-sensitive materials. Previous studies have also demonstrated that autonomous navigation in confined spaces leads to traffic congestion which results in decrease of the efficiency of logistics system. However, exclusive reliance on centralized control with static route planning cannot adequately address dynamic congestion scenarios.

This research proposes a hybrid control that integrates two control paradigms to address these challenges. It maintains the stability of centralized control while incorporating the adaptability of decentralized control.

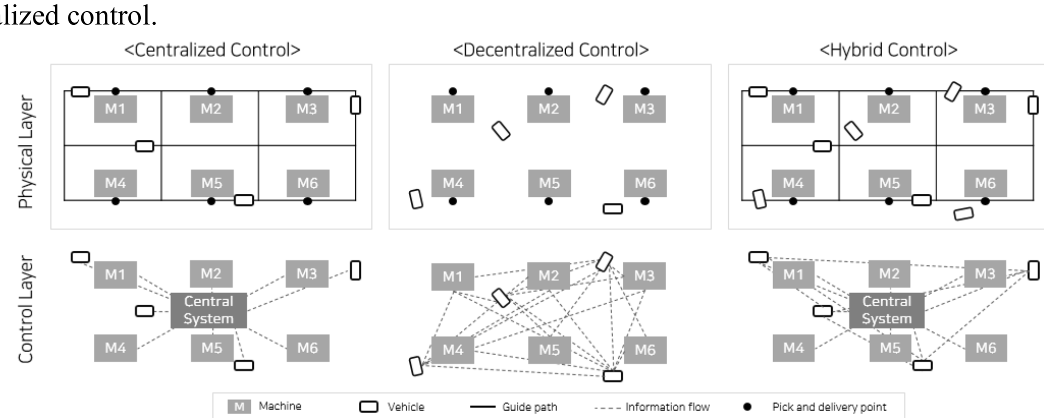

Figure 1: Centralized Control, Decentralized Control, and Hybrid Control.

2 ANALYSIS OF KEY FACTORS FOR DECENTRALIZED CONTROL

The effectiveness of decentralized control in AMR systems is significantly influenced by various operational and environmental factors. This section identifies and analyzes three key factors that critically impact the performance of decentralized routing decisions. The proposed factors include task status of blocking vehicles (f1), traffic conditions of adjacent segments (f2), and interference between planned routes (f3). Bypass strategy has been introduced by allowing blocked vehicles to bypass blocking vehicles which are in loading or unloading operations, with performance evaluated using average delivery time (ADT) and utilization.

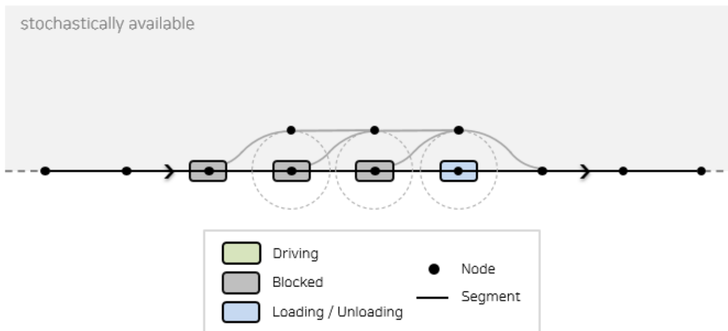

Figure 2: AMR Bypass Strategy.

We tested three individual factor-based policies and hybrid policies that combine pairs of these individual approaches against two baseline policies: Always Wait (b1) and Always Bypass (b2). The experiments were conducted in an AMR system with 60 vehicles, approximately 900 nodes, and 30 ports. The experimental result demonstrates that minimizing immediate delay is crucial for minimizing congestion, while considering future events can significantly enhance bypass effectiveness. Also, impact of bypass varies according to vehicle task type, depending on whether vehicles are idle or engaged in urgent tasks.

Table 1: Performance Comparison of factor-based policies and baseline policies.

Policy	**b1**	**b2**	**f1**	**f2**	**f3**	**f1 + f2**	**f1 + f3**	**f1 + f2 + f3**
ADT (sec.)	378.85	311.28	309.92	308.92	310.24	310.24	308.37	306.85
Utilization (%)	97.40	80.19	78.99	79.53	79.89	79.82	79.39	78.99

3 HYBRID CONTROL OPTIMIZATION CONSIDERING SPATIAL AND TASK CONDITIONS

Based on three identified factors, we aimed to optimize the hybrid control of AMRs. The problem was addressed through two phases. First, the maximum capacity of AMRs that can operate under decentralized control without causing additional congestion, considering spatial characteristics has been analyzed. Second phase determines which AMRs should transition to decentralized control to maximize machine utilization and system throughput considering each vehicle's task characteristics. This two-phase decision framework enables dynamic adaption to system conditions.

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