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Dual-Robot Collaborative Automated Sterile Pack Storage System for the Central Sterile Supply Department: Design and Performance Validation

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ABSTRACT: Objective This study aimed to address the low efficiency of sterile item storage management in the Central Sterile Supply Department (CSSD) and to construct and validate the actual performance of a dual-robot collaborative scheduling system. **Methods** A system integrating automated storage equipment and an intelligent scheduling algorithm was developed. A randomized controlled experiment was conducted to compare the time consumed to complete outbound and inbound tasks between a single-robot mode and a dual-robot mode. **Results** The dual-robot collaborative strategy significantly improved operational efficiency. Under the single inbound port configuration, outbound efficiency increased by 21.8% and inbound efficiency by 10.1%. Under the dual inbound port configuration, inbound efficiency rose by as much as 43.5%. The inbound/outbound port was identified as a critical bottleneck affecting system performance. **Conclusion** Dual-robot collaborative scheduling effectively enhances storage efficiency when combined with the optimization of key nodes, and has the potential for widespread adoption in similar hospital settings.

KEY WORDS: Central Sterile Supply Department; Sterile pack management; Intelligent warehousing; Robot; Collaborative scheduling

The management of sterile items in the Central Sterile Supply Department (CSSD) plays a critical role in ensuring medical safety and improving operating room turnover efficiency. Traditional manual management models are characterized by low efficiency, high error rates, and difficulties in expiration date management, which make it challenging to meet the demands of high-quality development in modern hospitals. Consequently, CSSDs are actively introducing automation and intelligent technologies to achieve breakthroughs.

Existing research on automation and intelligence in this field has primarily focused on cross-departmental vertical transport systems connecting the CSSD and the operating room. Studies by both domestic and international scholars, including JIN et al., WU et al., and ZHOU et al., have demonstrated that such “operating room-CSSD integrated” vertical warehouses significantly save space and improve item transport efficiency[1]. However, these large-scale vertical storage solutions demand specific building structures (e.g., utilizing elevator shafts), incur high implementation costs, involve extensive engineering work, offer limited post-installation flexibility[2], and are highly integrated; therefore, a single failure can disrupt the entire supply chain[3]. More critically, most existing research has concentrated on automating the “end-to-end” logistics between the CSSD and the operating room, namely, the cross-departmental transport of sterile items from the supply end to the point of use, while paying insufficient attention to the intelligent and refined management of the CSSD’s internal sterile storage area. Particularly, in-depth research is lacking in areas such as sterile pack storage optimization, high-frequency inventory counting, and dynamic scheduling[4].

Robotic technologies used in intelligent warehousing, particularly “goods-to-person” lifting robotic systems, have demonstrated excellent flexibility, scalability, and ease of deployment in e-commerce and manufacturing logistics[5]. This technology offers a flexible "system-as-a-warehouse" solution without the need for extensive civil engineering. Through robot collaborative scheduling, it achieves high-density storage and efficient picking, presenting a new pathway for upgrading internal CSSD storage[6]. However, the application of such "goods-to-person" robotic systems to medical scenarios that demand extremely high standards of sterility safety, real-time task response, and traceability still lacks rigorous empirical research regarding their feasibility, stability, and efficiency gains[7]. This study fills this gap by designing a dual-robot collaborative automated sterile pack storage system for the CSSD. A typical configuration of a lifting robotic system is shown in Figure 1.

Figure 1 Schematic diagram of a lifting robotic system

In this study, a multi-robot collaborative warehousing system was designed and implemented for the internal sterile storage area of the CSSD. Unlike large vertical warehouses that rely on fixed shafts, this solution employs a cluster of freely mobile warehousing robots to achieve highly compact storage of sterile packs, fully automated retrieval and storage, and accurate inventory counting within a limited space. Figure 2 presents the layout of the multi-robot collaborative warehousing system in the CSSD sterile storage area, to visually illustrate the system configuration and operational scenarios. The core innovations and contributions of this study are as follows: the first systematic application of a multi-robot "goods-to-person" solution to the refined management of internal CSSD sterile packs; the design and comparison of single- versus dual-robot scheduling modes, including quantitative analysis of their performance differences through controlled experiments (operational characteristics and differences are shown in Table 1); and the achievement of closed-loop automation for the entire process from receiving to dispatch, thereby providing a replicable technical pathway for the flexible upgrade of internal CSSD storage in hospitals.

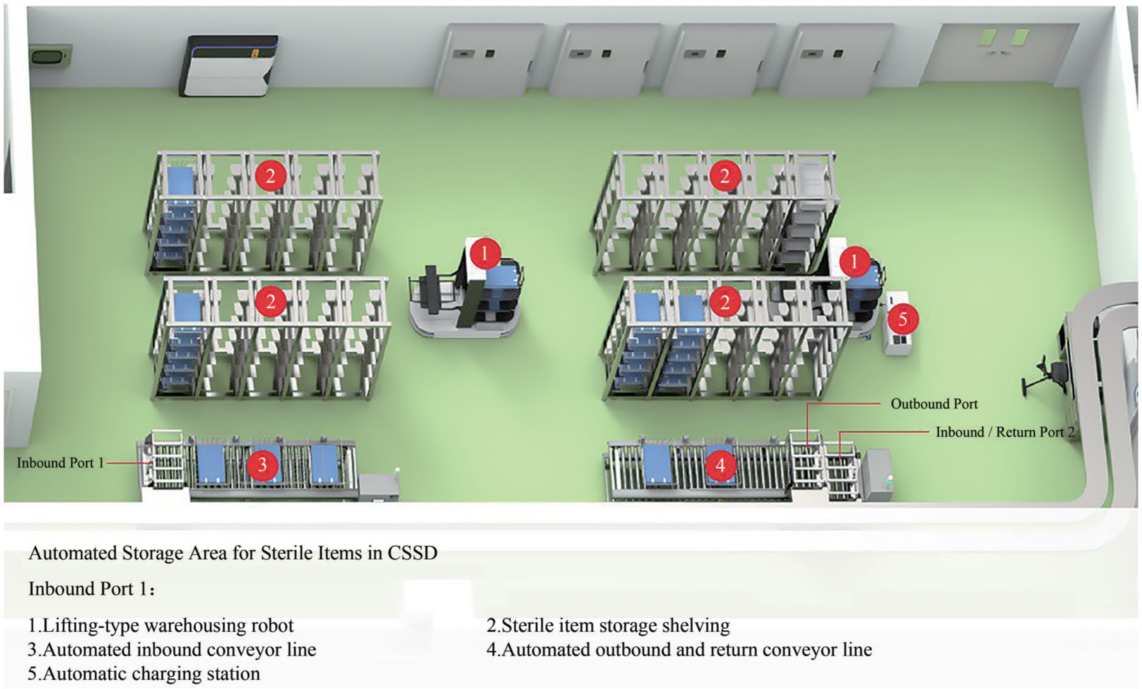

Figure 2 Layout diagram of the multi-robot collaborative warehousing system in CSSD sterile storage area

Table 1 Comparison of single-robot and dual-robot scheduling modes

Comparison Dimension	Scheme A: Single-Robot Mode	Scheme B: Dual-Robot Collaborative Mode
Number of robots	1 unit	2 units
Operation mode	Serial operations	Parallel operations
Task assignment	All tasks executed sequentially by a single robot	Scheduling system dynamically assigns tasks based on task status and robot positions
Path planning	Single-robot independent path planning	Multi-robot path planning with cooperative collision avoidance
Path conflicts	No inter-robot conflicts	Potential path intersections or meeting points
Resource contention	No inter-robot resource contention	Potential waiting at inbound port, outbound port, or meeting points
Scheduling complexity	Low	High
Efficiency characteristics	Stable but limited parallel capacity	System throughput improved through task parallelism

Based on the work described above, this study aims to demonstrate the advanced capabilities, feasibility, and high efficiency of a multi-robot-based warehousing solution for CSSD's internal management, thereby offering a more flexible and cost-effective approach for automating hospital storage logistics.

1 System Design and Experimental Methods

1.1 System composition

This system was designed to achieve automated storage management of sterile items within the CSSD. Its core architecture integrates hardware, software, and site layout in a coherent manner.

1.1.1 Hardware system

The hardware system constitutes the physical foundation of the solution and includes the following components. (1) Execution units: two Honjo lifting-type warehousing robots, equipped with QR code navigation and dynamic obstacle avoidance, are responsible for item transport. (2) Storage and infrastructure: stainless steel shelving forms a high-density storage area; one automatic charging station ensures continuous operation; automated inbound, outbound, and return conveying lines enable automatic connection with the sterilization area and dispatch window. (3) Standardized carriers and identification: ISO standard sterilization baskets with corresponding QR code identification plates serve as item units; a handheld PDA is used for rapid information binding and verification.

1.1.2 Software system

The software system serves as the control core and adopts a three-layer architecture. (1) Scheduling control layer (Fleet Management System, FMS): this layer is responsible for real-time task assignment, path planning, and collaborative scheduling for the two robots, ensuring efficient and conflict-free operation. (2) Business management layer (Honjo Intelligent Warehouse Management System, iWMS): this layer handles core warehousing logic, including location management, inventory management, and expiration date tracking, and generates operation instructions. (3) Interaction and integration layer (Honjo RoMAI Intelligent CSSD Operating System): this layer provides a user interface, connects with the Hospital Information System (HIS), and enables task issuance and full-process monitoring.

1.1.3 Site layout

The system layout follows the internal logistics flow of the CSSD, thereby forming a closed loop. Sterilized packs enter the system via the inbound line and are stored on shelves by the robots. The robots retrieve the packs and deliver them to the outbound line when a requisition order is triggered. Empty baskets are returned via the return line. The two robots share the operational space within this layout.

1.2 Experimental design

To quantitatively evaluate the efficiency advantages of dual-robot collaborative scheduling, this study designed separate rigorous comparative experiments for outbound and inbound operations.

1.2.1 Experimental protocol

A paired block randomized sequential design was adopted, consisting of the following elements.

(1) Task unit: one experimental unit was defined as the complete process of either outbound or inbound operations for a fixed batch of different types of instrument packs (8 or 10 packs). The batch of instrument packs and their corresponding target locations (outbound picking points or inbound storage locations) were kept constant across all experiments. (2) Scheme comparison: each task unit was executed under two modes. In Scheme A (single-robot mode), a single robot independently completed all tasks in the unit. In Scheme B (dual-robot mode), two robots collaboratively completed all tasks in the same unit. (3) Inbound port configuration: for inbound operations, two scenarios were defined: a single inbound port and dual inbound ports. In the single-port scenario, both robots shared the same inbound point, which could lead to resource waiting (see Figure 3 for an operational schematic). In the dual-port scenario, robots received sterile packs through two parallel inbound points, reducing queue waiting at the inbound end and allowing verification of the impact of parallel entry configurations on collaborative efficiency (see Figure 4 for an operational schematic). (4) Sequence and control: the execution order of Scheme A and Scheme B within each unit was randomized (either AB or BA). The experiment completed 44 or more valid units. All experiments were conducted using the same map, speed limits, and scheduling rules to ensure that only the independent variable differed.

1.2.2 Evaluation metrics

The primary outcome measure was task completion time, which is defined as the total time from the start of the first task to the completion of the last task. A secondary measure was resource waiting time. All data were automatically collected by the back-end system of the robot scheduler.

Figure 3 Schematic diagram of dual-robot operation during inbound tasks under a single inbound port configuration

Figure 4 Schematic diagram of dual-robot operation during inbound tasks under a dual inbound port configuration

1.3 Statistical analysis

SPSS version 19.0 was used for statistical analysis. Measurement data (e.g., task completion time) are reported as means. A paired-samples t-test was performed to compare Scheme A and Scheme B. Count data are presented as percentages (%). A p-value of less than 0.05 was considered statistically significant.

2 Results and Analysis

This study compared the performance of the single-robot (Scheme A) and dual-robot collaborative (Scheme B) modes in outbound and inbound operations, with a quantitative analysis of system operational efficiency. A total of 44 valid task units were completed, comprising 22 outbound and 22 inbound task units. The results of the data analysis are presented below.

2.1 Outbound operation efficiency

Outbound operations simulated the key process of sorting items according to orders from the iWMS and then transporting them to the outbound conveyor line. Data from 22 outbound task units (including 19 tasks with 8 packs and 3 tasks with 10 packs) were analyzed, and the results are presented in Table 2.

Table 2 Comparison of outbound operation efficiency between single and dual-robot modes under different task volumes

Indicator	Eight-pack task group (N=19)	Ten-pack task group (N=3)
Single-robot average duration (s)	385. 6 s	513. 7 s
Dual-robot average duration (s)	301. 4 s	388. 3 s
Average time saved (s)	84. 2 s	125. 3 s
Standard deviation of difference (s)	12. 6 s	13. 0 s
Average improvement rate (%)	21. 8%	24. 4%
T-value	29. 2	16. 7
P-value	<0. 000 1	<0. 005
Dual-robot resource waiting proportion	32. 0%	39. 4%

2.1.1 Core efficiency

As shown in Table 2, the dual-robot collaborative mode demonstrated highly significant efficiency benefits under both task volumes. In the 8-pack task group, the average operation time of the dual-robot mode was 301.4 seconds, representing a saving of 84.2 seconds compared to 385.6 seconds for the single-robot mode, which corresponds to a 21.8% efficiency improvement. The paired-samples t-test confirmed that this difference was highly statistically significant (t=29.2, p<0.000 1). Notably, the standard deviation of the time saved was relatively small (12.6 seconds), indicating that the efficiency gain from the dual-robot collaborative strategy is stable and reproducible rather than a random fluctuation.

In the 10-pack task group, the efficiency advantage of the dual-robot mode was even more pronounced despite the smaller sample size. The dual-robot mode averaged 388.3 seconds, saving 125.3 seconds compared to 513.7 seconds for the single-robot mode, with an improvement rate of 24.4%. The statistical test remained significant (t=16.7, p<0.005). This result preliminarily suggests that as task complexity increases (i.e., with more packs), the efficiency gain from dual-robot collaboration may become more substantial. The increased task volume results in a longer traversal path for a single robot, accentuating its “single-point bottleneck” effect, whereas the dual-robot configuration shares the workload more effectively through task parallelism, thereby achieving a greater relative advantage.

2.1.2 Mechanism analysis

The core mechanism underlying the efficiency improvement is task parallelization and path optimization achieved through dual-robot collaboration. In the single-robot mode, all outbound tasks must be completed serially by one robot, and its path is predetermined and cannot be shortened. In the dual-robot mode, FMS intelligently and dynamically assigns tasks from the task pool to both robots, allowing them to travel simultaneously to different shelf locations for picking and then proceed to the workstation in parallel for unloading, thereby transforming a lengthy serial process into an efficient parallel one.

A key observation concerns resource waiting time. In the dual-robot mode, one robot may wait for the other to finish unloading because both robots alternately arrive at the workstation. This waiting accounted for an average of 32.0% and 39.4% of the total dual-robot operation time, revealing a potential system bottleneck. Despite this waiting time, the overall efficiency of the dual-robot mode still far exceeded that of the single-robot mode, demonstrating that the benefits of parallel task execution far outweigh the cost of collaborative waiting at the terminal unloading point. Future optimization could focus on workstation design (e.g., setting up dual unloading stations) or on optimizing the unloading process to further reduce this waiting proportion and unlock greater potential.

In summary, the statistical analysis strongly supports the advantages of the dual-robot collaborative scheduling strategy in outbound operations. Not only does this strategy significantly reduce task completion time, improving efficiency by more than 20%, but it also suggests that this advantage may become even more pronounced with increased task volume. These findings provide solid data support and a theoretical basis for employing multi-robot collaboration in intelligent warehousing systems to meet high-throughput and high-timeliness demands.

2.2 Inbound operation efficiency

Inbound operations are a core component of intelligent warehousing and directly affect overall system capacity. Based on detailed experimental data, this section analyzes the performance of single- versus dual-robot collaborative strategies in inbound operations from three perspectives: core efficiency, system bottlenecks, and the impact of task size. Data are categorized by task pack size and inbound port configuration, with the primary comparisons presented in Table 3.

2.2.1 Core efficiency

Under all tested configurations, the dual-robot collaborative strategy demonstrated statistically significant advantages over the single-robot mode, further confirming the universal benefit of collaborative operation for enhancing warehousing system efficiency.

In the more challenging scenario of a single inbound port with 8-pack tasks, the dual-robot mode still achieved a 10.1% efficiency gain, saving 39.3 seconds. This demonstrates that even in light-task environments where resource competition is most unfavorable to collaborative synergy, parallel scheduling alone still yields a positive return.

In the optimized configuration with dual inbound ports, the efficiency improvement reached 43.5%, saving 171.7 seconds. This illustrates the higher performance ceiling achievable by the dual-robot collaborative system after the key bottleneck is removed.

In the higher-load scenario of a single inbound port with 10-pack tasks, efficiency improved by 22.2%, saving 116.3 seconds. This reflects that as the task base size increases, the absolute time benefit of the collaborative strategy becomes more substantial.

Dual-robot collaboration is a practical means of improving inbound operation efficiency, and its advantage appears to be universal, not constrained by specific configurations.

2.2.2 Key bottleneck analysis

A core finding of this experiment is that the inbound port, as a shared resource, constitutes a critical bottleneck restricting system performance.

For the dual inbound port / 8-pack task group, the resource waiting proportion was zero; the system achieved an ideal, conflict-free, fully parallel operational state. In all experiments with a single inbound port, resource waiting was clearly observed, representing time lost when robots queued to use the sole inbound port.

In the single inbound port / 8-pack task, resource waiting accounted for an average of 14.2% of the total dual-robot operation time. This means that in the single inbound port configuration, over one-seventh of the system's time was wasted on resource contention rather than productive work, di-

Table 3 Comparative analysis of inbound operation efficiency under different task volumes and inbound port configurations

Indicator	Single Inbound Port - Eight-pack Task (*N*=13)	Dual Inbound Ports - Eight-pack Task (*N*=7)	Single Inbound Port - Ten-pack Task (*N*=3)
A. Core efficiency: Single-robot vs. dual-robot			
Single-robot average duration (s)	387. 3 s	394. 9 s	524. 7 s
Dual-robot average duration (s)	348. 0 s	223. 1 s	408. 3 s
Average time saved (s)	39. 25 s	171. 7 s	116. 3 s
Standard deviation of difference (s)	13. 1 s	14. 4 s	11. 9 s
B. Efficiency improvement rate			
Average improvement rate (%)	10. 1%	43. 5%	22. 2%
T-value	10. 4	31. 6	16. 9
P-value	<0. 000 1	<0. 000 1	<0. 000 1
C. Key bottleneck: Waiting time analysis (dual-robot mode)			
Dual-robot resource waiting proportion	14. 2%	0	15. 7%

rectly explaining why the efficiency improvement was much lower than in the dual inbound port scenario.

Solution validation: adding an inbound port (i.e., switching to dual inbound ports) fundamentally eliminates resource contention, reducing resource waiting to zero and fully unleashing the potential of collaborative efficiency. The 43.5% efficiency improvement in the dual inbound port scenario validates the powerful effect of combining process optimization (collaborative scheduling) with a hardware upgrade (parallel entry points).

Intelligent warehousing system design must ensure that the parallel processing capacity of critical operational nodes (such as inbound ports) matches the number of robots; otherwise, resource competition will cause severe internal friction, drastically reducing system performance.

2.2.3 Impact of task size

Analyzing the effect of increasing the task size from 8 packs to 10 packs under the fixed constraint of a single inbound port bottleneck reveals dynamic changes in system behavior. The total dual-robot time for the 10-pack task (408.3 s) was 60.3 seconds longer than that for the 8-pack task (348.0 s), which is an expected increase. During execution of the 10-pack task, the resource waiting proportion rose to 15.7%, suggesting that the increased task load intensified competition for the bottleneck resource (the inbound port), leading to higher waiting-related losses and further degradation of system performance.

In a system with a primary bottleneck such as a single inbound port, increasing the task load both prolongs the total operation time and exacerbates contention for the bottleneck resource, resulting in greater efficiency loss.

Through detailed comparative experiments, this study not only quantitatively verified the universal advantage of dual-robot collaboration in inbound operations but also, for the first time, precisely identified and quantified the inbound port as a key performance bottleneck, demonstrating that adding parallel inbound ports is a highly effective solution. It also revealed the pattern by which task size expansion intensifies the bottleneck effect. These conclusions provide reliable data support and theoretical guidance for the architecture design, resource allocation, and capacity planning of intelligent warehousing systems.

3 Conclusion and Future Outlook

3.1 Research conclusions

Through rigorously designed controlled experiments, this study systematically investigated the efficiency gains and key constraints of robot collaborative strategies in intelligent warehousing systems. The main conclusions are as follows.

3.1.1 Universal advantage of collaborative operation

Across different task sizes (8-pack and 10-pack) and different system configurations (single vs. dual inbound ports), the dual-robot collaborative mode significantly accelerated task completion and improved operational efficiency compared to the single-robot mode. This advantage was statistically significant, thereby empirically confirming that adopting multi-robot collaborative scheduling in intelligent warehousing systems is an effective strategy for enhancing overall throughput efficiency.

3.1.2 Key performance bottleneck identification

A key finding of this study is that the inbound port, as a shared resource, constitutes a critical bottleneck limiting the performance of multi-robot systems. Experimental data clearly showed that under the single inbound port configuration, the dual-robot system experienced resource waiting due to contention, which accounted for 14.2% to 15.7% of the total operation time and effectively constrained the realization of collaborative efficiency. This conclusion shifts the focus of system optimization from purely algorithmic scheduling to the synergistic optimization of hardware resource allocation and process design.

3.1.3 Role of hardware configuration in collaborative potential

When the inbound port configuration was upgraded from a single port to dual ports, resource contention was eliminated, and the efficiency improvement of dual-robot collaboration increased from 10.1% to 43.5%. This finding conclusively demonstrates that optimized hardware resource configurations (e.g., parallelized processing nodes) are a prerequisite for fully unlocking the potential of multi-robot collaborative operations.

3.1.4 Amplification effect of task size on bottleneck

Under the single inbound port bottleneck condition, increasing the task size from 8 packs to 10 packs not only prolonged the total operation time but also raised the resource waiting proportion from 14.2% to 15.7%. When a bottleneck is present in the system, a higher task load intensifies resource competition, resulting in greater efficiency loss. This observation provides a key reference for system capacity planning and performance prediction.

This study not only confirmed the value of multi-robot collaboration but, more importantly, offered quantitative data support and clear theoretical guidance for the synergistic design and optimization of intelligent warehousing systems in terms of software (scheduling algorithm), hardware (resource allocation), and operations (task size).

3.2 Future outlook

Based on the findings of this study, future work can be directed along the following key lines to develop more intelligent, efficient, and reliable warehousing management systems.

3.2.1 Full-process integration and validation

The research scope can be extended from primary inbound and outbound operations to encompass full-spectrum warehousing activities, such as inventory counting and return processing. Further investigation is warranted to explore how multi-robot systems can collaborate effectively under these complex mixed-task workflows and to assess the overall impact on system throughput and accuracy.

3.2.2 Adaptive scheduling with dynamic priorities

Variables reflecting real-world operational busyness and task urgency can be introduced to construct a dynamically adjustable scheduling algorithm. This algorithm should be capable of intelligently adapting robot task execution sequences and path planning based on real-time order pressure, clinical emergency needs, and similar factors, thereby achieving an upgrade from uniform operation to on-demand prioritization.

3.2.3 Cost-benefit analysis model

A quantitative model can be developed for a comprehensive cost-benefit analysis of introducing and scaling robotic warehousing systems. This model should consider key economic indicators such as equipment investment, operation and maintenance costs, labor savings, efficiency gains, and error reduction, thereby providing scientific and intuitive data support for management decision-making.

3.2.4 Digital twin-based solution rehearsal and optimization

A high-fidelity digital twin model of the system can be constructed. This model can then be used for large-scale, risk-free simulation testing and optimization of various scenarios, including new scheduling algorithms, sudden failures, and extreme workloads. Such an approach significantly shortens the solution validation cycle and establishes a foundation for predictive maintenance and remote system management.

Continued exploration in these directions can propel intelligent warehousing systems beyond the improvement of single-process efficiency toward a new stage characterized by holistic operational refinement and intelligent decision-making.

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