Visual Exploration and Planning of the Automated Material Handling System for Smart Factory in the Immersive Environment

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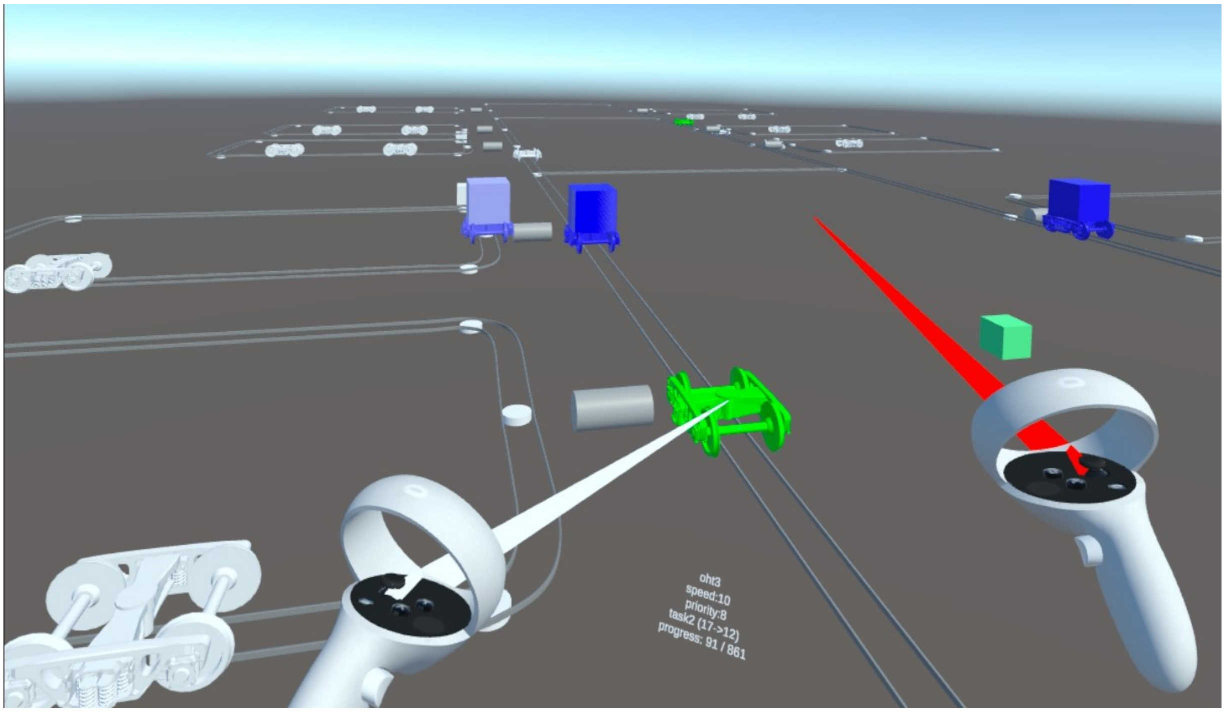

Figure 1: The visual exploration system for Automated Material Handling System. Users can explore and analyze AMHS through visualizations and a series of egocentric interactions.

Abstract

The combination of the digital twin and the smart factory has been a popular research direction in recent years. Automated Material Handling System (AMHS) is an important scene of smart factory, while most traditional simulation AMHS analysis tools only provide results or simple 2D displays. We introduce a visual exploration system that combines virtual reality (VR) with AMHS to allow users to observe and analyze the performance of the system in real-time, and we provide a series of egocentric interactions to help users analyze and interfere with the performance of the system. The interactions include ray interaction, task scheduling interaction, and path planning interaction, We demonstrate how to explore AMHS using visualization and interaction in our system through case studies.

1 Introduction

With the trend of automation and intelligence in the manufacturing industry, manual handling of materials in traditional factories is gradually being replaced by automatic handling by machines. Automated Material Handling System (AMHS), saving labor costs by automatically moving raw materials or semi-finished products between stations in a factory, improves production efficiency and eliminates the possible ergonomic hurts [1, 9].

In a large-scale AMHS, hundreds of vehicles run in dozens of loops, so traffic congestion among vehicles may frequently occur, notably when vehicles are permitted to perform cross-bay transportation [15]. Additionally, AMHS must assign a large number of handling tasks to these vehicles. Implementing reasonable vehicle route planning and task allocation strategies can reduce transportation costs, alleviate congestion, and enhance production efficiency [16]. The primary focus areas and issues are to increase throughput for AMHS, decrease average delivery times, and improve its reliability. Many studies use simulation experiments to calculate the throughput or average transit time of AMHS as an indicator to evaluate the performance of AMHS. However, as map scenes, vehicles, and scheduling strategies in AMHS become increasingly complex, traditional simulated AMHS methods have limitations in observing, analyzing, and interacting with the system. To understand why the current AMHS performance is sub-optimal, more intuitive information about the system's operation is required to analyze the reasons for the AMHS performance being affected, such as vehicles frequently congested in a certain location or the assignment of a certain type of task being unreasonable.

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It is challenging to visually observe and analyze AMHS. In a typical 300 mm semiconductor fabrication line, there can be as many as 5000 wafer cassettes waiting for about 100 types of tools to finish thousands of manufacturing steps [6, 25]. For such a large-scale, 3D system with possible multiple floors [11], traditional 2D fixed perspective observation can be inconvenient. In addition to providing users with a view of the system's operation, it is also necessary to provide data information related to vehicles and tasks through appropriate visualization methods. This will help users obtain quantitative information on the system's operation for analysis and decision-making. Observing and analyzing AMHS in a virtual environment has advantages over traditional interfaces. Virtual reality allows users to freely change their perspective while viewing AMHS, providing a better view of detail and 3D information than traditional interfaces. Also, it is inconvenient to use traditional interfaces to carry out interactive operations such as planning the path of OHTs and moving components in the 3D structures, which can be better solved by using virtual reality technology.

In our visual exploration setting, we utilize cross-reality to enhance the observation and planning of AMHS. We construct the AMHS model and framework based on the real-world factory and create a digital twin in the digital world. Then, we place the digital twin in a virtual reality environment, allowing users to generate insights and receive feedback for operations in the real-world factory. Cross-reality can fully combine the advantages of real and virtual environments to aid in the analysis and exploration of various scenes.

For the reasons stated above, we have proposed a visual exploration system that combines Virtual Reality (VR) with Automated Material Handling Systems (AMHS). This allows users to engage in immersive analysis and interaction to better observe, analyze, and interfere with AMHS. Our system enables users to test different scenarios, planning strategies and observe their impact on the system's performance in real time, which can aid in identifying areas for optimization. The primary contributions of our work include:

- Introducing a visual exploration system that explores the smart factory setting (AMHS) in a cross-reality manner with interactive and immersive technology.
- Providing an immersive environment for exploration of the real-time factory operation, enhanced with in-context visualization.
- Proposing an interactive exploration method for smart factory configurations, planning strategies, and identifying possible optimization directions.

2 Related Work

This section summarizes previous studies closely related to our work in the following categories.

2.1 AMHS Design and Evaluation

Many factors need to be considered when designing AMHS, such as scenario configuration, path planning, and task assignment. Kurosaki et al. [13] divided the tracks into two categories based on whether interbay and intraday were directly connected and found that interconnected lines are recommended for bays with a lot of transport between different bays, and isolation of interbay transport and intrabay transport is recommended for bays with high levels of transport within the same bay. Mackulak et al. [21] used a combination of simulation and design of experiments to compare the intrabay layout of two AMHS and found that the distributed storage option is preferable for maximizing manufacturing performance. Ben-Salem et al. [2] proposed a simulation combining Discrete Event and Agent-Based approaches to develop an effective AMHS design and found that the way lots are assigned to storage space and the storage capacity have an impact on workshop performance. Mohammadi et al. [22] developed a novel aggregation model based on a queueing network approach to estimate the cycle time of a job-shop production system, providing an accurate and fast estimation of the overall cycle time. Jimenez et al. [11] proposed four rail decision rules and four lifter decision rules to minimize average transfer time and found that simulation modeling can be used to evaluate decision rules and scenarios and determine the lowest average delivery time. These studies evaluated the performance of AMHS based on quantitative results obtained by simulation, but there was no method to further explore the modes in the system operation process, such as the scheduling and operation process of specific tasks, which presents limitations to AMHS analysis.

2.2 Visualization for Smart Factory

The development of Industry 4.0 and the emergence of the smart factory concept has led to changes in the traditional philosophy of manufacturing systems [10, 20]. Data mining and knowledge discovery can provide a scientific basis for planning and scheduling of manufacturing products [4, 27]. The use of visualization and mixed reality technology can further assist in understanding smart factory scenarios [26]. Paelke [24] applied augmented reality in assistance systems within a smart factory environment and found that AR is a promising user interface concept through public tests with several hundred users. Zhong et al. [29] introduced an IoT-enabled smart factory visibility and traceability platform to ultimately achieve real-time production visualization and demonstrated how it can facilitate typical decision-making, production, and logistics operations in a smart factory. Zhong et al. [30] created a virtual electronic assembly factory to help workers familiarize themselves with the entire assembly process. C. Zhou et al. [31] simulated the heat loss near the door of the blast furnace in steel rolling production in the form of animation, which deepened experts' understanding of the internal state of the heating blast furnace. Lee [14] et al used MR technology to provide a complete data interface including product monitoring data, structural physical information, and other relevant information to assist engineers in understanding equipment status. Espindola et al. [3] assisted managers in completing overall workshop layout planning by assigning the pose and position of real mechanical equipment to pictures of the production environment. In our system, multiple dimensions of system operation information will be displayed to assist users in analyzing and making decisions on automated material handling systems.

2.3 Immersive Analytics

As immersive technologies have rapidly matured and brought commercially successful virtual and VR/AR devices and mass market applications, researchers have sought to leverage their benefits, such as enhanced sensory perception and embodied interaction, to aid human data understanding and sensemaking [7, 8]. Zhang et al. [28] combined urban design and virtual reality by introducing an immersive analytics system with effective visualization and interaction techniques, to enable architects to assess designs in a VR environment. Lin et al. [18] presented a user-centered design study of developing interactive embedded visualizations for basketball fans to improve their live game-watching experiences and enhance game understanding and engagement. Lin et al. [19] presented an observational study comparing co-located and situated real-time visualizations in basketball free-throw training by designing both a situated 3D visualization on a head-mounted display and a 2D visualization on a co-located display. Chu et al. [5] proposed an immersive visual exploration system to assist users in exploring and explaining badminton tactics from multiple levels, allowing users to adjust the perspective to suit the needs of the analysis. Kim et al. [12] used an immersive VR technique to empirically examine the D/H ratio principle in urban public spaces. In our work, we will combine VR technology to provide users with an immersive analysis environment, with a free perspective and a series of egocentric interactions to enhance user understanding and engagement.

3 Overview

In this section, we discuss the domain requirements we learned from domain experts, followed by the system overview.

3.1 Background

We will focus on AMHS track and transport patterns. Take the example of AMHS in a wafer factory, there are two types of AMHS in a wafer factory. One is the interbay system, which is transporting cassettes or boxes of wafers between process bays; and the other is the intrabay system, which is transporting cassettes or boxes of wafers within one process bay [17]. Within the interbay system and the intrabay system, there are several vehicles responsible for carrying materials, such as overhead hoist transport (OHT) or automated guided vehicle (AGV).

3.2 Domain Requirements

Simulation models are both expensive and time-consuming to construct, and require long execution time to produce statistically valid estimates [23]. Our goal is to obtain useful information while the system is running, rather than waiting until the end of execution. When the results of system operation are abnormal or not satisfactory, we aim to identify existing problems in the system through direct observation and analysis. Through intuitive exploration of AMHS, it is easier to gain inspiration in the aspects of scene design, parameter setting, task scheduling strategy, and path planning strategy. In general simulation systems, the configuration of the system is often difficult to change after the system starts running. We aim to allow users to intervene in the system's running process, in order to better utilize the subjective role of people in the system. In addition, visual interfaces, flexible viewing angles, and user-friendly interactions are believed to improve user understanding and experience. We summarize the domain requirements as follows:

- R1: The system should provide simulated AMHS, and users can freely and intuitively observe the system operation in an immersive manner.
- R2: The system can support the visualization of real-time data information of components in the scene.
- R3: Users can explore AMHS through a series of interactions and can examine and optimize important strategies such as task scheduling and path planning.

3.3 System Overview

Our system builds a simplified AMHS in a virtual reality environment, allowing users to observe vehicles performing tasks on the track. The system provides a variety of visual information, including vehicle and task information. Users are free to move their perspectives to view global information or local details. Additionally, the system offers a range of interactions that allow users to interfere with the operation of the AMHS. The whole system is implemented using Unity 2021.3.8f1c1 with C#. The Oculus Quest2 is used in our VR-based system. It has a 2160 × 1200 resolution (1080 × 1200 per eye) OLED panel with a 110-degree field of view, a 90 Hz refresh rate, and comprises two controllers that are used to interact with the virtual environment, in addition to a headset that tracks the user's view.

4 Visual Exploration System

The design of our visual exploration system consists of three components: data and model setting, visualization design, and interaction design.

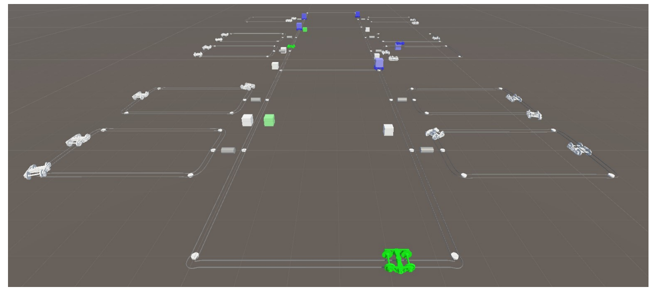


Figure 2: The AMHS scene in virtual reality. The scene consists of tracks, OHTs, and position points.

4.1 Data and Model setting

First, we introduce the system model and parameter setting in the visual exploration system and analyze the task model in the system.

4.1.1 Scene Setting

A common interbay and intrabay separation track [13] is used in our designed system. We have set up ten small ring tracks in the scene as intrabay (40m long, 25m wide) and one large ring track as interbay (320m long, 50m wide). The connection between the interbay and intrabay is made through stockers. There are 68 points on the track (18 on the interbay and 50 on the intrabay, marked by a white circular pattern), which represent the locations used for processing, storage, or delivery of materials. 26 Overhead Hoist Transports (OHTs) for material handling are placed on the track, including six on the interbay and two on each intrabay. According to the real parameter information of OHT, we have set the maximum no-load operating speed of OHT as 2m/s, maximum load operating speed as 1.5m/s. For safety reasons, when the OHT goes through a curve, the speed should be reduced to 40% of the maximum speed.

4.1.2 Task Model

When scheduling, the tasks that OHT needs to perform can be viewed as similar processes. For example, if processed chips need to be stored, This task requires OHT to first go to the processing facility, then load the chips on arrival, then carry the chips to the warehouse, and finally unload the chips at the warehouse. For simple handling or processing tasks on the same ring track in AMHS, the tasks can be divided into the following four stages:

- No-load stage: OHT starts from the current position to the start point of the task (i.e. the location of materials).
- Loading stage: OHT loads materials at the start point of the task.
- Loaded stage: OHT moves materials from the start point to the end point (i.e. the target position of the materials).
- Unloading stage: OHT unloads materials at the endpoint of the task.

For the task that needs to transport materials between intrabay, we can break it down into two tasks transporting materials within intrabay and one task transporting materials within interbay. More complex handling or processing tasks can be decomposed into multiple simple tasks by similar methods, so we take such simple tasks as the basic unit of tasks in the system. Tasks have different priorities. In our system, priorities range from 0 to 10.

4.2 Visualization Design

The visualization component is designed to provide users with more intuitive information about the system and a more immersive experience (R2). The component mainly consists of four parts:

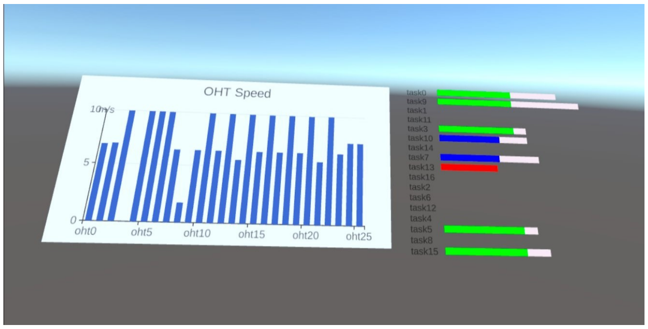


Figure 3: The real-time statistic view presents the speed of OHTs and the completion progress of tasks.

4.2.1 Virtual Reality Scene

Our visual exploration system is based on the virtual reality scene. We build the AMHS scene in Unity to allow users to explore the scene in an immersive way. The Oculus controller allows users to freely adjust the position and angle of the view to understand better the global landscape and local details (R1). The AMHS scene we built is shown in Figure 2.

4.2.2 Real-time Statistic View

This view provides the real-time speed of all the OHTs in the system and the completion progress of all the tasks. The real-time running speed of the OHT is visualized using the bar chart. The completion progress of a task is measured by the ratio of the mileage completed to the total mileage of the task and is represented by the progress bar. The length of the progress bar is positively correlated with the total mileage of the task. The color of the progress bar is associated with the phase the task is in. Green indicates the no-load phase, blue indicates the load phase, and red indicates the loading or unloading phase. A real-time statistic view is shown in Figure 3. Global information view can help users quickly understand the overall operation of the system and provide inspiration for subsequent exploration. For example, when the user finds that the speed of an OHT continues to be low or the progress of a task stagnates, which may represent an abnormal situation such as deadlock in the system, the user can then explore the local details.

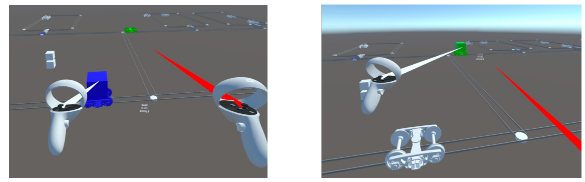
4.2.3 OHT and Task Visualization

We provide visual status information for OHTs and Tasks using color and location for encoding. We use cubes in the scene to represent the task. The initial position of the cube representing the task is located below the start point of the task. When the OHT corresponding to the task arrives, the cube will be loaded onto the OHT and moved with it. After the OHT finishes the unload stage, the cube will disappear, indicating that the task has been completed. Both the OHT and the cube use color to indicate their current running state. White indicates that the OHT is idle or the task has not started, green indicates that the OHT or task is in the no-load stage, blue indicates that the OHT or task is in the load stage, and red indicates that the OHT or task is in the load or unload stage. The shade of the OHT color is positively correlated with its running speed, and the shade of the task cube color positively correlates with its priority. With these visual cues, users can easily and intuitively understand the status of OHTs and tasks in complex scenes.

4.2.4 Text Annotation

We provide text annotations in the scene to offer easy access to details. These text tags include information about OHTs, task cubes, position points, and task numbers at the start and end of each running task (green at the start and blue at the end). Users can use the controller to toggle the display of text annotations on or off. To provide users with a satisfying observation experience from different perspectives, we adjust the angle and font size of these text annotations based on the user's perspective, so that the text always faces the user and the size of the text appears consistent at different distances for the observer.

4.3 Interaction Design



(a) Remove a cube from an OHT. (b) Place the cube on another OHT.

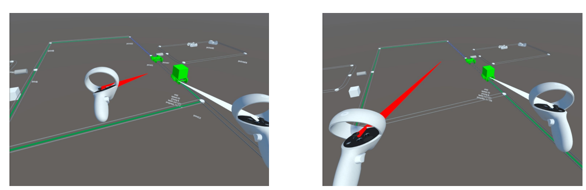
Figure 4: A task cube is moved from one OHT to another. One OHT becomes idle and the other one starts to perform the task.

Convenient and intuitive interaction is an advantage of immersive analysis systems. In order to better leverage the subjective role of human beings in exploring systems, we develop a series of egocentric interactions, including ray interaction, task scheduling interaction, and path planning interaction (R3).

4.3.1 Ray Interaction

To make it easy for the user to view or select specific components from different perspectives, our visual exploration system supports the following interactions through rays emitted by Oculus controllers.

- Hover. When the ray hovers on the OHT, task cube, or position point, it will display detailed information about the component.
- Selection. When the ray selects an OHT, the path of the OHT will be displayed on the track. If the user continues to select a position point, the path planning interaction will be enabled.
- Grab. The ray can select the task cube and move it by dragging.



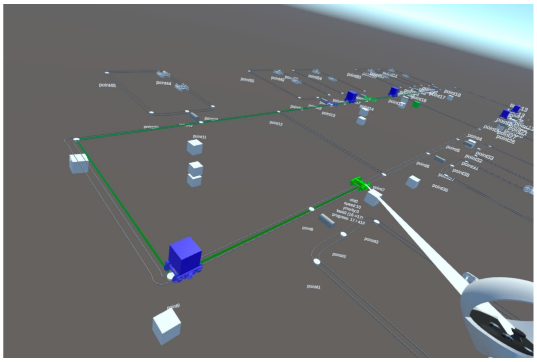
(a) The initial path of the OHT. (b) The updated path of the OHT.

Figure 5: When an OHT is selected, its path is displayed on the track. Continue to select a position point, then the OHT will re-plan a new path through the selected point.

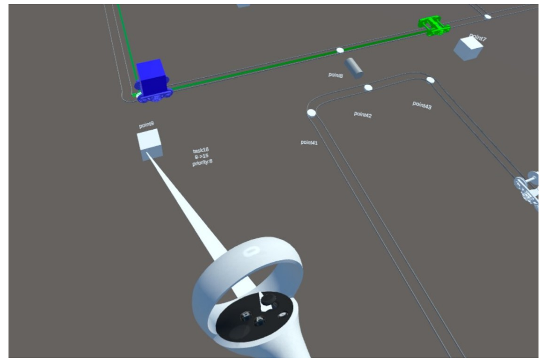
4.3.2 Task Scheduling Interaction

Based on grab interaction, our visual exploration system allows users to interfere with the system's task scheduling by grabbing and dragging task cubes. The specific interaction process is as follows:

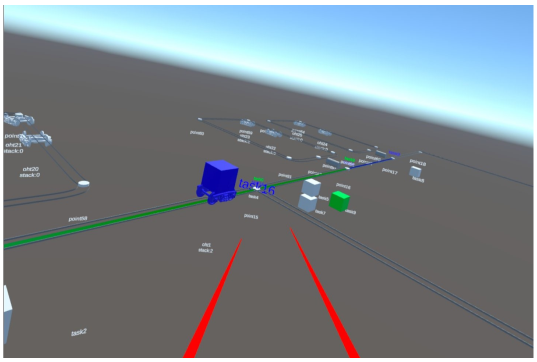
- Remove a task cube from an OHT. The OHT will be idle and the task will return to its original state.



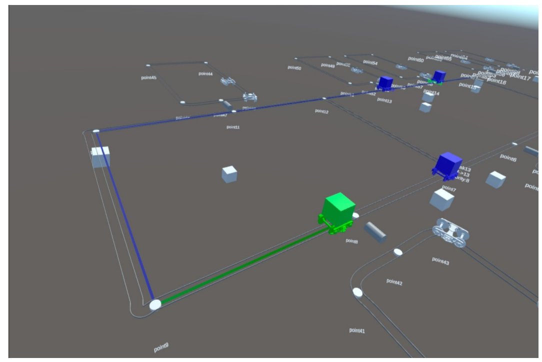
(a) The initial path of an OHT.



(b) Observe a new task in the OHT's path



(c) Observe the end point of the task



(d) The path of the OHT after re-planning

Figure 6: Explore task scheduling strategies through visualizations and interactions

- Place a task cube on an OHT. The OHT will abandon other missions it is performing to perform this one instead.

We illustrate the process of removing a task cube from one OHT and placing it on another (Figure 4). By manipulating task cubes in the scene, users can freely explore the impact of different task scheduling, interfere at any time during system operation, and get intuitive and timely feedback.

4.3.3 Path Planning Interaction

The visual exploration system provides an interactive method to interfere with path planning in order to support users to have a deeper understanding and exploration of OHT path planning in the system. When an OHT is selected by the ray, the path of the OHT consisting of line segments with different colors will be displayed on the track, where the color represents the running state of the OHT on this path, and the corresponding relationship between color and state is the same as in Sect. 4.2. If the ray continues to select a position point on the track, the OHT will re-plan a new path through that point to reach the target point. Figure 5 illustrates the process of changing the OHT path through interaction. By interfering with OHT path planning, users can explore the effects of different path planning modes during system operation, which can provide inspiration for solving abnormal situations such as congestion and optimizing path planning strategies.

5 Case Studies

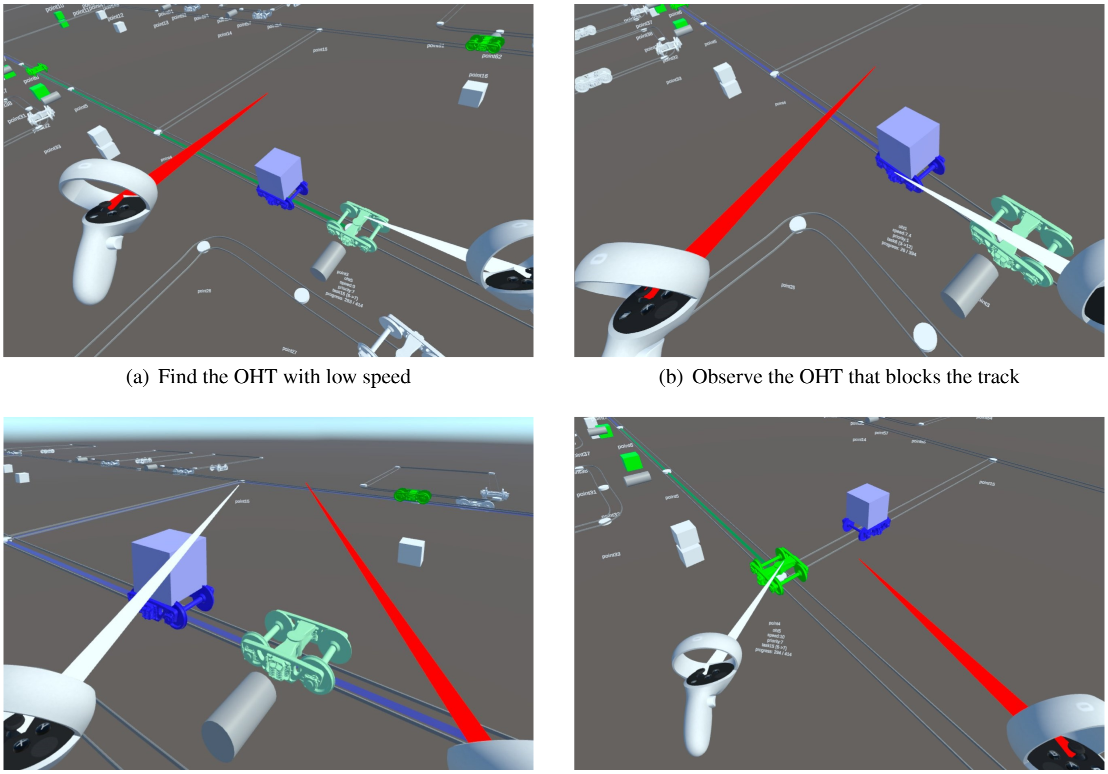
We demonstrate how to better explore AMHS with our system through two case studies. These two case studies address issues relate to task scheduling and path planning, respectively.

5.1 Exploration of flexible dynamic task scheduling

In this case study, our AMHS adopts a prioritized "nearest idle OHT" policy for task scheduling. Tasks are assigned in order of priority from highest to lowest, and each task is assigned to the nearest idle car. We explore the limitations of this task-scheduling strategy and try to find ways to improve it.

First, we find that unreasonable task scheduling can lead to long mileage tasks by using a real-time information view's progress bar. We select the corresponding OHT to find the task with the most extended total mileage and observe its path, as shown in Figure 6(a). It can be found that most of the path is green, indicating the OHT is idle most of the time while performing this task. then we notice there is another pending task in the OHT's path and we hover over it to observe its information, as shown in Figure 6(b). The detailed information indicates the end point of this task is also on the OHT's no-load route as shown in Figure 6(c), which means that the OHT can perform this newly discovered task on its way to the mission, thus reducing the degradation of system performance caused by the OHT being idle for long periods of time. By grabbing and dragging the new task cube onto the OHT, we assign this task to the OHT. After the new scheduling, the OHT's no-load time is significantly reduced by 76.7%, as shown in Figure 6(d), improving the AMHS system performance. This process shows us that, in addition to priority, no-load time and other factors should be considered in task scheduling, and dynamic adjustments should be made flexibly during task execution.

We use global visualization information to identify key components and then go to specific locations to observe the local details. After analyzing the possible problems of existing task scheduling strategies through path visualization, we use task scheduling interaction to explore optimization methods for task scheduling strategies.



(a) Find the OHT with low speed

(b) Observe the OHT that blocks the track

(c) Re-plan a path for the loaded OHT

(d) Blocking problem is solved

Figure 7: Explore path planning strategies through visualizations and interactions

5.2 Exploration of Path Planning Based on Priority

In this case study, the path planning strategy adopted by the AMHS is the shortest path strategy. Every OHT will plan a path with the shortest total mileage. We already know in advance that this path planning strategy will make the system performance low, and we try to explore the specific reasons through a visual exploration system and explore a better path planning strategy.

First, we find the lowest speed OHT through the bar chart of the real-time information view and locate this no-load OHT on the track. By selecting the OHT with the right controller, as shown in Figure 7(a), we can tell intuitively from the light color of the OHT that it is slow, and from the text annotation that the tasks it performs are of high priority. Then we notice a loaded OHT very close in front of the no-load OHT. From this, we deduce that the low maximum allowable speed of the loaded OHT prevents the normal high-speed operation of the no-load OHT. By selecting the loaded OHT with the controller we can find that its path overlaps with that of the no-load OHT, and the priority of the task it executed is much lower than that of the no-load OHT, as shown in Figure 7(b). If both OHTs continue to run, the lower-priority OHTs will always block the higher-priority OHTs. Hence, we generate the idea that low-priority OHTs should make way for high-priority OHTs. Through the interaction of path planning, we can make the loaded OHT turn at the forward intersection, as shown in Figure 7(c). After the loaded OHT turns, the no-load OHT is no longer blocked and starts to run at full speed, as shown in Figure 7(d). This inspires us to consider priority factors when designing path-planning strategies.

By combining a visual view and interactions to explore the path planning strategy, we can intuitively find the deficiencies of the existing strategy. Additionally, the scene and methods provided by the visual exploration system support us to explore better strategies.

6 Discussion and Conclusion

Our visual exploration system combines virtual reality with AMHS, providing a series of visual views and interactions to enable users to better understand and explore the system. This method of observing and interacting in the process of system operation overcomes the limitations that common AMHS simulation systems can only provide results and are not conducive to exploring the system's operation process, and it is inconvenient to use traditional interfaces to carry out flexible interactive operations. Focusing on two key problems in AMHS, task scheduling and path planning, we explored them respectively through case studies, demonstrating the noteworthy role of the visual exploration system in AMHS exploration.

Currently, we address the concept of cross-reality combining the digital twin and virtual reality. The model and tasks of AMHS connect the physical and virtual worlds. Users' feedback and exploration results in the immersive environment can further enhance the factory settings in the physical world. In the future, we will carry out further research to make our system support more cross-reality functions. We will cooperate with the virtual environment and reality and support users to flexibly switch between virtual and reality. Also, we will try to support collaboration between users using systems with multiple realities.

Acknowledgments

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References

[1] U. Bader, J. Dorner, J. Schlieber, T. Kaufmann, and M. Garbers. Cost efficient future automation and transport concepts. In *Proceedings of the 7th IEEE International Symposium on Semiconductor Manufacturing*, pp. 57–60.

[2] A. Ben-Salem, C. Yugma, E. Troncet, and J. Pinaton. A simulation-based approach for an effective amhs design in a legacy semiconductor manufacturing facility. In *2017 Winter Simulation Conference (WSC)*, pp. 3600–3611. IEEE.

[3] D. BUENO ESPINDOLA, L. FUMAGALLI, M. GARETTI, C. E. PEREIRA, S. S. BOTELHO, and R. VENTURA HENRIQUES. A model-based approach for data integration to improve maintenance management by mixed reality. *Computers in industry*, 64(4):376–391, 2013.

[4] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin. Smart factory of industry 4.0: Key technologies, application case, and challenges. *Ieee Access*, 6:6505–6519, 2017.

[5] X. Chu, X. Xie, S. Ye, H. Lu, H. Xiao, Z. Yuan, Z. Chen, H. Zhang, and Y. Wu. Tivee: Visual exploration and explanation of badminton tactics in immersive visualizations. *IEEE Transactions on Visualization and Computer Graphics*, 28(1):118–128, 2021.

[6] S.-L. Chung and M. Jeng. An overview of semiconductor fab automation systems. In *2003 IEEE International Conference on Robotics and Automation (Cat. No. 03CH37422)*, vol. 1, pp. 1050–1055. IEEE.

[7] T. Dwyer, K. Marriott, T. Isenberg, K. Klein, N. Riche, F. Schreiber, W. Stuerzlinger, and B. H. Thomas. *Immersive analytics: An introduction*, pp. 1–23. Springer, 2018.

[8] B. Ens, B. Bach, M. Cordeil, U. Engelke, M. Serrano, W. Willett, A. Prouzeau, C. Anthes, W. Büschel, and C. Dunne. Grand challenges in immersive analytics. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–17.

[9] K. Gartland. Automated material handling system (amhs) framework user requirements document: Version 1.0. *International SEMATECH*, 1999.

[10] E. Hozdić. Smart factory for industry 4.0: A review. *International Journal of Modern Manufacturing Technologies*, 7(1):28–35, 2015.

[11] J. Jimenez, B. Kim, J. Fowler, G. Mackulak, and Y. I. Choung. Operational modeling and simulation of an inter-bay amhs in semiconductor wafer fabrication. In *Proceedings of the Winter Simulation Conference*, vol. 2, pp. 1377–1382. IEEE.

[12] J. Kim and S. Kim. Finding the optimal d/h ratio for an enclosed urban square: Testing an urban design principle using immersive virtual reality simulation techniques. *International journal of environmental research and public health*, 16(5):865, 2019.

[13] R. Kurosaki, N. Nagao, H. Komada, Y. Watanabe, and H. Yano. Amhs for 300 mm wafer. In *1997 IEEE International Symposium on Semiconductor Manufacturing Conference Proceedings (Cat. No. 97CH36023)*, pp. D13–D16. IEEE.

[14] J. Lee, S. Han, and J. Yang. Construction of a computer-simulated mixed reality environment for virtual factory layout planning. *Computers in Industry*, 62(1):86–98, 2011.

[15] D.-Y. Liao and H.-S. Fu. Dynamic oht allocation and dispatching in large-scaled 300 mm amhs management. In *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292)*, vol. 4, pp. 3630–3635. IEEE.

[16] D.-Y. Liao and H.-S. Fu. Speedy delivery-dynamic oht allocation and dispatching in large-scale, 300-mm amhs management. *IEEE Robotics Automation Magazine*, 11(3):22–32, 2004.

[17] J. Lin, F. Wang, and C. Wu. Connecting transport amhs in a wafer fab. *International Journal of Production Research*, 41(3):529–544, 2003.

[18] T. Lin, Z. Chen, Y. Yang, D. Chiappalupi, J. Beyer, and H. Pfister. The quest for: Embedded visualization for augmenting basketball game viewing experiences. *IEEE transactions on visualization and computer graphics*, 29(1):962–971, 2022.

[19] T. Lin, R. Singh, Y. Yang, C. Nobre, J. Beyer, M. A. Smith, and H. Pfister. Towards an understanding of situated ar visualization for basketball free-throw training. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–13.

[20] M. M. Mabkhot, A. M. Al-Ahmari, B. Salah, and H. Alkhalefah. Requirements of the smart factory system: A survey and perspective. *Machines*, 6(2):23, 2018.

[21] G. T. Mackulak and P. Savory. A simulation-based experiment for comparing amhs performance in a semiconductor fabrication facility. *IEEE transactions on semiconductor manufacturing*, 14(3):273–280, 2001.

[22] M. Mohammadi, S. Dauzère-Pérès, C. Yugma, and M. Karimi-Mamaghan. A queue-based aggregation approach for performance evaluation of a production system with an amhs. *Computers Operations Research*, 115:104838, 2020.

[23] D. Nazzal and L. F. McGinnis. Analytical approach to estimating amhs performance in 300 mm fabs. *International journal of production research*, 45(3):571–590, 2007.

[24] V. Paelke. Augmented reality in the smart factory: Supporting workers in an industry 4.0. environment. In *Proceedings of the 2014 IEEE emerging technology and factory automation (ETFA)*, pp. 1–4. IEEE.

[25] W. Qin, J. Zhang, and Y. Sun. Multiple-objective scheduling for interbay amhs by using genetic-programming-based composite dispatching rules generator. *Computers in Industry*, 64(6):694–707, 2013.

[26] M. Resman, M. Turk, and N. Herakovič. Methodology for planning smart factory. *Procedia CIRP*, 97:401–406, 2021.

[27] D. R. Sjödin, V. Parida, M. Leksell, and A. Petrovic. Smart factory implementation and process innovation: A preliminary maturity model for leveraging digitalization in manufacturing moving to smart factories presents specific challenges that can be addressed through a structured approach focused on people, processes, and technologies. *Research-Technology Management*, 61(5):22–31, 2018.

[28] C. Zhang, W. Zeng, and L. Liu. Urbanvr: An immersive analytics system for context-aware urban design. *Computers Graphics*, 99:128–138, 2021.

[29] R. Y. Zhong, X. Xu, and L. Wang. Iot-enabled smart factory visibility and traceability using laser-scanners. *Procedia Manufacturing*, 10:1–14, 2017.

[30] Y. Zhong and B. Shirinzadeh. Virtual factory for manufacturing process visualization. *Complexity International*, 12(1):1–22, 2008.

[31] C. Zhou, J. Wang, G. Tang, J. Moreland, D. Fu, and B. Wu. Integration of advanced simulation and visualization for manufacturing process optimization. *JOM*, 68, 03 2016. doi: 10.1007/s11837-016-1892-3