Optimization of Charging Management in Electric Scooter Battery Swapping Stations based on Level 3 Digital Twin System

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***Abstract*—A battery swapping station has been attracting attention to reduce long battery charging times of electric scooters. For quality service, effective charging management is necessary to be able to provide charged batteries on request. This study proposes a level 3 digital twin system to optimize the charging management. The proposed system synchronizes an agent-based simulation model, describing battery exchange process between drivers and stations, with the collected actual data via a preprocessor. Then, an optimal charging schedule is derived based on the synchronized model through an efficient simulation-based optimization tool and applied to the physical system.**

Keywords—Electric scooter, Battery swapping stations, Digital twin, Charging management, Optimization.

I. Introduction

As eco-friendly policies expand, the demand for conversion to electric scooters (ESs) is increasing. However, well-known drawbacks of ES, such as long battery charging times and short battery life are impeding this conversion. In particular, since ESs are typically used for commercial purposes such as delivery, these drawbacks are more fatal. As a solution to this problem, a battery swapping station (BSS) has recently been attracting attention because a discharged battery can be quickly swapped with a charged battery on request [1].

Since ESs do not require high-capacity batteries, BSS is operated in the form of an unmanned vending machine with a small number of batteries to obtain operational efficiency. For quality service of BSS, it is necessary to be able to provide charged batteries on request. Since the BSS of ES has a small number of batteries, utilizing slow charging will most likely not achieve this due to the long charging times; thus, rapid charging is used, but this reduces the efficiency. That is, optimized charging management is necessary to keep the efficiency.

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Various studies have been done on the charging management of BSS [2]. However, most of the existing studies have focused on personal vehicles, and there are limitations in reflecting the characteristics of ES, which are mainly used for commercial purposes. Although taxi and bus have been considered in some studies, their characteristics are somewhat different from those of ESs in that they require high-capacity batteries. In addition, most studies have focused on charging management in a single BSS with many batteries, which is difficult to be applied to the BSS of ES, where vending machines with a small number of batteries in different places operate in a cluster form.

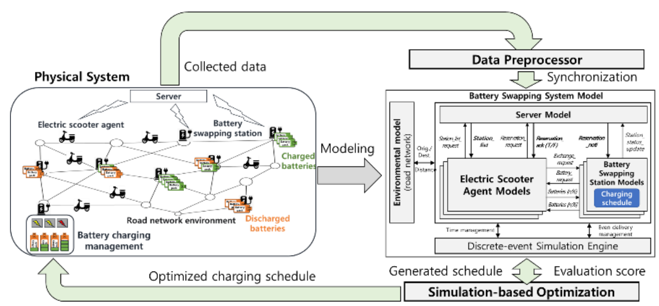

Fig. 1. Level 3 digital twin system for optimizing the charging management of BSS of ES.

This study proposes a level 3 digital twin (DT3) system for optimizing charging management of the BSS of ES. The digital twin refers to a cyber model corresponding to a physical system and has three implementation levels. Among them, the third level means optimizing the physical system through simulation-based optimization of the cyber model continuously synchronized with the physical system [3]. The proposed DT3 system consists of three parts: 1) an agent-based simulation (ABS) model describing ES drivers' work pattern and battery exchange process, 2) a data preprocessor synchronizing the model with actual data collected from the physical system, and 3) an efficient simulation-based optimization (SBO) tool for deriving an optimal charging schedule using the synchronized model, as shown in Fig. 1. Unlike previous studies based on analytical methods, the ABS model allows to consider the behavior of ESs used for commercial purposes. Consequently, a more effective charging schedule that responds to demand and minimizes the cost can be derived, thereby optimizing the charge management in the BSS of ES.

II. Level 3 Digital Twin System

A. *Data Preprocessor*

The data preprocessor synchronizes the ABS model by not only the status information of each BSS (e.g., battery, reservation, failure, etc.) but also the battery status and location of ES drivers. In addition to synchronizing the collected data directly, the preprocessor extracts and reflects the behavior pattern based on the periodically collected data; thus, the ABS model can predict the drivers' reachability and arrival time for each station accurately, and this increases the fidelity of the ABS model.

B. *Agent-based Simulation Model*

To describe ES driver's work pattern and battery exchange process, the ABS model consists of ES agent models, BSS models, and a server model. In addition, this ABS model includes a road network environmental model that interacts with ES agent models. In the digital twin system, the simulation model analyzes the quality of battery exchange service provided when a given charging schedule is applied.

The server model is responsible for information exchange between the ES agent models and BSS models. Figure 2 shows the state transition diagram of the ES agent model that reflects the behavior of ES drivers. In the WORK state, the ES agent model travels on the road network according to the behavior pattern derived from the data preprocessor. When a battery warning occurs, the ES agent model receives the list of nearby available stations through the server model, determines the station to visit, and reserves batteries to be exchanged. If the reservation is confirmed, the ES agent model moves to the station and exchanges the reserved batteries; otherwise, it will try to make a reservation by requesting a newly updated list again.

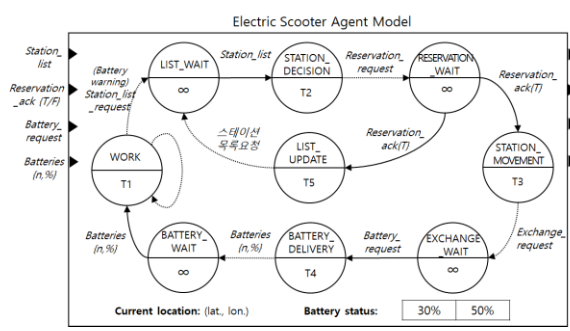

Fig. 2. State transition diagram of electric scooter agent model.

Figure 3 shows the state transition diagram of the BSS model. This model continuously charges the retained batteries according to the given charging schedule and periodically reports the charging status to the server model. When the ES agent who reserved the batteries arrives, the BSS model proceeds with the battery exchange with that agent. Since battery exchange is possible with one ES driver at a time in BSS, if another ES agent arrives during the exchange, this agent waits in the queue and the exchange proceeds sequentially.

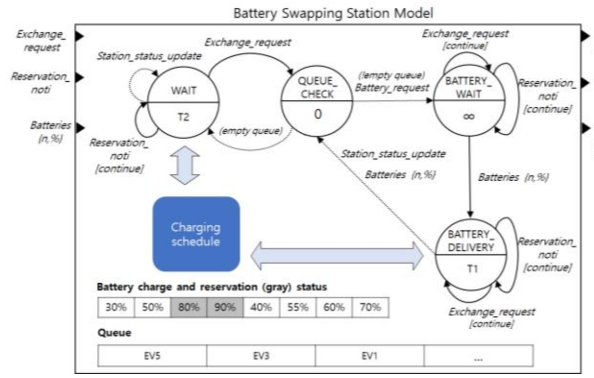

Fig. 3. State transition diagram of battery swapping station model.

This ABS model is implemented based on PythonPDEVS [4], a Python-based discrete-event simulation engine. It utilizes a dynamic structure for efficient simulation between multiple ES agent models and BSS stations.

C. *Simulation-based Optimization Tool*

An efficient SBO tool plays a key role in building a DT3 system, which optimally controls the physical system with the synchronized simulation model in real-time. Since the ABS model consists of multiple agent models and has stochastic elements, many repeating simulations are required to obtain an accurate service quality of a charging schedule. To handle this efficiency concern, the proposed DT3 system utilizes the SBO framework for DT3 [5]. This framework generates promising schedule alternatives through a genetic algorithm and efficiently selects the optimal one by intelligently allocating the simulation budget through ranking and selection. In addition, since the framework conducts replicated simulations through a distributed parallel environment, it is possible to quickly derive the optimal charging schedule based on the synchronized ABS model.

III. Conclusion

This study proposed a DT3 system to optimize the charging management of the BSS of ES through the SBO of the ABS model synchronized with collected data from the physical system. Although this system is designed to quickly derive the optimal charging schedule, it can be used for analyzing battery lifecycle management, new station installation, and battery relocation.

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