Towards an IIoT-Based Architecture for Baggage Handling Systems

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Abstract —This paper presents an IIoT-enabled architecture for the baggage handling system (BHS) at airports. Instead of the static control over physical objects as in the current practice, the new structure powered by the IIoT leads to more dynamic and intelligent operations. The infrastructure collects more data as compared to the current implementations and makes use of the data to figure out the optimal configurations for the subsystems inside the BHS. Eventually, the control system is capable of autonomous adjustments according to the operating condition for achieving optimized performance.

Index Terms—Industrial Internet of Things, baggage handling system, industrial communication, system engineering

I. Introduction

Baggage Handling System (BHS) is a type of logistic system installed at airport, transferring passenger bags automatically from the source to the destination (e.g., from check-in counters to departure areas). The major functionalities of a BHS are baggage check-in, transportation, screening, tracking, sortation, early-storage, etc., and are implemented by corresponding logistical equipment [1]. The carriers to transfer baggage can be conveyors, trays, carts, or their combinations within the system. One of the recent technological advancements in the BHS is destination-coded vehicle (DCV) [2].

Over last a few years, the Internet of Things (IoT) has attracted significant attentions from universities, research institutes and industries [3]–[5]. The IoT establishes networked connections of physical objects, and consequently enables smart, autonomous and optimized processes and services. Transformation of existing industrial systems such as manufacturing systems, logistic systems, etc., are expected to occur with the assistance of the IoT. Industrial IoT (IIoT) is capable of fulfilling more stringent real-time and deterministic requirements as compared to commercial IoT [6], [7]. It is critical for many recent industrial initiatives including IoT@Work [8], [9]. The extended accessibility of the physical objects, such as sensors, actuators and other devices, leads to increased intelligence in system functionalities and services. One of the major application domains of the IoT is logistics [5].

At the moment, the IIoT technologies are not widely applied in airport BHS industry. Consequently, smart operations of the BHS cannot be commonly enabled to solve existing problems. This paper presents those existing problems in the BHS and explores the possibility of applying IIoT to the control system (both high-level control (HLC) and Low-Level Control (LLC)). The contribution of this paper is three-fold. First, a new IIoT-based paradigm is introduced for the BHS. Second, the paper discusses about how the BHS can become more autonomous and optimized with the assistance of the IIoT. The conceptual study of the IIoT application in baggage merging, screening, and sortation are presented. Third, it inspires BHS practitioners to think of more IIoT applications in the conventional airport logistic industry. It should be highlighted that this approach can be applied further to other material handling systems.

The remainder of the paper is organized as follows: Section II introduces the system overview of the BHS, including problem statements. Section III describes the application of the IIoT in baggage screening. The IIoT-enabled dynamic merging control is presented and discussed in Section IV. The benefit of the IIoT for the sortation subsystem is described in Section V. Finally, section VI concludes the paper.

II. System Overview

A. Baggage Handling System

A typical BHS is illustrated in Fig. 1. Bags coming from check-in counters or early-baggage storage are integrated into the main line by merge conveyors. Each bag is then transferred via a number of transport conveyors to a screening conveyor to get X-rayed for security check. If the screening machine returns a “green” signal, the bag is allowed to proceed to the destination. Otherwise, it is transferred to another checkpoint with more stringent check-up. After screening, bags are transported in high-speed to the baggage sortation area. Sortation is carried out at the end of the system based on the baggage destination. The sorted bags are at last loaded onto a tug manually or by automated robots.

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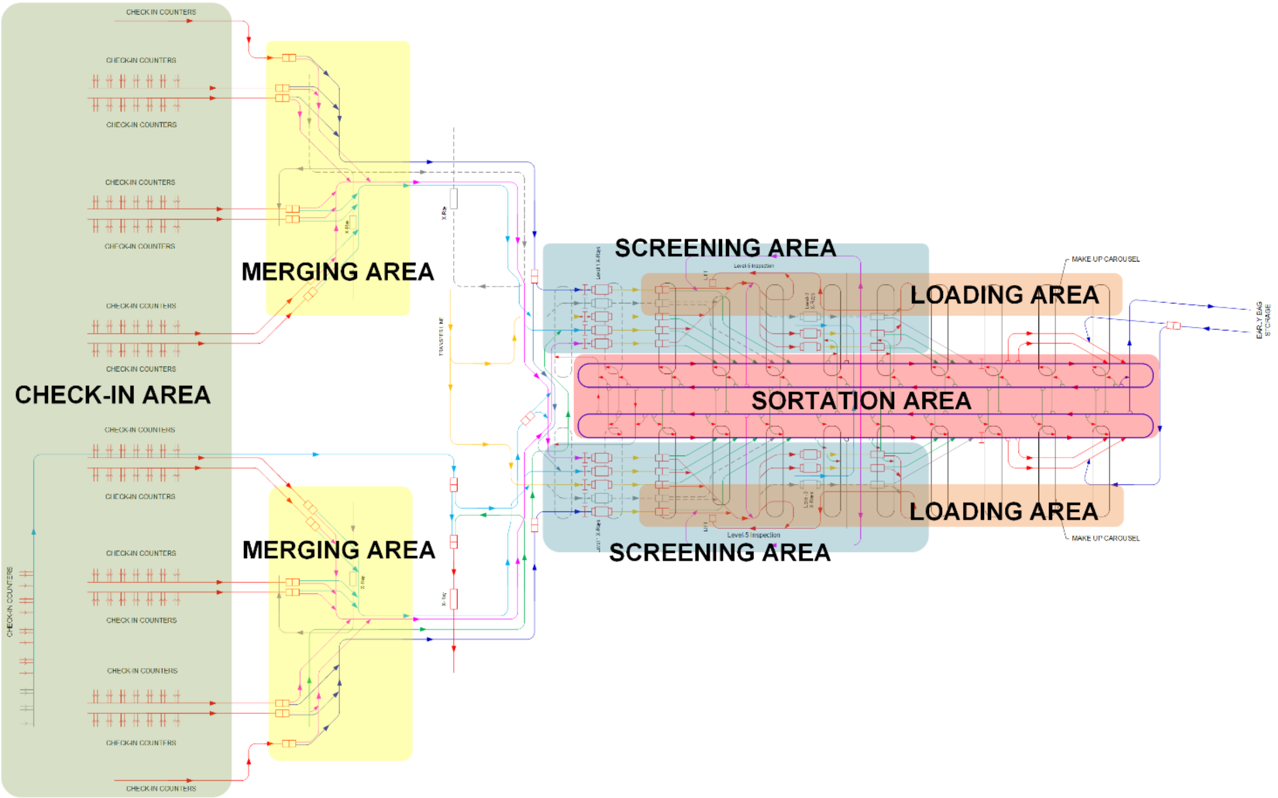


Fig. 1. A typical baggage handling system

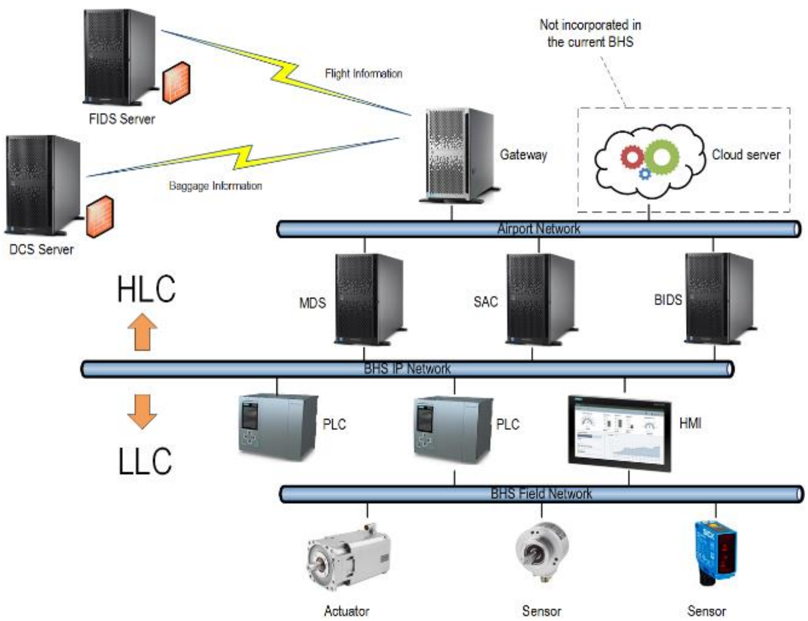


Fig. 2. IIoT-powered control of a BHS.

A BHS is made up by a number of subsystems [10]. A subsystem is normally consisted of a number of buffers (queue conveyors) and machines that handle the bags such as merge conveyors, screening machines, loading robots, etc. Subsystems are usually cascaded and therefore one can potentially become the bottleneck of the whole system. The control of a BHS can be classified into the HLC and the LLC [11]. The BHS hierarchy is illustrated in Fig. 2.

High-level servers, i.e., sortation and allocation control (SAC) and maintenance diagnostic system (MDS), exchange data with departure control system (DCS) database and flight information display system (FIDS) database server in order to obtain flight and baggage information from airport operational database. When bag tags (bar-code or RFID tag) are printed, the DCS gives the baggage information to the BHS SAC, such as tag identifier, passenger name, flight number, departure time and etc. With this information, the SAC can then issue instruction to the programmable logic controllers (PLCs) for the sortation when the bag reaches a diversion point. The FIDS provides the flight schedule information to the SAC. The SAC makes use of this information to decide the handling of the baggage (early bag, "hot" bag or bag-too-late).

The LLC of each subsystem is fulfilled by a PLC [12], [13]. In principal, all physical objects in the field of the BHS are controlled by the PLCs. The PLCs communicate with the HLC servers (the SAC and the MDS) and field devices (such as actuators, sensors, distributed controllers). The inter-connection between the PLCs and the HLC units is commonly implemented by an IP-network. The corresponding communication protocol is built on top of TCP and UDP.

There are also data consumers (the HLC MDS and the LLC HMI) in the control system. These components visualize the system- and device-level operating status so that faults can be swiftly identified and recovered.

B. Physical Objects within Systems

The physical objects located within a BHS are equipment (including conveyors, carts, carriages, DCVs, etc.) together with sensors, actuators, and possibly local controllers. For example, tracking sensors are used to trace bags and/or detect whether a bag is present on a conveyor. It is usually a photoelectric sensor installed at the head-end of the conveyor where the measurement is necessary. Baggage identifying sensors can be a bar-code or RFID reader, installed only on certain conveyors [14], [15]. It returns the bag identifier embedded in the bag tag to the PLCs. Speed sensors are incremental encoders installed at conveyor shaft where the speeds of transport conveyors can be measured. Motor starters (without speed control) or motor controllers (with speed regulation) are used to drive the mechanical parts of the conveyors.

C. Problem Statement

As described in [16], a BHS can be treated as a number of cascaded queueing systems. It can be known from queueing model that subsystems of merging, screening, sortation, and loading areas can potentially become the bottlenecks of the system performance, especially when the subsystem is designed without enough mathematical modelling and/or simulative verification. It is therefore important if the system can be adaptively configured and behaved depending on the operating condition.

At the moment, however, system configurations must be done before commissioning and cannot be easily adjusted during operation. The LLC is static in the current practice as conveyors are configured to transfer bags at fixed speed. Conveyors operate away from their speed constraints, and correspondingly, the baggage handlers such as screening machines, robots, etc., perform below their maximum possible efficiency. During peak hours, there could be a number of bags waiting on the queue conveyors for the security screening, owing to the high baggage load. This could further cause additional travel time of bags. In the worst-case scenario, it could happen that bags cannot make it to the aircraft on time.

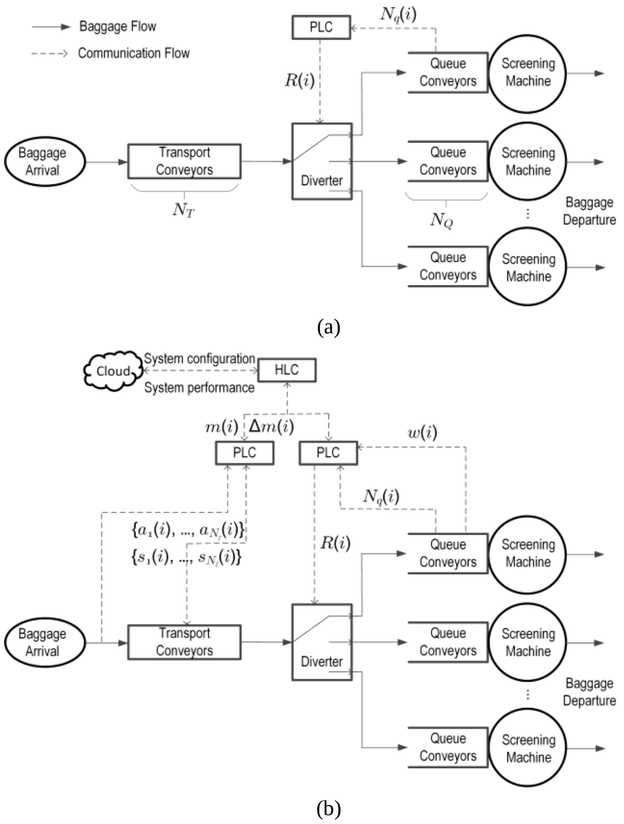


Fig. 3. (a) Current screening subsystem; (b) IIoT-based baggage screening.

On the HLC side, the relationship between system performance and key system parameters is not established. The system performs daily routine without any data analysis due to the missing IIoT infrastructure and the consequently the lack of data available from the communication networks. This leads to the fact that the system is not capable of self-learning and self-improving. The system cannot be autonomously controlled to achieve optimal system performance based on a weighted sum of KPIs (bag lead time, system throughput, cost, etc.).

III. Smart Baggage Transportation

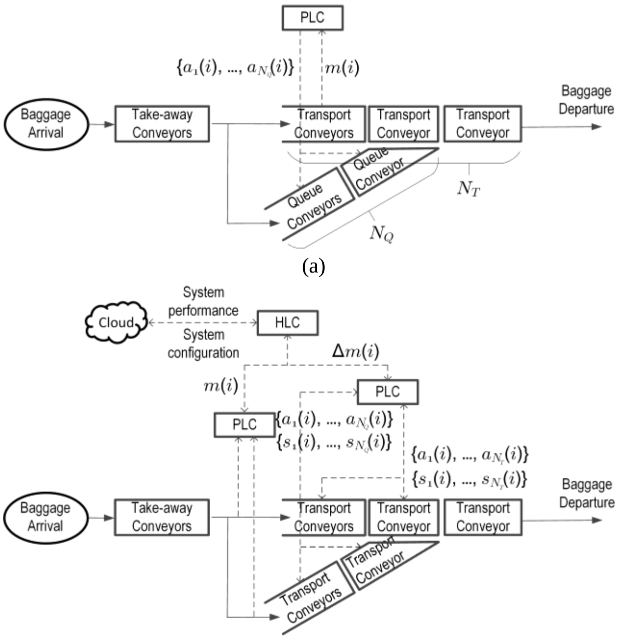
All passenger bags checked in have to be centralized in the screening area since the security inspection is mandatory. Each screening line consists of an X-ray machine and N_Q queue conveyors located upstream of each machine for buffering. All system parameters used in the current screening system are presented in Figure 3(a). The diverter is controlled by the PLC. We let $R(i)$ denote the output of the load balancing policy implemented at the diverter for the i-th bag. Common algorithms for load balancing $R(i)$ include round-robin and join-the-shortest-queue [17]. $R(i)$ is one of the factors which has influence on the baggage waiting time spent in the screening system. In this paper, we focus on the factor of the variability in baggage arrival.

The objective is to decrease waiting time $w(i)$ under the constraint of queue length $N_q(i) \leq N_Q$ in the presence of the i-th bag. Waiting time $w(i)$ can be approximated by the formula given in [18]. The formula suggests that variability in baggage arrival and screening machine causes congestions in the queue. Since the screening rate is uncontrollable, the waiting time can be only influenced by variability in baggage arrival. The adjustment requires global information on the bags (current location of each bag, inter-gap between bags, etc.). Photoelectric sensor is capable of detecting the existence of a bag by returning an active signal when its light is blocked by a bag. The time difference between the i-th and $(i+1)$-th bag can be obtained via the sensor by considering the speed of the conveyor from the encoder reading. Inter-baggage gap between the i-th and $(i+1)$-th bag $m(i)$ is collected by the PLC of the transportation area and provided to the PLC located in screening subsystem and to the HLC via the IIoT infrastructure so that it is globally known.

The waiting time can be reduced if the control system can make use of the transport conveyors installed in the upstream of the subsystem to have baggage arrival regulated dynamically before bags are conveyed to a screening line. The arrival rate can be adjusted by varying the speeds of the transport conveyors. System performance can be improved by regulating speeds for transport conveyors via message $a_1(i), \cdots, a_{N_T}(i)$. For closed-loop control, messages which contain the feedback $s_1(i), \cdots, s_{N_T}(i)$ from the sensors are also needed. The bag loaded into the diverter is therefore of a new inter-arrival time of $m(i) + \Delta m(i)$, after travelling over N_T transport conveyors.

Based on all information collected from the IIoT infrastructure, the new $m(i)$ can be calculated by an optimization algorithm on global performance indicators, i.e., delivery time, throughput and cost per handled bag. This optimization is done on the cloud. The cloud platform generates a new $m(i)$ which would lead to optimal performance and passes the results to the PLC which is in charge of the transportation conveyors. The PLC receives the objective $m(i)$, computes set points $a_1(i), \cdots, a_{N_T}(i)$, and transmits the outbound message to all transport conveyors. Speed targets are achieved by closed-loop speed control of the actuators of relevant transport conveyors. Moreover, the waiting time $w(i)$ and the queue length $N_q(i)$ can be collected and saved to the cloud server. This enables deep data analysis on the system performance against configurations in order to further improve the operation day by day. The system configuration can be automatically adjusted at run-time for performance optimization.

By comparing Fig. 3(b) with 3(a), it is obvious that much higher bandwidth is needed in the IIoT-based architecture. The speed set-points should be propagated to the actuators as fast as possible. Real-time communication protocols are therefore preferred to form the device-level network. Currently, fieldbus protocols are dominating in the low-level network of the BHS [19]. Industrial Ethernet protocols, for example PROFINET IO, EtherCAT, EtherNet/IP, etc., are suitable candidates to form the IIoT backbone in the field level [20], [21] due to the baudrate and other advantages over the existing fieldbus technologies.



(b)

Fig. 4. (a) Static merging; (b) IIoT-enabled dynamic merging.

IV. Smart Baggage Merging

In the merging area of a conveyor-based BHS, baggage from a feeder line is combined into the main flow (see Fig. 4(a)). The feeder line usually consists of N_Q (usually $N_Q \leq 3$) queue conveyors as a buffer [22]. At present, feeder bags are merged using static control method, e.g., feeder conveyors carrying bags have to be fully stopped for queueing if the sensors have detected baggage appearances near to the junction in the main line. The safety distance is pre-defined and cannot be changed without re-programming the PLC. The actuators on queue conveyors can be started or stopped with Boolean interface $a_1(i), \cdots, a_{N_Q}(i)$. This causes frequent start-stop on the motors and therefore leads to considerable noise and consumption of the conveyor belts of the queue conveyors.

A dynamic merging approach was described in patent [23] and its mathematical proof is given in [24]. The approach enables acceleration and deceleration on conveyors in the neighborhood of the intersection point according to the baggage traffic. Unnecessary abrupt stop of the conveyors can be avoided. It provides benefits such as more power efficient, longer system up time and higher throughput. Baggage claim area could also benefit from this dynamic scheme [25].

In the dynamic approach, queue conveyors are replaced by transport conveyors (see Fig. 4(b)). Transport conveyors are equipped with frequency converters with real-time Ethernet connectivity so that their speeds are controllable [26]. The PLC installed in the upper stream has the knowledge of inter-baggage space $m(i)$. This information is received by the HLC for both baggage tracking and dynamic control of the merging area. The HLC, at the same time, also receives the actual speeds of transport conveyors from the main line $s_1(i), \cdots, s_{N_T}(i)$ and the feeder line $s_1(i), \cdots, s_{N_Q}(i)$. With these inputs, the SAC determines the best strategy for the spacing change $\Delta m(i)$ which would eventually enhance the merging performance. $\Delta m(i)$ is transmitted to the PLC which has the control over the merging area. The PLC determines the speed set points in both main line and feeder line, denoted by $a_1(i), \cdots, a_{N_T}(i)$ and $a_1(i), \cdots, a_{N_Q}(i)$, respectively. The performance of merging process (such as baggage throughput, power consumption due to speed control) can be stored, calculated and analyzed by the cloud platform. The optimal merging strategy can be determined by considering all necessary KPIs, e.g., throughput, cost, noise, etc.

V. SMART BAGGAGE SORTATION

The tilt tray sorter (TTS) is a subsystem inside the BHS that carries out the main sortation of bags to other subsystem for the necessary handling. The challenge for the TTS design is that the wireless communication has to be incorporated as the carriages are moving all the time during system operation. Currently, the most common communication technologies used in the TTS is infrared (IR) combined with fieldbus such as PROFIBUS and AS-Interface [27]. The IR transceivers act as access points for carriages to exchange data with the PLC. The PLC sends control commands $a_1, \cdots, a_{N_C}$ to the carriages and receives status feedback $s_1, \cdots, s_{N_C}$ from the carriages, where N_C is the number of carriages in the TTS. A control command contains the information on whether the tray needs to be tilted to unload the baggage and by which motion profile the tilt should be performed. A status message contains the operating status of a carriage, for example the sensor and actuator status, motor running hours, etc. As shown in Fig. 5(a), the IR transceivers are deployed before the discharging points. In this design, however, the data exchange only occurs when a carriage moves to the specific place where the IR transceiver is installed. Therefore, only partial tracking is possible. The data size exchangeable between the access points and the carriages are limited due to the characteristics of the IR.

The system can be improved by deploying radio frequency (RF) technologies such as IEEE 802.15.4 or 802.11 Wi-Fi. Fig. 5(b) shows a solution to employ a RF transceiver on every carriage. IEEE 802.15.4 is recommended here as the technology targets at wireless applications which require low data rates but secure networking. An IEEE 802.15.4 network can be organized with different topologies: star, mesh or hybrid (star-mesh). Mesh topology can be considered here to cover the distance issue in the TTS. In a mesh network, each access point acts as a router, communicating with other access points. However, unlike start topology, the transmission delay between two access points in the mesh network is non-deterministic. This may affect the real-time capability of the network. The gateway interacts with the PLC directly, collecting all the data packets collected from the routers and converting the packets into Ethernet protocol or other serial communication for the PLC.

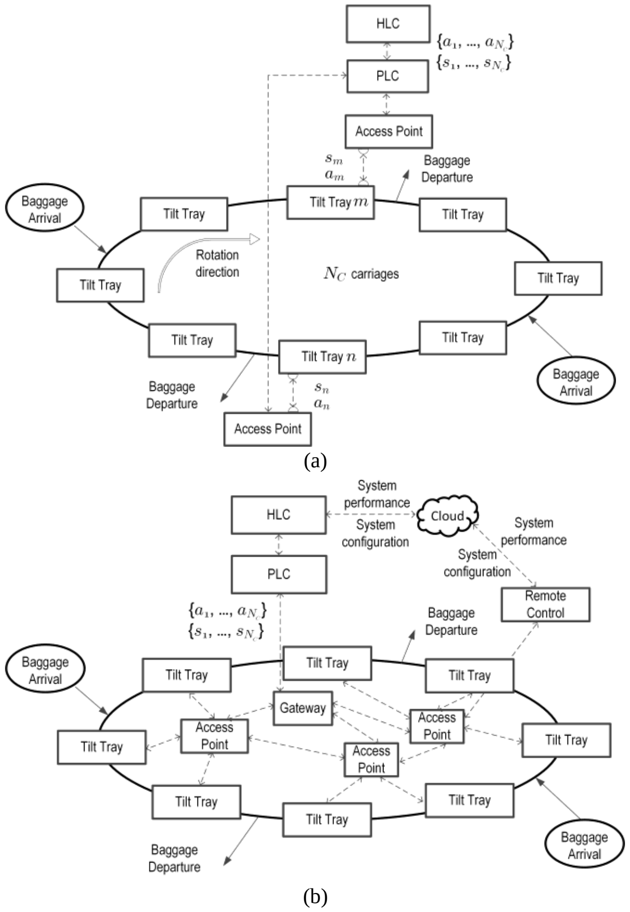


Fig. 5. (a) IR-based TTS; (b) 802.15.4-based TTS.

This new architecture offers a number of advantages over the existing IR-based system structure. First advantage is that the communication is completely contactless for the LLC. Cabling is no longer needed for the connections between the PLC and the access points. Secondly, the PLC is aware of the status of carriages any time, regardless of the position of the carriages, i.e., the tracking is complete on the MDS. Third, more data can be exchanged between the PLC and the carriages based on IEEE 802.15.4 to facilitate system analysis on the cloud server. Lastly, monitoring and control can be carried out via also remote control devices. The remote control devices can be synchronized with the cloud to enable easier commissioning and maintenance.

VI. Conclusions

An IIoT-enabled system architecture is presented for the airport BHS. In our IIoT-based structure, more data from field devices are collected, stored and analyzed by the cloud. A new HLC server, with cloud platform incorporated, needs to be established as the central place for data storage and processing for every subsystem. Smart control logics can be implemented with the assistance of the IIoT infrastructure to improve the system KPIs.

Deploying IIoT infrastructure may incur initial material and set-up cost. However, it is worthwhile if the new architecture is able to bring more benefits by improving system performance while saving cost over operation and maintenance. Performance analysis against system configurations can be possible with all the information gathered from the physical objects. This further leads to autonomous and intelligent control over the physical objects and therefore optimized performance for the whole system. In addition, the architecture can be further extended to other type of material handling systems.

One of the future works is to quantify the analysis given in this paper by mathematical modelling in order to better demonstrate the operational benefits of the new IIoT-based architecture.

References

[1] H. Yu and C. Xu, “Design and implementation of the key technologies for baggage handling control system,” in *Proc. International Conference on Measuring Technology and Mechatronics Automation*, vol. 1, March 2010, pp. 958–961.

[2] Y. Zeinaly, B. De Schutter, and H. Hellendoorn, “An integrated model predictive scheme for baggage-handling systems: Routing, line balancing, and empty-cart management,” in *Proc. IEEE Transactions on Control Systems Technology*, vol. 23, no. 4, pp. 1536–1545, July 2015.

[3] L. D. Xu, W. He, and S. Li, “Internet of things in industries: A survey,” *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[4] H. P. Breivold and K. Sandström, “Internet of things for industrial automation – challenges and technical solutions,” in *Proc. IEEE International Conference on Data Science and Data Intensive Systems*, Dec. 2015, pp. 532–539.

[5] L. Atzori, A. Iera, and G. Morabito, “The internet of things: A survey,” *Computer Networks*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[6] R. S. Oliver, S. S. Craciunas, and G. Stger, “Analysis of deterministic ethernet scheduling for the industrial internet of Things,” in *Proc. IEEE 19th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks*, Dec. 2014, pp. 320–324.

[7] M. Diaz-Cacho, E. Delgado, P. Falcon, and A. Barreiro, “IoT integration on industrial environments,” in *Proc. IEEE World Conference on Factory Communication Systems*, May 2015, pp. 1–7.

[8] S. Gusmeroli, S. Piccione, and D. Rotondi, “IoT@Work automation middleware system design and architecture,” in *Proc. IEEE 17th Conference on Emerging Technologies Factory Automation*, Sept. 2012, pp. 1–8.

[9] A. M. Houyou, H. P. Huth, C. Kloukinas, H. Trsek, and D. Rotondi, “Agile manufacturing: General challenges and an IoT@Work perspective,” in *Proc. IEEE 17th Conference on Emerging Technologies Factory Automation*, Sept. 2012, pp. 1–7.

[10] B. van de Laar, “Analysis of systems within vanderlande industries,” Master’s thesis, Eindhoven University of Technology, 2009.

[11] Y. Zeinaly, B. D. Schutter, and H. Hellendoorn, “Towards a robust multilevel control approach for baggage handling systems,” in *Proc. IEEE 52nd Annual Conference on Decision and Control*, Dec. 2013, pp. 281–287.

[12] W. Dai and V. Vyatkin, “Redesign distributed PLC control systems using IEC 61499 function blocks,” *IEEE Transactions on Automation Science and Engineering*, vol. 9, no. 2, pp. 390–401, 2012.

[13] R. Sinha, K. Johnson, and R. Calinescu, “A scalable approach for reconfiguring evolving industrial control systems,” in *Proc. Emerging Technology and Factory Automation*, Sept. 2014, pp. 1–8.

[14] T. Ahmed, T. Calders, and T. B. Pedersen, “Mining risk factors in RFID baggage tracking data,” in *Proc. 16th IEEE International Conference on Mobile Data Management*, vol. 1, June 2015, pp. 235–242.

[15] L. Ye-Won and C. Yong-Lak, “Proposal for air-baggage tracing system based on IoT,” in *Proc. 9th International Conference on Future Generation Communication and Networking*, Nov 2015, pp. 25–28.

[16] R. D. Neufville, “The baggage system at Denver: Prospects and lessons,” *Journal of Air Transport Management*, vol. 1, no. 4, pp. 229–236, 1994.

[17] X. Wu and L. Xie, “On load balancing strategies for baggage screening at airports,” *Journal of Air Transport Management*, vol. 62, pp. 82–89, July 2017.

[18] R. D. Nelson and T. K. Philips, “An approximation for the mean response time for shortest queue routing with general interarrival and service times,” *Performance Evaluation*, vol. 17, no. 2, pp. 123–139, 1993.

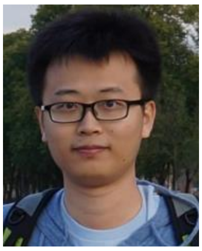
[19] X. Wu, L. Xie, and F. Lim, “EtherCAT-enabled next generation baggage handling systems,” in *Proc. IEEE 18th Conference on Emerging Technologies Factory Automation*, Sept. 2013, pp. 1–6.

[20] B. Galloway and G. P. Hancke, “Introduction to industrial control networks,” *IEEE Communications Surveys Tutorials*, vol. 15, no. 2, pp. 860–880, 2013.

[21] R. Sousa, P. Pedreiras, and P. Gonalves, “Enabling IIoT IP backbones with real-time guarantees,” in *Proc. IEEE 20th Conference on Emerging Technologies Factory Automation*, Sept. 2015, pp. 1–6.

[22] M. Johnstone, D. Creighton, and S. Nahavandi, “Simulation-based baggage handling system merge

analysis," *Simulation Modelling Practice and Theory*, vol. 53, pp. 45–59, 2015.
[23] G. Schäfer, "Material-flow control for collision avoidance in a conveyor system," U.S. Patent 12 642 748, Jun 24, 2010.
[24] S. Gasperin and D. Jodin, "Dynamic merge of discrete goods flow–impact on throughput and efficiency," *Logistics Journal*, no. 1, 2012.
[25] R. M. Wiese and I. J. W. Cottrell, "Baggage claim security device," U.S. Patent Application 20 110 132 726, Jun. 9, 2011.
[26] X. Fang, K. Lim, L. Kyaw, X. Wu, and H. Yang, "Motor drive controller," U.S. Patent Application 20 150 012 140, Jan. 8, 2015.
[27] BEUMER Group. 2D E tray sorter with contactless energy supply. [Online]. Available: https://www.beumergroup.com/uploads/tx_bbbrochures/beumer_e_tray_sorter_en.pdf



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