DIGITAL TWIN-DRIVEN SIMULATION FOR A CYBER-PHYSICAL SYSTEM IN INDUSTRY 4.0

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Abstract: *Nowadays, digital twin technology enables autonomous objects to mirror the current state of processes and their own behaviour in interaction with the environment in the real word. Cyber-physical systems (CPS) are increasingly communicating with each other and with human participants in real time via the Internet of things. This study focuses on attaining digital twin-driven simulation and implement simulation experiments with real-time data. Using a distributed model equipped with sensor as the physical system, a simulation model is constructed to reflect the physical system and simulation experiments are carried out. The proposed modelling method can be further applied in the simulation-based support tools for decision-making with real-time data.*

Key words: *Digital Twin, Industry 4.0, Physical/Cyber Space, Simulation*

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1. Introduction

The increasing customization of products will require dramatic changes in the market, forcing manufacturing to cope with complex and uncertain situations with flexibility and adaptability. In 2010, the German government initiated the concept of "Industrie 4.0" to promote its economic development and pursue stronger global competitiveness in manufacturing. The fourth industrial revolution (Industry 4.0) is now a collective term for a number of technologies involving automation, data exchange, and manufacturing that include cyber-physical systems (CPS), the Internet of things (IoT), and cloud computing (Kukushkin et al., 2016; Takakuwa, 2016).

CPS refers to a new generation of systems with integrated computational and physical capabilities that can interact with each other and with humans in real time over new modalities (Baheti & Gill, 2011). Digital twin technology is a methodology that enables autonomous objects (products, machines, etc.) to link the current state of their processes and behaviour in interaction with the environment of the real world. In this manner, manufactured products could increasingly employ converged cyber-physical data to become smart products that incorporate self-management capabilities based on connectivity and computing technology. Under data twinning, manufacturing machines become software- enhanced machinery equipped with sensors and actuators with computing power that can respond quickly to uncertain situations (Almada-Lobo, 2015). Furthermore, Simulation is a thoroughly proven approach to analysing system behaviour and design, which can conduct numerical experiments at a low cost. As a fidelity simulation method, digital twin can be used not only during system design but also during runtime to predict system behaviour online (Gabor et al., 2016).

The topics of CPS and digital twin have received increasing attention from researchers in recent years. Lee et al. (2015) defined a five-level (Connection, Conversion, Cyber, Cognition, Configure) architecture for CPS. Gabor et al. (2016) presented an architectural framework centred on the information flow within a CPS that incorporates a digital twin. Uhlemann et al. (2017) presented an approach to demonstrate the potential for real-time data acquisition using a digital twin concept. Most of these studies focused on the modelling concepts and framework of a CPS digital twin.

The goal of this study was to build a simulation model to reflect a physical system and then to use the resulting digital twin system to carry out experiments in the run-time.

2. Digital Twin

The digital twin paradigm has been applied in the NASA U.S. Air Force Vehicles project (Boschert & Rosen, 2016), where it was defined as,

"A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin."

The digital twin concept model contains three primary components (Grieves, 2014):

1) A physical object in real space;
2) A virtual object in virtual space;
3) Data and information connections that converge the physical and virtual systems.

The characteristics of a digital twin can be summarized as real-time situation reflection, physical/ cyber convergence and interaction, and self-evolution. In the manufacturing field, sensor-equipped machines could collect data in real-time from the production system. By connecting physical and cyberspace, the digital twin would reflect the system's real state. By updating data in real time, the model can undergo continuous improvement by comparing cyber space with physical space in parallel (Boschert & Rosen, 2016; Tao et al. 2017).

3. Modelling Framework

The composition and modelling framework of a CPS are shown in Fig. 1. The system comprises physical space, cyber space, and connected data that tie the two together.

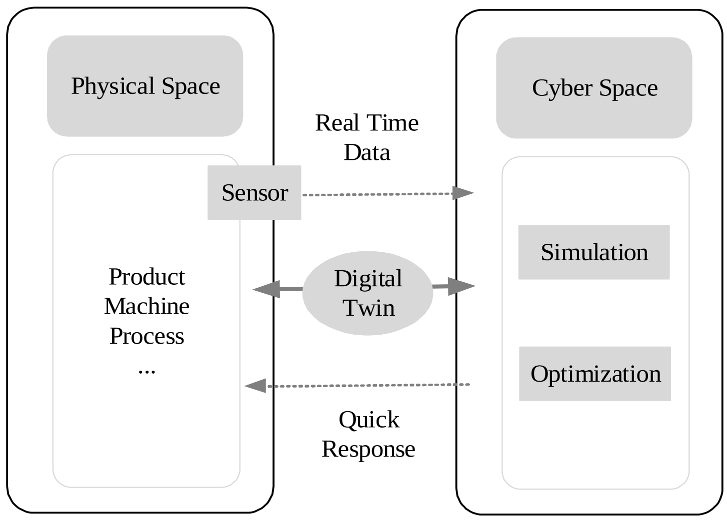

Fig. 1. Composition and the modelling framework of the CPS.

Based on the digital twin concept, sensor and data communication technology is employed to update the twin of the physical system in real time and the real-time data of an object in the physical space is transmitted to a constructed cyber simulation model to obtain linkage between cyber and physical space.

On the other hand, with the collected real-time and historical data, statistical analysis, intelligent system evaluating, forecasting and decision-making support can be performed online in the real time.

4. Simulation

4.1 Physical System

This section illustrates an example of a real physical system that was modelled based on digital twin concept. For this purpose, a distributed model called a mini-vehicle system was used as the physical system object in the study. An image of the distributed system is shown in Fig. 2. The mini-vehicle is driven by dry battery and controlled by an on/off switch; as long as the switch is turned "on," the vehicle continues to run until the battery runs down. In this manner, the mini-vehicle model can be seen to represent a flow production line, with the defined position (as illustrated in Fig. 2) assumed to represent a processing point.

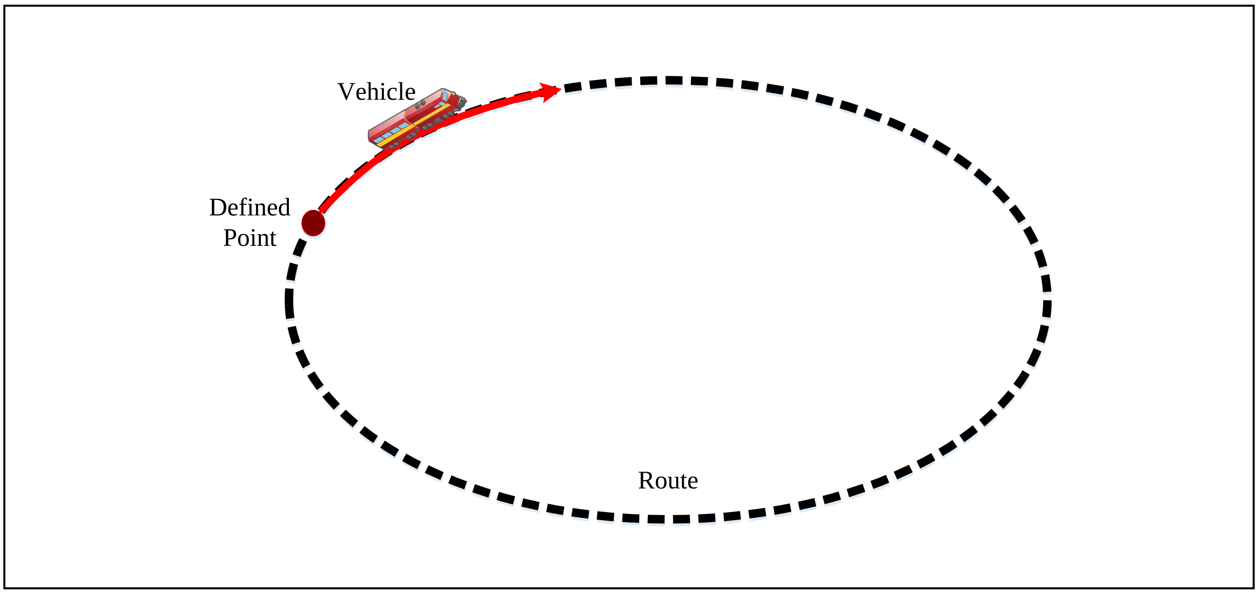

Fig. 2. Image of the distributed model.

In the study, a light sensor (peak wavelength 540 nm ***) was set at the position of the defined point shown in Fig. 2. The sensor generates an output signal (0/1) indicating the intensity of light. To acquire real-time data from system, a simple shading item was tied to the left side of the vehicle. The signal was set to turn to *one* when the received light wavelength was less than 100 nm and to remain at *zero* otherwise. In this manner, a changed signal could be sent by the sensor when the vehicle passed the defined point.

Furthermore, an Excel VBA program was developed to record the times at which the sensor single turned to one, i.e., the times at which the vehicle passed the defined point. The time difference between each succeeding one signal could therefore be defined as the system cycle time, allowing real-time data from physical system to be recorded in the cyber system (in this case, i.e., in a Microsoft Excel Workbook).

To constructing the simulation model, two main objectives were as follows:

1) To reflect the physical system's real situation for the purpose of using sensing data;
2) To experimentally assess the ability of the twin model to use real-time and historical data.

4.2 Digital Twin-driven Simulation

1) Simulation Model

To achieve the first objective above, a simulation model to reflect a real distributed model was constructed. The model was developed using the simulation software Arena. The main parameter used in the model is the system cycle time, which is defined as a route time required for the entity to travel through the defined point.

Additionally, the ReadWrite module was used to import the real-time cycle time from Microsoft Excel into the Arena model.

2) Improved Model

To achieve the second objective, the simulation model was improved with the following procedures: Firstly, a VBA input interface was developed to define a lap number that implement the experiment. Subsequently, run the simulation model. The model reads the cycle time data acquired from the sensor, which exactly like the processes discussed in the 4.1, until the defined number of laps is reached. From the (defined number+1) th lap, the cycle time of the model was generated randomly based on the average and standard deviation of the historical data. An Excel VBA program was designed to control the model. The logic procedure of the program is shown in Fig. 3.

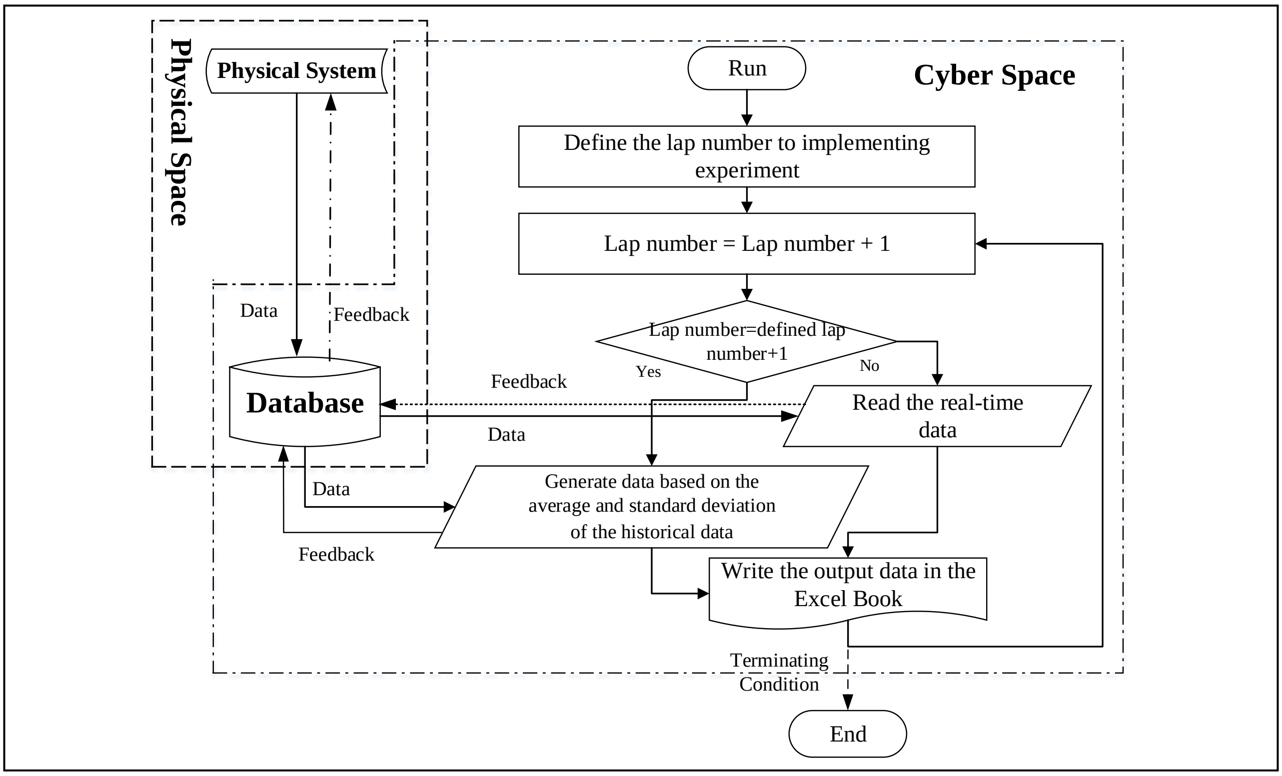

Fig. 3. Logic procedure of the VBA program.

By combining the simulation capabilities of Arena and VBA via the sensor data, a customized integrated simulation model could be constructed that is both dynamic and flexible.

4.3 Experiments

Simulation Experiments were designed to demonstrate that the model can reflect the system's real state and implement run time experiments using historical data.

In this case, the lap number to generate cycle time based on the historical data was set to 30. A screen shot of the simulation model in the run mode is shown in Fig. 4. A partial output data example of the model is shown in Tab. 1. There are five columns in the Tab. 1. Column A shows the times at which the vehicle passes the defined point, as recorded automatically by light sensor. Column B shows the difference (millisecond) between the time in column A and 0:00:00 of that day. Column C shows the cycle time calculated from the differences between the adjacent rows in column B. Column D shows the model input data using as the vehicle route time. Moreover, Column E shows the output of the cycle time written by the simulation while the model is running.

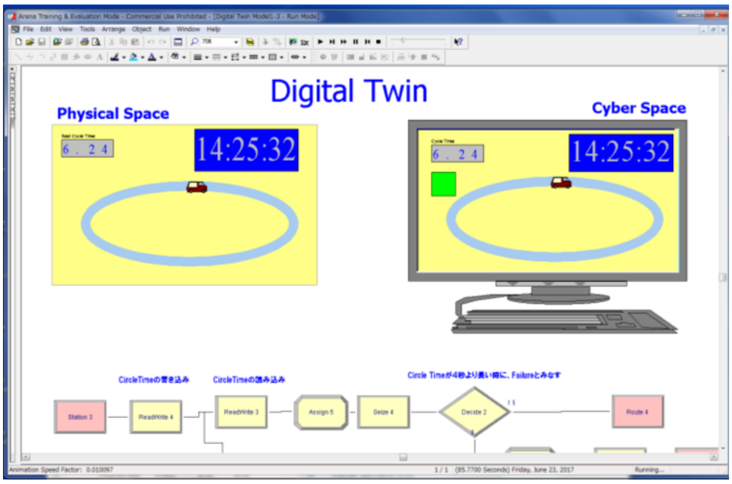

Fig. 4. A screen shot of the simulation model.

As shown in Tab. 1, the output cycle time from 1st to defined (30th) laps is the same with the sensor tracking data in the real-world system, which proved that the simulation model reflects the physical system real situation correctly. Whereas, cycle time from the 31st lap is not equal to the corresponding real data from physical space. The model uses an estimated cycle time based on historical data, which shows that the simulation experiments can be carried out successfully in the run-time.

5. Conclusion

Under the Industry 4.0 environment, physical space can be connected with cyber space via IoT. A digital twin-driven model was developed as a preliminary study, using a distributed model equipped with sensors as a physical system. It was found that the model could reflect real situation of the physical system with the real-time data. In addition, experiments were executed to evaluate the system performance in terms of its ability to simulate run-times in the real system.

The proposed modelling method for capturing real-time data together with simulation experiments can be further applied in the implementation of simulation-based support tools. The resultant insights can be referenced for better decision-making on the corresponding physical system. The distributed model used in the study was a rather simple system; further studies will be performed for actual manufacturing systems.

	A	B	C	D	E
1	14:24:38.570	51878.57	6.13	6.13	6.13
2	14:24:44.700	51884.7	6.09	6.09	6.09
3	14:24:50.790	51890.79	6.02	6.02	6.02
4	14:24:56.810	51896.81	6.05	6.05	6.05
5	14:25:02.860	51902.86	6.04	6.04	6.04
6	14:25:08.900	51908.9	6.16	6.16	6.16
7	14:25:15.060	51915.06	6.10	6.10	6.10
8	14:25:21.160	51921.16	6.08	6.08	6.08
9	14:25:27.240	51927.24	6.16	6.16	6.16
10	14:25:33.410	51933.41	6.18	6.18	6.18
11	14:25:39.580	51939.58	6.16	6.16	6.16
12	14:25:45.740	51945.74			
[illegible]	[illegible]	[illegible]	6.05	6.05	6.05
25	14:27:05.900	52025.9	6.22	6.22	6.22
26	14:27:12.120	52032.12	6.18	6.18	6.18
27	14:27:18.300	52038.3	6.16	6.16	6.16
28	14:27:24.460	52044.46	6.18	6.18	6.18
29	14:27:30.640	52050.64	6.18	6.18	6.18
30	14:27:36.820	52056.82	6.21	6.21	6.21
31	14:27:43.020	52063.02	6.12	6.15	6.15
32	14:27:49.140	52069.14	6.16	6.23	6.23
33	14:27:55.300	52075.3	6.15	6.22	6.22
34	14:28:01.450	52081.45	6.11	6.07	6.07
35	14:28:07.560	52087.56	6.10	6.20	6.20
36	14:28:13.660	52093.66			
[illegible]	[illegible]	[illegible]	6.05	6.13	6.13
46	14:29:14.610	52154.61	6.08	6.07	6.07
47	14:29:20.700	52160.7	6.05	6.18	6.18
48	14:29:26.750	52166.75	5.98	6.18	6.18
49	14:29:32.730	52172.73	6.02	6.23	6.23
50	14:29:38.750	52178.75	6.04	6.16	6.16

Tab. 1. Partial data example from the experiment.

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7. References

Almada-Lobo, F. (2015). The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES). *Journal of Innovation Management*, Vol.3, No.4, pp. 16-21, 2183-0606

Baheti, R. & Gill, H. (2011). Cyber-physical systems, *The Impact of Control Technology*, pp. 161-166, 0018-9162

Boschert, S. & Rosen, R. (2016). Digital twin - the simulation aspect, In: *Mechatronic Futures - Challenges and Solutions for Mechatronic Systems and their Designers*, Hehenberger, P. & Bradley, D., (Ed.), pp. 59-74, Springer International Publishing, 978-3-319-32154-7, Switzerland

Gabor, T.; Belzner, L.; Kiermeier, M.; Beck, M. T. & Neitz, A. (2016). A simulation-based architecture for smart cyber-physical systems. *Proceedings of 2016 IEEE International Conference on Autonomic Computing*, Kounev, S.; Giese, H. & Liu, J. (Ed.), pp. 374-379, 978-1-5090-1654-9, Wurzburg, Germany, July 2016, Conference Publishing Services, Washington

Grieves, M. (2014). Digital twin: manufacturing excellence through virtual factory replication, *Available from:* http://innovate.fit.edu/plm/documents/doc_mgr/912/1411.0_Digital_Twin_White_Paper_Dr_Grieves.pdf *Accessed:* 2017-9-8

Kukushkin, I.; Zavrazhina, A.; Grabenweger, J.; Kildibekov, A.; Katalinic, B. & Haskovic, D. (2016). Model-based concept for scheduling analysis of packaging lines, Proceedings of the 26th DAAAM International Symposium,B. Katalinic (Ed.), pp.1149-1157, 978-3-902734-07-5, DAAAM International, Vienna, Austria

Lee, J.; Bagheri, B. & Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, Vol 3, pp. 18-23, 2213-8463

Takakuwa, S. (2016). Operations management of shop floor in the Industry 4.0 environment. *Proceedings of Asia Pacific Conference on Information Management 2016*, Sato, O.; Minh, N. D.; Jung, C. Y. & Mao, J. (Ed.), pp. 251-260, 978-604-62-6481-1, Hanoi, Vietnam, October 2016, Vietnam National University Press, Hanoi

Tao, F.; Cheng, Q.; Qi, M.; Zhang, H. & Sui, F. (2017). Digital twin-driven product design, manufacturing and service with big data. *Available from:* https://doi.org/10.1007/s00170-017-0233-1 *Accessed:* 2017-9-8

Uhlemann, T. H.-J.; Schock, C.; Lehmann, C.; Freiberger, S. & Steinhilper, R. (2017). The digital twin: demonstrating the potential of real time data acquisition in production systems. *Procedia Manufacturing*, Vol 9, pp. 113-120, 2351-9789

***https://www.seeedstudio.com/Grove-Light-Sensor-v1.2-p-2727.html - GROVE - light sensor v1.2, *Accessed:* 2017-9-8