Digital Twin Development for Serial Manipulators: Data Driven Optimized Planning and Sequencing of Tasks

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INTRODUCTION

Digital Twin (DT) has been identified as one of the key technologies in the era of smart manufacturing to achieve several business benefits, such as improvements in productivity, efficiency and reduction of time to market for new products. Since the concept of a DT model was first introduced, research and development efforts in this topic were scarce due to the immaturity of enabling technologies.[1] Fortunately, recent breakthrough advancements in high performance computation engines, data acquisition systems, communication protocols, cloud computing, big data analytics and Artificial Intelligence (AI) algorithms have enabled the widespread implementation of DT and allowed for more studies on this topic.[2] [3] Studies in this area focus mostly on concepts, modeling approaches, frameworks and use cases of DT.[4] For example, various use cases of DT were presented, such as designs of products and production lines,[5] [6] optimization of production processes[7] and shop floor DT.[8] Tesla, Siemens, General Electric, Dassault Systems and PTC have also implemented DT concepts in order to enhance their manufacturing capability.[9] Meanwhile, some researchers concentrate on

[1] Grieves, M. (2014). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. US Florida Institute of Technology.

[2] Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. Procedia Manufacturing, 11, 939-948.

[3] Tao, F., Qi, Q., Wang, L., Nee, & A.Y.C. (2019). Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. Engineering, 5, 653-661.

[4] Liu, Q., Liu, B., Wang, G., & Zhang, C. (2019). A comparative study on digital twin models. AIP Conference Proceedings, 2073.

[5] Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., & Nee, A. Y. C. (2019). Digital twin-driven product design framework. International Journal of Production Research, 57(12), 3935-3953.

[6] Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J. (2017). A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. IEEE Access, 5, 26901-26911.

[7] Uhlemann, T. H. J., Lehmann, C., & Steinhilper, R. (2017). The digital twin: Realizing the cyber-physical production system for industry 4.0. Procedia Cirp, 61, 335-340.

[8] Tao, F., & Zhang, M. (2017). Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing. IEEE Access, 5, 20418-20427.

[9] Schleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin for design and production engineering. CIRP Annals, 66(1), 141-144.

background studies, such as developing frameworks for applications of DT.[10] [11]

Although studies on DT are various, its prevalent implementation has not been realized. One of the main reasons is that companies still encounter challenges to identify the implementation scope where DT will create worthwhile business value.[12]

Motivated by the above research gap, in this article, a practical use case of DT developed and implemented in the Model Factory (MF) program at Advanced Remanufacturing and Technology Centre (ARTC), Singapore, is introduced. In this use case, a DT is developed for a gearbox assembly line automated by a collaborative robot (cobot) for new gearbox sub-assembly configuration requirements. Once the customer order containing customized configuration of gearbox sub-assembly is received, new assembly and component designs are trained to build with an object recognition model using machine vision and deep learning algorithms. The trained model is integrated with the desired operation sequence to pass the information to the robot motion planning software. Next, robot planning and simulation are executed to teach the robot with expected movements. Subsequently, the virtual robot setup enables engineers to review and verify the new robot motion path. Finally, the approved path is released to the robot controller linked with the programmable logic controller (PLC) of the assembly line to execute assembly operations. During training and operation, the cobot keeps publishing its critical status information to the virtual environment in real time. By following these steps, which are also aligned with the vision of a cyber-physical system implementation in Industry 4.0,[13] [14] the order is executed with efficient monitoring, planning, simulation and optimization. Such an implementation is novel as it is generic and can be used for any serial manipulators. This differs from the state of the art which is targeted towards specific machine or work cell DT POCs.

In the first section of this article, the definition and advantages of a DT model will be recapped. Next, the DT model developed by ARTC will be presented. In particular, the novelty and innovation of the development of the DT model will be discussed in detail.

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[10] Söderberg, R., Wärmefjord, K., Madrid, J., Lorin, S., Forslund, A., & Lindkvist, L. (2018). An Information and Simulation Framework for Increased Quality in Welded Components, CIRP Annals, 67:1, 165–168.

[11] Zhuang, C., Liu, J., & Xiong, H. (2018). Digital twin-based smart production management and control framework for the complex product assembly shop-floor. The International Journal of Advanced Manufacturing Technology, 96(1-4), 1149-1163.

[12] Parrott, A., & Warshaw, L. (2017), Industry 4.0 and the digital twin. Deloitte University Press.

[13] Luo, W., Hu, T., Zhang, C., & Wei, Y. (2019). Digital twin for CNC machine tool: modeling and using strategy. Journal of Ambient Intelligence and Humanized Computing, 10(3), 1129-1140.

[14] Zhao, R., Yan, D., Liu, Q., Leng, J., Wan, J., Chen, X., & Zhang, X. (2019). Digital Twin-Driven Cyber-Physical System for Autonomously Controlling of Micro Punching System. IEEE Access, 7, 9459-9469.

Finally, the authors will draw some conclusions and suggest future directions for the research topic.

DIGITAL TWIN CONCEPT

Before the use case of the DT model of this article is presented in detail, it is worthy to discuss background knowledge about the DT concept. Enders and Hoßbach[15] summarized the essential features of a DT as follows: First, a DT is defined as a virtual model of a physical object, which can be a product, a machine, a process, a factory, a supply chain, etc. Second, the physical object is connected with its twin. Third, thanks to the connection, the DT can reflect current or historical behaviors of the object, simulate and predict its future states, and control it. Finally, these features must create observable business values.

In order to explain how a DT can provision enterprises with business values, its fundamental components should be well understood. According to Parrott and Warshaw, a DT is constituted by the following components: sensors, data, integration, analytics, DT application and actuator. These components are depicted in Figure 1. Sensors are installed properly to collect data of the physical object that is required to realize the pre-defined business values. Sensor data will then be combined with data from enterprise systems such as Enterprise Resource Planning (ERP), PLM and Manufacturing Execution System (MES). The combined data will then be aggregated accordingly depending on functions of the DT. The bridge between the physical object and its DT is the integration that includes edge, communication interfaces and security. After data is collected, aggregated and transferred to the DT through the integration, analytics techniques such as AI, machine learning and simulation, are executed to monitor, simulate and predict behaviors of the physical object. Subsequently, an application is required to combine all the components and realize the business values. The application can visualize the variations of the physical object, multi-layer data and business related KPIs in real-time. It can also reflect the deviation of the current performance to the expected performance. In addition, it can derive insightful advice to improve the performance. Finally, the application can suggest actions by the analytics to control or interfere the physical object when it is necessary through an actuator mechanism, which is the final element of the DT.

In the next section, the DT model developed by ARTC and its business values will be presented and explained in detail.

[15] Enders, M. R., & Hoßbach, N. (2019). Dimensions of Digital Twin Applications-A Literature Review.

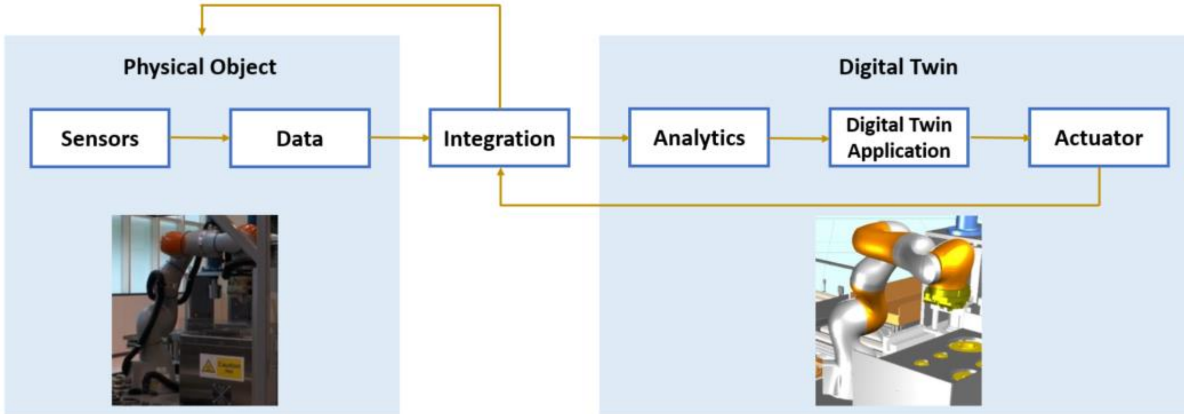

Figure 1: Essential Components of a Digital Twin

DIGITAL TWIN FOR SERIAL MANIPULATORS

In Singapore, manufacturing is a key pillar of the economy. In order to remain competitive in manufacturing, the Singapore government invested in R&D and promoting technology adaption towards the Future of Manufacturing (FoM) to open up new manufacturing business models. The Agency for Science, Technology and Research (A*STAR) led the implementation of FoM in Singapore. A*STAR has created two Model Factories, namely Model Factory @ SIMTech and Model Factory @ ARTC.[16]

The full gearbox production is carried out in Model Factory (MF) @ ARTC testbeds. The testbeds include the gearbox shaft fabrication process by Computer Numerical Control (CNC) machines, gearbox assembly line, warehouse, Coordinate Measuring Machine (CMM), automated guided vehicle (AGV), Manufacturing Intelligence Control Room (MICR), Virtual Manufacturing Lab (VML) and more. The entire workflow of gearbox production running in MF @ ARTC is designed and based on the Reference Architecture Model Industrie 4.0 (RAMI 4.0) as shown in Figure 2. The RAMI 4.0 consists of a three-dimensional coordinate system that describes all important aspects of Industrie 4.0, such as hierarchy levels, life cycle and value stream and layers. The hierarchy levels represent the different functionalities in the MF. The life cycle axis represents the life cycle of facilities and products for the life cycle management while the vertical layer axis describes the breakdown properties of a machine or complex system.[17] The vertical architecture dimension is made up of six layers and describes the top-down approach derived

[16] A*STAR. "Future of Manufacturing Initiative". September 2017 2014. Last visit March 2019. Available online: https://bit.ly/2Y4Wac2.

[17] Schweichhart, K., Reference Architectural Model Industrie 4.0 (RAMI 4.0), Dr. Karsten Schweichhart, https://ec.europa.eu/futurium/en/system/files/ged/a2-schweichhart-reference_architectural_model_industrie_4.0_rami_4.0.pdf.

from a business need to the actions of physical assets in the real world.

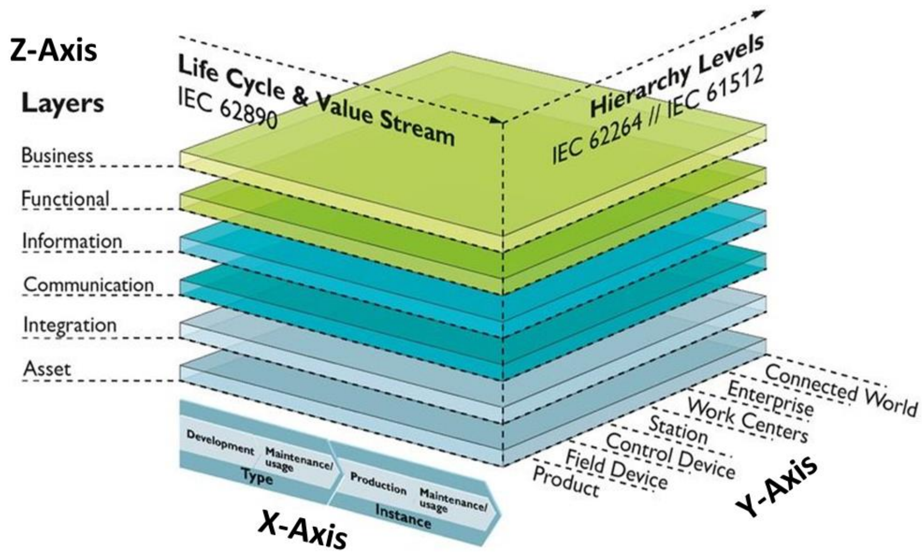

Figure 2: The Reference Architectural Model for Industrie 4.0 (RAMI 4.0) coordinate system[16]

Every asset in MF shop floor is designed and modeled with an asset administration shell (AAS). An AAS is a knowledge structure that explains the asset type, its technical functionality and its relationship with other assets.[18] The reason for modeling the assets with the AAS concept is to provide the efficient integration of assets in a modular way with high agility. There is vertical integration constructed from machines, equipment, stations and sensors to the ERP system; and the horizontal integration between all assets at the shop floor is also established through an Industrial IoT (IIoT) platform.

The gearbox production workflow in MF @ ARTC program is illustrated as shown in Figure 3. This workflow is supported by the digital system architecture described in Figure 4. At the start of gearbox production business, the e-commerce web page which connects with the ERP system obtains any gearbox order from the customers. The sale orders are planned and scheduled for the production accordingly with ERP and scheduling systems. Those two systems are connected with an IIoT software platform to integrate with other system in the gearbox production lines. The MES software links with the IoT platform and other major

[18] Seif, A., Toro, C., & Akhtar, H. (2019). Implementing Industry 4.0 Asset Administrative Shells in Mini Factories, 23rd International Conference on Knowledge-Based and Intelligent Information & Engineering Systems, Procedia Computer Science, Accepted and Presented

equipment of gearbox production, such as shaft fabrication CNC machines (NTX1000 and NLX2500), the gearbox assembly line and the warehouse. In the data aggregation system, hardware and software—for example, gateway server, database server, data acquisition (DAQ), data ingestion, data storage and edge analytic systems—are included. The outputs of DAQ and edge analytic software are integrated with the IIoT software platform for creating IoT applications at manufacturing sites. Each work station has an operator running MES to perform the work order arranged by the scheduling software. MES is configured by the station owners according to their respective standard operation procedures (SOP). The graphical user interface (GUI) of MES beside each station allows an operator to manage the work orders derived from the scheduling software. All required raw materials, fabricated shafts and completed gearboxes are located in the warehouse, and AGV is utilized to transport those materials to and from the warehouse via the docking station based on the operation requests through an IoT application. The inventory updates are directly linked to the ERP system from the warehouse. The data from sensors, actuators and machines of all stations on the shop floor are acquired with DAQ systems, and some data are transformed into useful data or information through edge analytic algorithms.

All those connections and integrations enable delivery of gearbox orders from customers more efficiently and effectively. The implementations of digital twin systems for the complex applications are not achievable and rational without the systematic data model, connection, communication and integration. Only with those capabilities, it is feasible that a customized gearbox sub-assembly order can be processed and delivered in relatively short time with minimum setup requirement using DT technology. In the next section, the authors will demonstrate how a customized order of gearbox sub-assemblies is handled and operated efficiently using a DT model with minimum interruption on the existing whole gearbox production workflow.

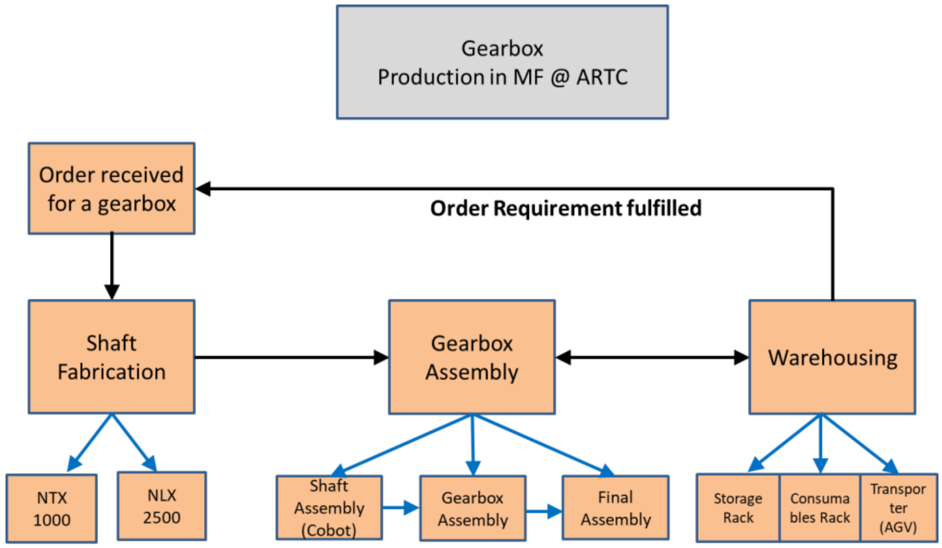

Figure 3: The work stations and their links in a gearbox production line at MF @ ARTC

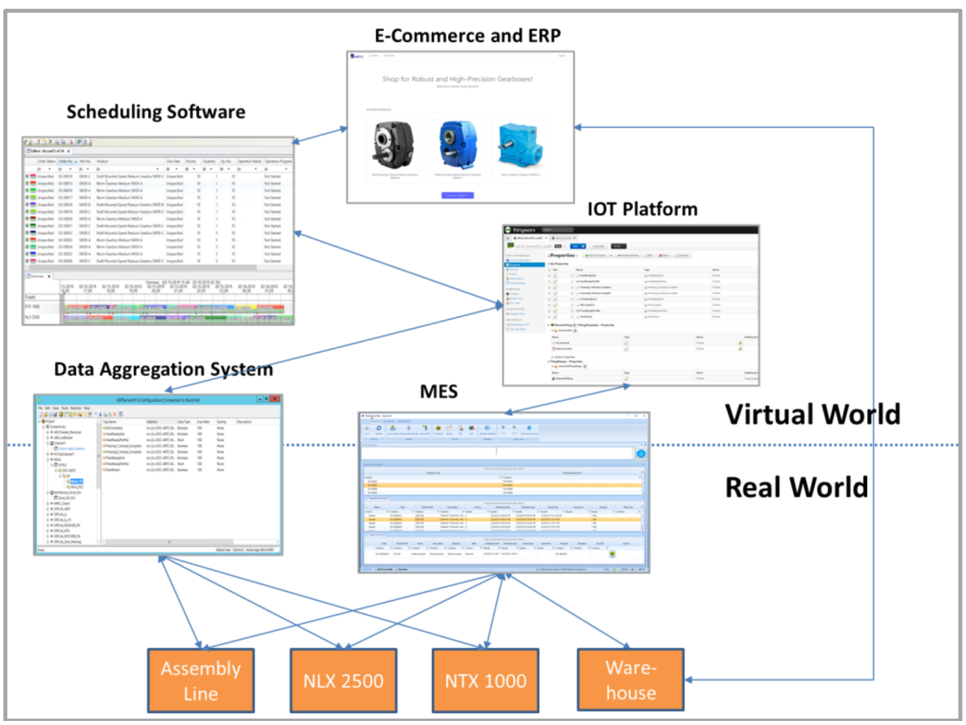

Figure 4: The system architecture of a gearbox production line at MF @ ARTC

Overview of the Digital Twin Model

The implemented manufacturing intelligence and capabilities in those testbeds will be demonstrated with the Manufacturing Magic Cube (MMC) concept. The MMC concept was evolved from the digital twin concept and is applied for a number of Industry 4.0 applications on the shop floor of MF @ ARTC. As the workflow of gearbox production running in MF @ ARTC is designed and models the assets with AAS, the data from equipment sensors and actuators could be collected systematically and converted as monitoring, signaling or controlling prerequisites of a digital twin application. The distributed data from physical sensors throughout the manufacturing process enable the digital twin to attain operational and environmental data on the shop floor. Those data are aggregated and advanced to integrate with the data acquired from the enterprise systems, such as ERP, MES and PLM via an IoT platform.

After communicating and integrating the data between the physical and digital worlds, the data are analyzed with analytic techniques and processed through algorithmic simulations and visualization procedures to deliver the gearbox production insights. In MF @ ARTC, the Virtual Manufacturing Lab (VML) testbed is designed to perform the operation monitoring, diagnostics, control and improvement processes with the simulated, optimized or analyzed solutions inside. After verifying the planned or optimized solution in the virtual workspace, the final decision will be made inside or through the Manufacturing Intelligence Control Room (MICR) if the solution will be preceded or revised again with the business data and perspectives. If the proposed solution is approved, the digital twin will integrate with the respective machine controllers and actuators to execute the physical process in the real world. This is the overall practice of the MMC concept in MF @ ARTC shop floor, as shown in Figure 5.

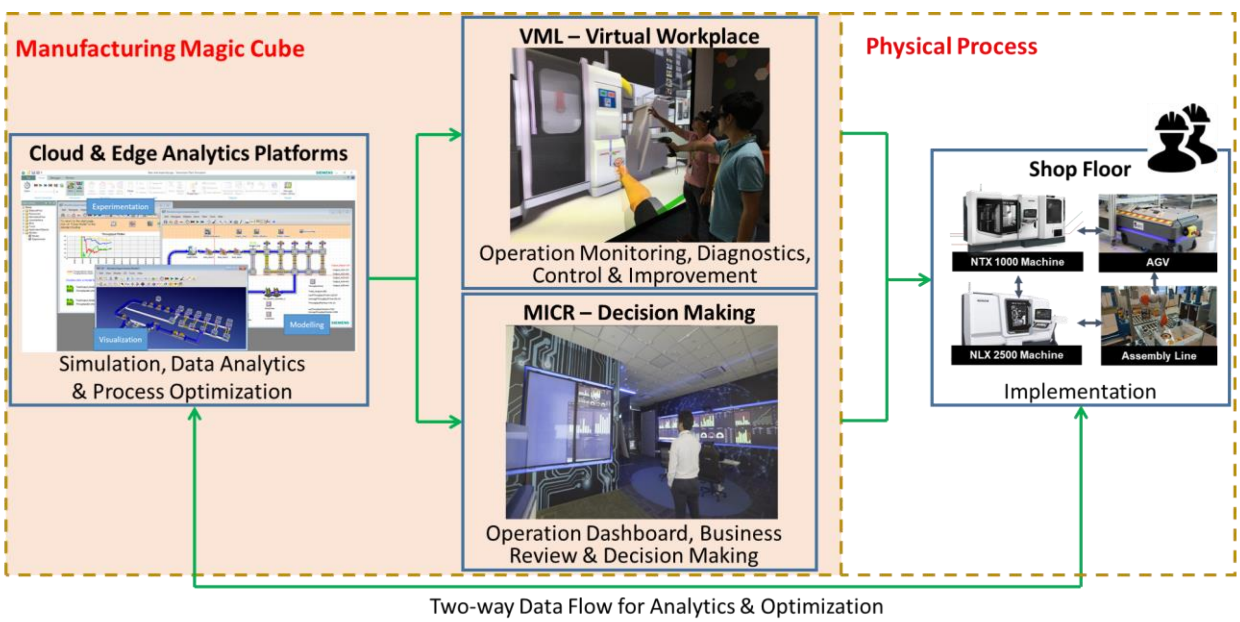

Figure 5: The overall workflow of the MMC concept in MF @ ARTC

Based on this MMC concept and method, the authors identify a use case of DT application related with the gearbox production line. A customized sale order, which contains the combination of shaft sub-assemblies consisted in a gearbox, is received from a customer to deliver in a high-priority setting. There are three types of shaft sub-assemblies: output, input and transfer. The production manager applies the MMC concept-based DT model in planning, simulating, monitoring, controlling and executing the resources of the production line to fulfill such a customized order.

Explanation of workflow, components, technologies

When a high-priority sale order of the combination of shaft sub-assemblies is received, the production manager requires planning, simulating, monitoring, verifying and executing the necessary tasks to fulfill the order efficiently with minimum interruption on the full gearbox production line. In order to achieve this business need, the manager utilizes the MMC DT model which requires developing two adaptable functions—collecting necessary raw materials and picking, placing and assembling shaft assembly parts. The assets and their connections involved in this operation are described in Figure 6. Hence, the digital architecture of production is modified with the Cobot Digital Twin application as in Figure 7.

The first task occurs at the smart warehouse and trolley docking area. The warehouse is equipped with a piezoelectric weighing machine for each part to obtain the real-time stock update. The inventory data is connected and integrated with an ERP system via an IoT platform. When the raw material stock level hits below the minimum setting, the required stock replenishing alert appears at the ERP, and the purchasing process for required materials is initiated. The material transportation is performed by an AGV between the warehouse and assembly line via the docking stations. The trolley carries the gearbox parts, and the AGV transports the trolley to any desired location on the shop floor. The trolley is prepared by a warehouse operator to be secured and fetched by an AGV from the docking area once the shaft assembly starts. The computer vision system with an intelligent part recognition system is equipped above the trolley to monitor the parts located there. The recognition system can identify the part types and count the quantity. It is also integrated with the IoT platform and notifies the operator at the warehouse dashboard to replenish the parts on the trolley if needed. The transportation of sub-assembly parts for the customized order only starts when the second task, the configurations of the specific sub-assembly process, is ready.

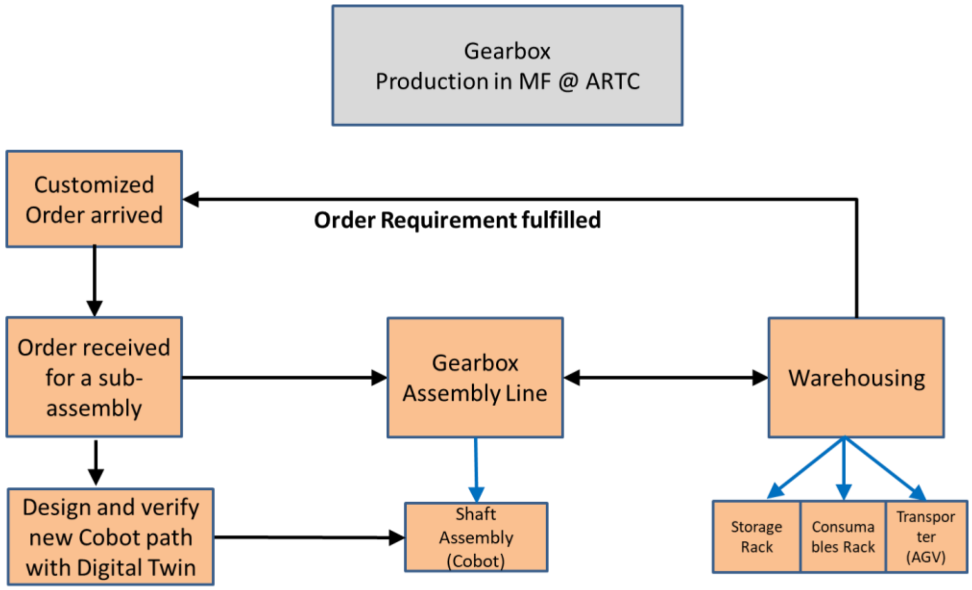

Figure 6: The work stations and their links in shaft sub-assemblies operations at MF @ ARTC

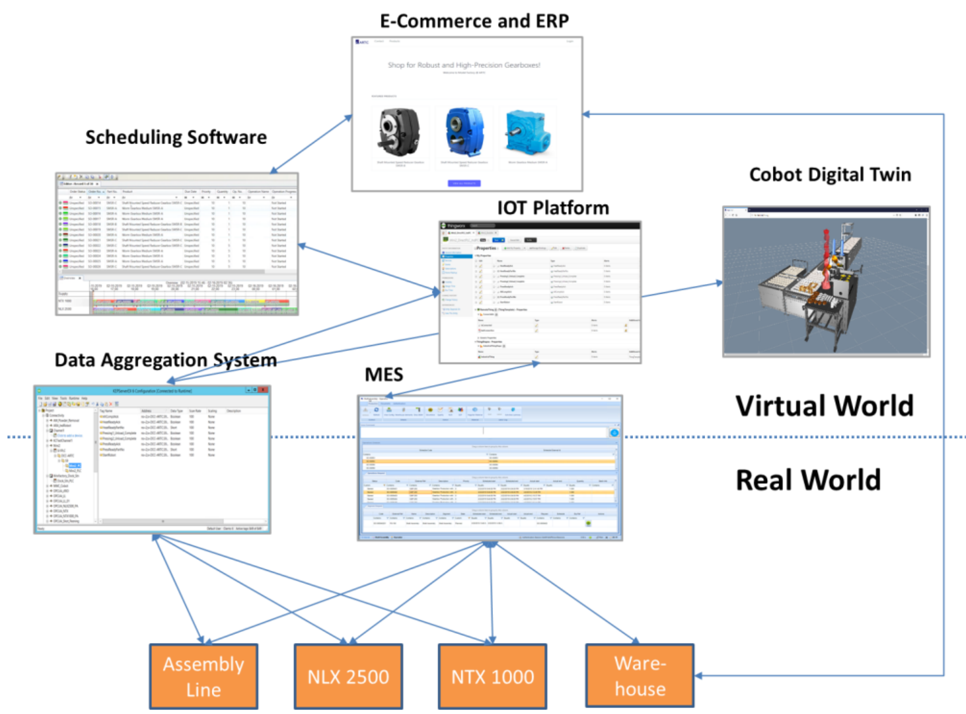

Figure 7: The system architecture of a gearbox production line at MF @ ARTC with a cobot Digital Twin

At the shaft assembly station, a cobot with intelligent object recognition system is an efficient solution to achieve the second function for the sub-assembly order.

Initially, the part recognition system of shaft assembly parts is constructed with the trained deep learning model using computer vision (CV) techniques. The CV system at the station requires a 3-dimensional (3D) camera in this application as the point cloud data provides more accuracy for cobot motion and material handling processes. Afterward, the new cobot motion planning and simulation for specific shaft assemblies are performed by a robotic engineer as shown in Figure 8. Once the new cobot motion path is achieved, the engineer can review and validate it with the virtual cobot in VML. When the confirmation is complete, the new cobot path is released to the robot controller, and the cobot setup is ready to execute the customized shaft sub-assembly operations.

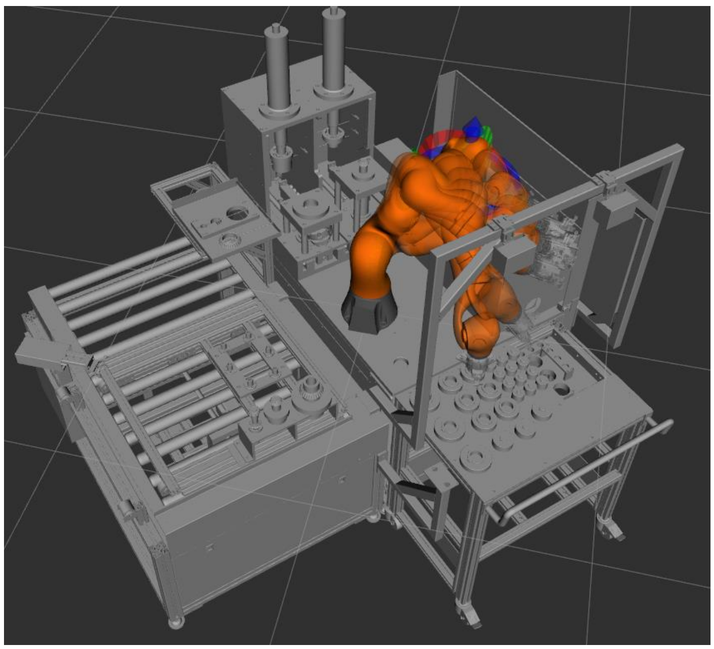

Figure 8: The cobot simulation model running in the robot motion planning software

Novelty & innovation of the DT model

In order to minimize the effect on the on-going full gearbox assembly line process, applying the cobot digital twin model to validate and verify a newly developed cobot motion plan is cost-effective and efficient. This is because the planning, simulation, analysis and verification of the new cobot motion plan can be completed with the virtual cobot (cobot DT model), which can then be connected to the simulation model or a real physical cobot on the shop floor, based on the requirements. In VML, the cobot DT model is running and links with the actual cobot at the shaft assembly station. The detail cobot DT design and implementation steps are published in a conference paper by Huynh et al.[19] The real-time cobot joint data from the cobot asset are streamed to the cobot DT model for live monitoring and synchronized cobot movements.

The robotic engineer starts working on creating the new cobot motion path virtually once he is notified about the customized work order from the manager. This process will not interrupt any operations on the on-going production line. There can be many iterations and validation processes carried out for developed simulation models, and the virtual cobot is useful for reviewing the new cobot path planning. As for the preparation of the customized work order, the deep learning model of assembly parts recognition is trained with computer vision techniques at the same time. Later, the trained part recognition model will be tested and integrated with the new motion plan for picking, placing and assembling accordingly for the shaft assembly process. The result of motion planning software is transferred to the cobot DT model (virtual cobot) for verification of correct cobot paths by the engineer. This is where the data is transformed into information used for effective decision-making. After confirmation, the motion plan is released through the information gateway to the robot controller.

Only after the verification of the new cobot path is completed in the virtual world, the final motion path is laid out into the robot controller which connects with a cobot at the shaft assembly station. Next, the engineer examines the actual cobot with a new path as a final test and releases for shaft sub-assembly productions. That will trigger the warehouse system to start delivering the necessary parts to the shaft assembly station by an AGV. Subsequently, the shaft assembly station operator starts the customized work order at MES, and the cobot assembles the sub-assemblies accordingly. The completed products are moved to the warehouse by the AGV and the smart inventory system informs ERP for the order completion.

In this use case, the communication and information flow between the associated assets on the shop floor are critical to realize the digital twin technology. With those capabilities, the monitoring and control of the production process and accessing enterprise information are possible for the production manager to make decisions in the MICR. Apprehending the resource requirements and planning necessary tasks are the initial steps taken by the manager to complete a customized order on time. Hence, once the cobot at the shaft assembly station is ready to perform the customized work order, this state triggers to allow that order to start in MES. That order is scheduled to proceed next at the assembly line in the MES interface as soon as the on-going work order is finished. The vertical integration of process, asset data and enterprise information at the IoT platform enables this operation. Once that work order is started, the appropriate raw materials are collected

[19] Huynh, B. H., Akhtar, H., & Myo, K. S. (2019). A Universal Methodology to Create Digital Twins for Serial and Parallel Manipulators, 2019 IEEE International Conference on Systems, Man, and Cybernetics, IEEE, Accepted.

and delivered to the assembly station to start assembling shaft assemblies as per the work order requirements. The detail work flow of implementing this manufacturing intelligence system of producing shaft sub-assemblies with DT is described in Figure 9.

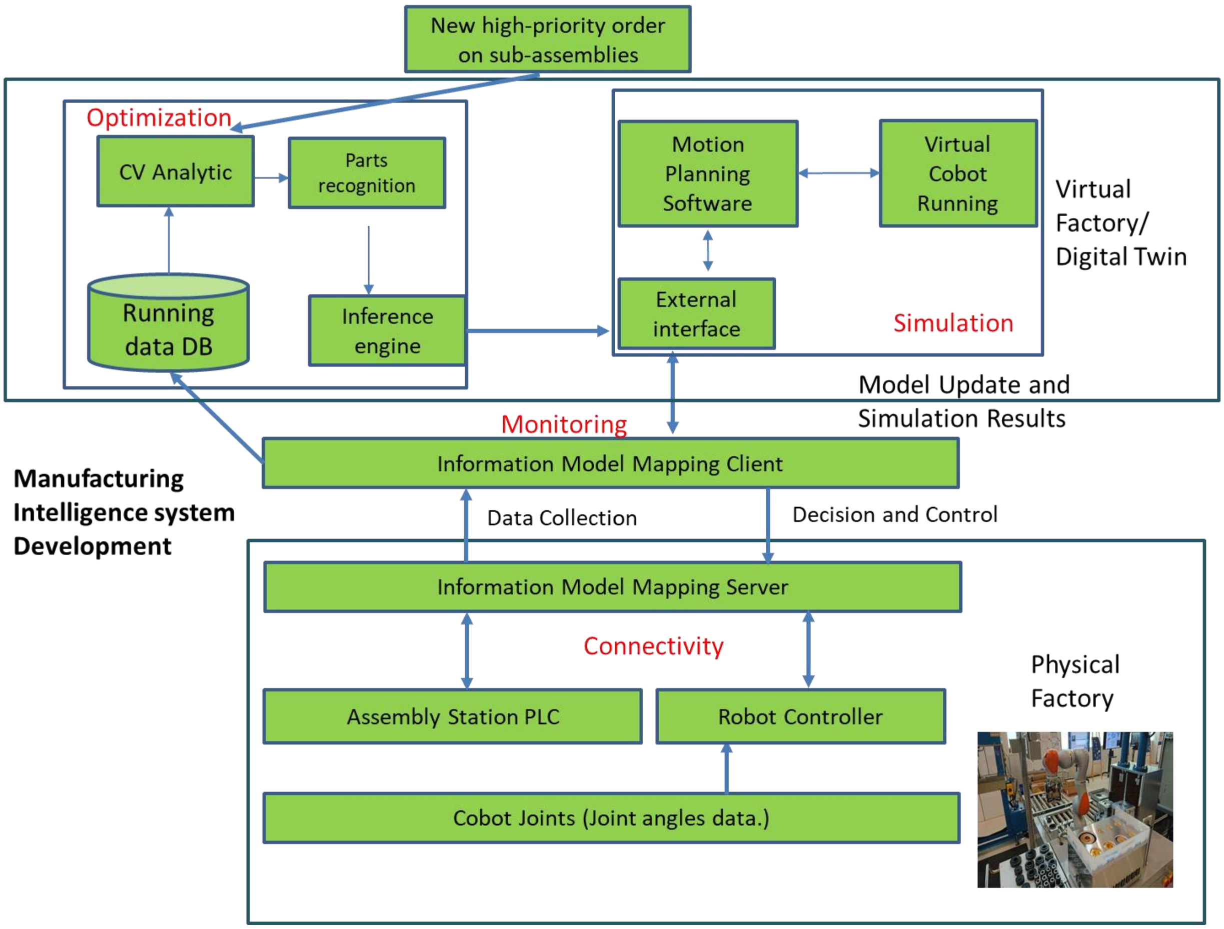

Figure 9: The detail work flow of sub-assemblies production with DT at Model Factory @ ARTC

The final implementations at the asset level, with the RAMI 4.0 layers describing how the business idea is implemented to the physical assets in the real world using a DT model, is shown in Figure 10. In this demonstration, the MMC-based DT cobot model is utilized to successfully deliver a high-priority shaft sub-assemblies order on time. Again, it is highlighted that this use case is convincing due to the RAMI 4.0 model structure of MF @ ARTC, the MMC concept and AAS implementations.

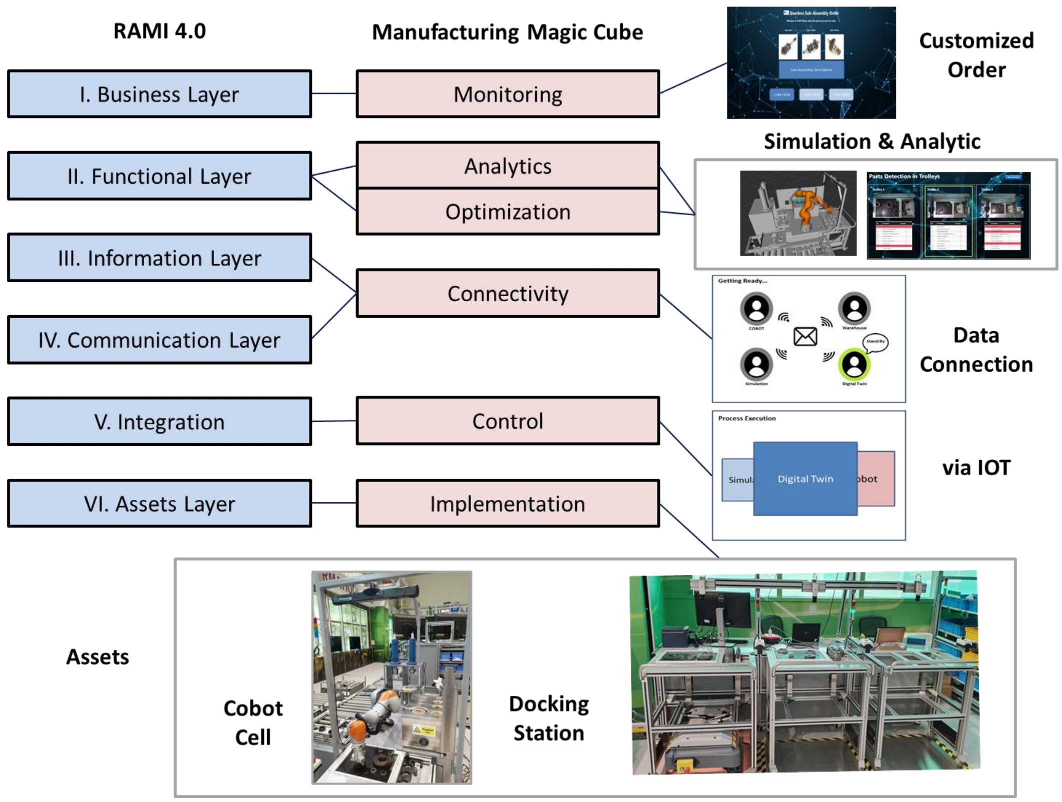

Figure 10: The implementations on the cobot cell and docking station with RAMI 4.0 layers and MMC based digital twin model

Challenges faced; Limitations & Lessons learned

Establishing the connectivity and integration between associated assets is essential to complete new gearbox assembly configurations demanded from any customized sale order. Amending some hardware and software configurations to integrate with the assets are definitely required, but they are challenging. Due to the nature of customized assembly configurations, the existing work flow and procedure of the shaft assembly process require to be reviewed and modified when necessary, as there are some technical limitations to implement changes in the current work setting in this use case.

For example, the shaft assembly process of a whole gearbox assembly is designed to follow the fixed sequence of cobot motions for the conventional work orders. To change the fixed configurations, adding an industrial PLC as a cobot motion controller permits more flexible and adaptive motion sequences of the shaft assembly process demanded by any particular customized order. However, handshaking of signals between the PLC and robot controller is required to perform customized shaft assemblies, and those hardware must be connected and integrated with other assets through the IoT platform. After this function is created, the limitation of carrying out the business of new shaft sub-assembly production is removed. Hence, the vertical integration from ERP to the associated assets and the horizontal integration of sensors, actuators and those assets on the shop floor are completed. Therefore, a work order of customized sub-assemblies is able to be accomplished efficiently and effectively.

CONCLUSION AND FUTURE DIRECTIONS

In this article, the feasible use case of a DT model is identified and demonstrated by fulfilling an order containing customized configurations of gearbox shaft sub-assemblies with high efficiency and minimized time-to-market of new products. The customized order is completed with efficient monitoring, planning, simulation, optimization and execution with an MMC-based cobot DT model. Such an implementation with the MMC concept is novel, yet it is generic to apply for any serial manipulator.

With the RAMI 4.0 model and AAS structured architecture, the business need of delivering a high-priority customized shaft assembly drives this use case, and the digital facilities at MF @ ARTC Singapore allow successful demonstrations. After realizing the required resources and configurations, the functions of necessary assets are identified and planned for next actions. The communication and information flow between the associated assets on the shop floor are critical to realize the digital twin technology. The real-time data from those assets require synchronizing and transforming to the useful information correspondingly for effective decision-making. In order to ensure this outcome, the integration of asset data at the IoT platform is also essential with the structured data model. All those requirements are fulfilled in MF @ ARTC, and the digital twin application can successfully deliver the high-priority shaft sub-assemblies order. The scalability of this implementation is straightforward as the assets are structured with an AAS model. Therefore, the demonstration of multiple cobots working together in many gearbox assembly lines is feasible for producing more customized gearbox assembly configurations in the future.

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