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Research paper

Solution pattern for machine-to-cloud integration in medical robotics

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Abstract

Industrial Revolution 4.0 is bringing a paradigm shift into the industrial world and also indirectly revolutionising the healthcare domain. The Internet of Things (IoT) brings a revolution in the healthcare industry and medical education. One of the vital developments involves integration of medical devices and robots with cloud through the internet. This paper thus describes a general solution guideline for developing the IoT compliant medical robots. For that, an upper limb part-task trainer for upper limb spasticity evaluation training for rehabilitation named BITA is used to demonstrate how cloud integration could be achieved at its system-level design.

Keywords: *Machine to Cloud Integration; Cloud Technology; Medical Robotics; Medical Education; Smart Healthcare.*

1. Introduction

The paradigm shift brought by the fourth industrial revolution which is also known as Industry 4.0 is not only revolutionising the manufacturing processes but also reforms the healthcare industries. The idea of smart factory which has emerged as a consequence of the increasingly convergence of the physical and cyber worlds has also brought the current healthcare and medical education into the "smart health" era.

One of the very vital components of smart health is the ability to make all the health-related information, feedback, and suggestion accessible from any geographical location on the earth. The data storage and computing parts can be done by any computer, while the global accessibility can be made possible by the power of internet. The delivery of these hosted services over the internet is termed as cloud computing.

1.1. Cloud computing

Cloud computing is computing service offered by cloud providers over the internet. These services can be as simple as online servers and data storage, up to the intricate networking, databases, data analytics, and software solution. The offered services are normally based on demand and pay per usage basis. The advantages offered by cloud computing include latest software update, cost effectiveness solution, collaboration improvement, mobility, and environment friendly that could lead to quantifiable improvements in businesses [1].

As the field of medical robotics are progressively expanding all over the world, the demand to move data collection, distribution, and processing to the cloud computing has become greater than ever. The shift to cloud computing could bridge the gap between physical and cyber worlds in preparation for the development of the advance medical systems in the near future.

There are three major models of cloud service: infrastructure-as-a-service (IaaS), platform-as-a-service (PaaS), and software-as-a-service (SaaS).

IaaS is a self-service model where user could initialise the processes, networks, data storage system and other resources through virtual interface. The IaaS providers in the market are Amazon Web Services (AWS), Microsoft Azure, Google Compute Engine, IBM Smart Cloud Enterprise et cetera.

PaaS is a service which allows the users to use the platform to build, run, and manage applications without an in-house infrastructure. It reduces the management overhead and lowers the costs. Platform such as Google App Engine, Microsoft Azure, and AWS are popular PaaS products that help users with programming environment treating designers separately from physical server and other technical compounds of computer network.

SaaS replaces the traditional licensed software which is rarely on subscription basis. The user can use the supplements of providers to run on the cloud-based infrastructure. The examples of such cloud-based services are Salesforce, Google G Suite, Microsoft Office 365, AWS et cetera that can be accessed from a web browser without any local installation needed [2].

There are some foundational requirements for the integration of cloud in medical robotics including openness, flexibility, extensibility, security, manageability, reliability, scalability, and it must be optimised[3]. To that end, organizations need to consider which service models is better for the implementation by thinking about the trade-off between the effort to manage and level of control [4].

1.2. Cloud computing in smart health

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There are some functions of the cloud computing which can be utilised for smart health application.
First of all is the data storage provided by the cloud services. The related data and information related to the health of patients or the training progress of the trainees can be stored, retrieved, and accessed from any simple web service interface. Data is stored in a virtual pool of storage hosted by a third party based on the specified and customised requirements of the customers[5].
Besides, data analytics capability provided by the cloud computing can be made useful for the smart health era. This is a service model in which elements of the data analytics process are provided through a public or private cloud. The six key elements of the analytics are data sources, data models, processing applications, computing power, analytic models and, sharing or storage of results[6]. Data analytics can be used to process the health information of the patients or the training progress of the trainees based on the established and programmed analysis procedures.
The third useful function of the cloud computing is the artificial intelligence. More natural interfaces such as oral or written conversation can be used to develop personalised quotes for customers based on the specific situations[7].
The few functions mentioned above can be combined and structured to produce a few models of cloud services that could be considered in the smart health. These models can be implemented either for health record keeping, home-based rehabilitation, or even for medical education purpose.
The paper is organised as followed. The next section will discuss about the solution patterns and general architecture of different level of machine-to-cloud integration. The following section gives a current example of an ongoing project of upper limb spasticity rehabilitation part-task trainer with the name of BITA. The fourth section will briefly highlight the future work while the final section will conclude this paper.

1.3. Solution patterns of machine-to-cloud integration

Machine-to-cloud integration is a very vital part for the area of smart health in the nearestmost future. A general architecture of machine-to-cloud integration for medical robots for the purpose of home-based rehabilitation or medical education will be explained in this section.
Four levels of cloud integration listed below are discussed in this paper:

i) Level 1: Basic cloud integration
ii)Level 2: Analytical cloud integration
iii) Level 3: Cloud-based controller integration
iv) Level 0: No cloud integration

1.3.1. Level 0: no cloud integration

System of Level 0 means there is no cloud integration for the medical robots. Level 0 symbolises the general medical robots with local controller and no connectivity to a cloud. The general architecture of cloud integration for Level 0 system is visualised in **Error! Reference source not found.**.

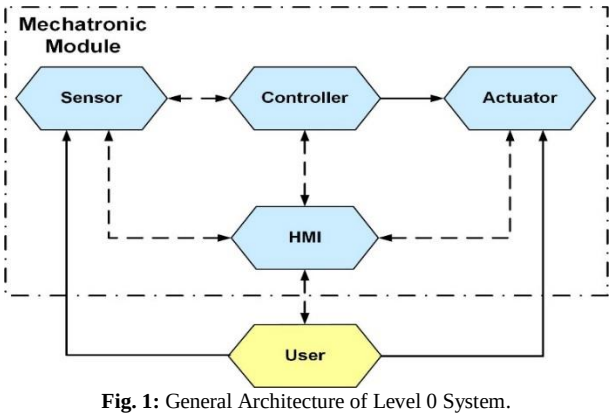


Fig. 1: General Architecture of Level 0 System.

A zeroth level system is a conventional medical robot. The clinical data required for the system is directly keyed into the control algorithm which would be running on a local controller. There could be single or multiple sensors attached to the user or to the mechanism itself to acquire specific feedbacks or data needed. That means there could be one or more sensors attached to the user or medical robot part which will be sent to the controller through a connector and a terminal of the controller. The data or feedbacks from the sensors will be processed according to the control algorithm, and corresponding information or energy will be sent to the actuator for the pre-programmed responses. Meanwhile, a human-machine interface (HMI) would be needed for the user to communicate and interact with the system in order to select the suitable mode according to the required situation.

1.3.2. Level 1: basic cloud integration

System of Level 1 is a medical robot system with basic integration to cloud, i.e. the data can be uploaded or downloaded from the cloud service, but only minimum communication between the cloud service and the medical robot which will not involve any analysis in the cloud server. The data can be stored in or downloaded from the cloud platform. The general architecture of cloud integration for Level 1 System is visualised in Fig. 2.

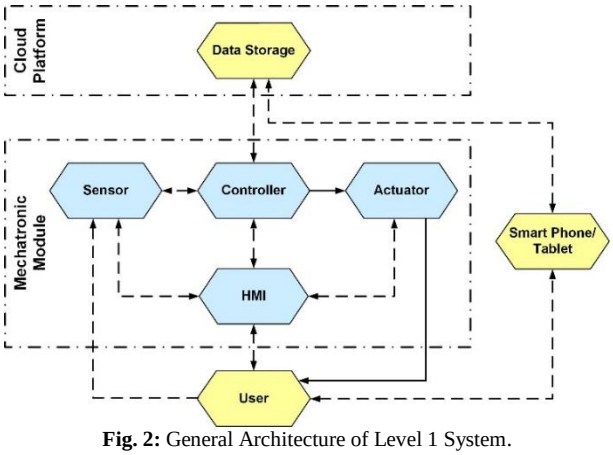


Fig. 2: General Architecture of Level 1 System.

From the user part to the controller part, it is exactly the same with the zeroth level system. The main difference and distinguished feature of first level system is the existence of IoT program running in the controller and also the existence of cloud platform in the whole system architecture. The IoT program embedded in the controller contains the communication protocol needed to be connected to the cloud service. Another difference is that the clinical data would now be stored in the cloud server instead of being stored inside the controller directly, thus reducing the storage memory required by the local control unit. The data of the results of training can either have a live streaming all the time or being stored in the device storage and be uploaded regularly depending on the requirement. Besides, the user can access the data in the cloud platform through a smart device such as a smart phone or a tablet.

1.3.3. Level 2: analytical cloud integration

System of Level 2 is a medical robot system with additional analytics or computing program integrated into the cloud platform, i.e. the data can be uploaded or downloaded from the cloud service, and the data will be computed according to the program and be analysed for further feedbacks and comments for the users of the medical robot. The system is now a level two system, symbolising that it is of a higher level of integration with cloud server and services. The general architecture of cloud integration for Level 2 System is visualised in Fig. 3.

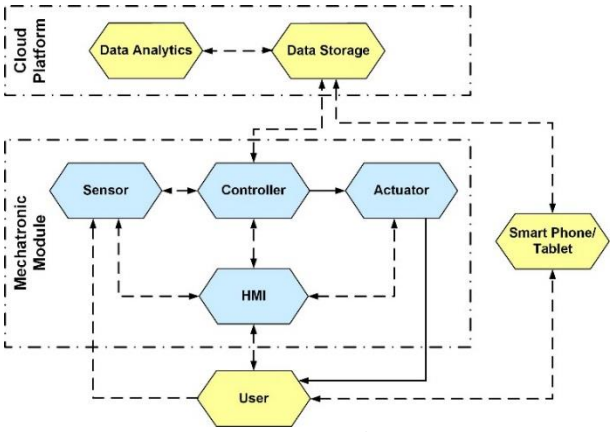


Fig. 3: General Architecture of Level 2 System.

The component that distinguishes a second level system from the first level is the existence of data analytics or computing program running on the cloud service. The data in the first level system is only for storage and minimum functions or purposes, but the data in a level two system would now be analysed in order to provide more feedback to the user. E.g. the data received from the sensors of a medical robot for home-based rehabilitation purpose will be sent to the cloud service and be analysed in the add-on analytics or computing program, and then further enhancement or suggestion for follow-up training could be provided to the user.

1.3.4. Level 3: cloud-based controller integration

System of Level 3 is a medical robot system with the control algorithm and analytics or computing program integrated in the cloud server. In other words, all the feedbacks and data collected from the sensors will be sent to the cloud service, and all the responses of the actuator of the medical robot will have to come from the computation of the programmed algorithm placed in the cloud server. At the same time, the received data will be further analysed to provide additional comments for the user. The general architecture of cloud integration for Level 3 System is visualised in Fig. 4.

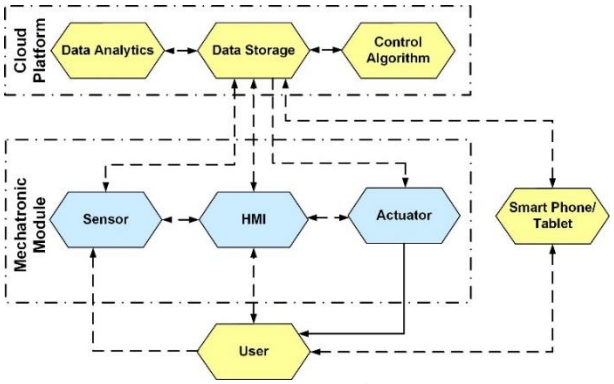


Fig. 4: General Architecture of Level 3 System.

The third level system has no local controller. As a substitute, a coupler is being inserted into the overall system to act as a connector to the cloud server. The IoT program will run on the coupler, thus enabling the connection to the cloud service through the internet. All the information and data collected by the sensors will be sent to the coupler through the connector to be sent to the cloud service for computation and further analysis.

2. Case study of ULS part-task trainer, BITA2.0



Fig. 5: A Trained Professional Physician is engaging with BITA1.0.

The case study and example for the aforementioned building architecture is the part-task trainer, BITA, as shown in Fig. 5. BITA is used for medical education purpose specified in training the novices for upper limb spasticity rehabilitation as discussed in the previous papers under the same project in [8]–[12]. BITA is able to emulate the symptoms of upper limb spasticity, thus enabling the students undergoing training as therapists or doctors to train in a safe environment without directly engaging with the patients.

The first version of BITA is BITA1.0, which is a zeroth level system. It is a purely standalone medical education device with a local controller and all the clinical data is inserted into the local controller. All the detailed information of BITA1.0 can be referred to in [8]–[12].

BITA is currently in its system-level design stage for a first level system according to the categorisation in the previous section. It is developed according to the steps of developing a principle solution in [13]. The project of BITA is currently in its second stage, thus being named as BITA2.0. The BITA2.0 is envisioned to be an internet connectivity enabled part-task trainer, and it will be able to interact with the cloud platform and the coach through the internet connection. The schematic description of BITA2.0 is shown in Fig. 6.

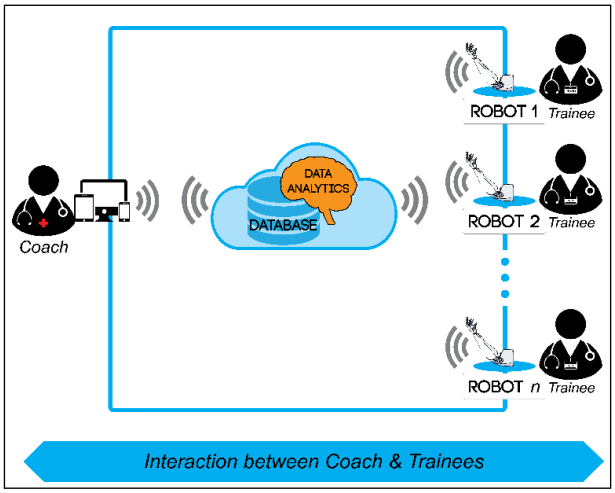


Fig. 6: Schematic Description of the Cloud-Based Robotic Part-Task Trainer.

2.1. Function

BITA2.0 is a part-task trainer to be used in medical education, specialising in evaluation training for upper limb spasticity rehabilitation. It is able to emulate the symptoms of patients with upper limb

spasticity of different Modified Ashworth Scale (MAS) level, which is a measure of spasticity. The feature that distinguished the current BITA2.0 is its ability to be connected to the cloud service. BITA2.0 is able to connect to the cloud database where all the clinical data is stored and could be updated regularly. The data from the training could be logged into the cloud database to be analysed by the experienced trainer.

2.2. Behaviour

When the system is initialised, the MAS severity level to practice with can be chosen manually by the user. The choices given are MAS 0, 1, 1+, 2, 3, or 4. In every selected MAS level, the event routine will proceed as programmed either as a fast extension or slow extension according to the speed of extending the forearm. The programmable logic controller (PLC) program will function as programmed and the torque will be produced by the servomotor according to the angular position of the robotic arm.
It is noted that the cycle must be completed before the system will be allowed to be switched to another severity level. When the robotic arm return to its full flexion position, the user can choose to either continue with the training or switch to another severity level to practise with. The system will come to a halt and the whole behaviour routine will come to an end if the power is switched off.

2.3. Active structure

BITA2.0 is a level one system as mentioned. Thus, the general architecture displayed in Fig. 2 is now replaced with more specified building architecture. First and foremost, the user of BITA2.0 is a physician or therapist under training. The medical robot in the building architecture is now the overall BITA2.0 upper limb mechanism. There is a capacitive sensor which is directly engaged by the user for the detection of user engagement, replacing the sensor as mentioned in the general architecture, and an angle encoder and a homing sensor which resemble in the general architecture. The actuator is the servomotor which would give the upper limb mechanism the corresponding torque as programmed.

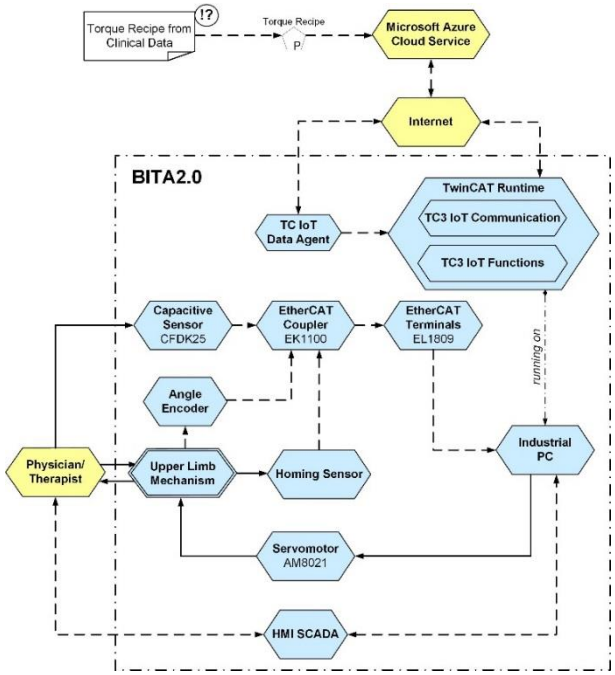


Fig. 7: Active Structure of BITA2.0.

The controller used in BITA2.0 is an Industrial Personal Computer (IPC), which has TwinCAT (TC) Runtime software, and nested within it is the TC3 IoT Communication and TC3 IoT Functions so that it can be connected to the Microsoft Azure cloud service through the internet. The torque recipe derived from the clinical data is inserted directly into the cloud server and latest clinical data could be updated into the cloud database from time to time to be accessed and updated onto separate BITA2.0 at different location. The Human-Machine Interface (HMI) used is a HMI Software Control and Data Acquisition (SCADA). Meanwhile, the EtherCAT coupler and the EtherCAT terminals act as the medium and connector between the sensors and the IPC.
BITA2.0 is envisioned as a system that is able to download and upload the data into the cloud service. The physician or therapist in training can engage with the robotic arm which consists of the forearm and the arm, and also interact with the IPC to choose the MAS severity level through the HMI SCADA. The data of the clinical symptoms will be downloaded from the cloud database and executed through the DC motor.
It is mentioned that the cloud service that would be employed for the system is Microsoft Azure which has partnered with the Beckhoff Automation by using TwinCAT 3 IoT. The TwinCAT 3 IoT engineering and automation software is able to provide a fast, efficient and complete solution for this specific application. The protocols for cloud communication is standardised globally and the messaging protocols supported include Message Queue Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP), and OPC Unified Architecture (OPC UA).

2.4. Environment

BITA2.0 is intended to be an upper limb part-task trainer which can be connected to the cloud. The cloud database is envisioned to store the torque recipe derived from the clinical data to be sent to the controller for the corresponding reaction at the actuator. The environment of BITA2.0 is shown in Fig. 8.

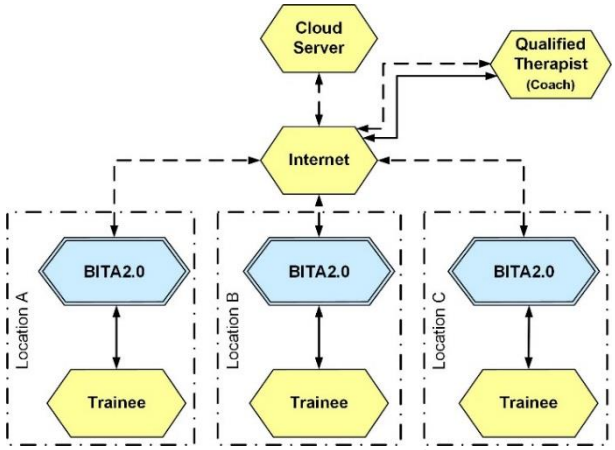


Fig. 8: The Environment Diagram Of BITA2.0.

Besides requesting data from the cloud database, the IPC could also store the training data of the users during the engagement with the part-task trainer to the cloud database through the internet. The stored data can then be retrieved by the coach to be analysed manually.

3. Future work

BITA2.0 can be further upgraded to level two or level three system. In order for BITA2.0 to be upgraded to the system of different level, the requirements are:

3.1. System level 2

- Add on extra analytics function capacity in the cloud service by buying more features from the cloud service provider.
- Design a suitable analytics program to be inserted into the cloud to automatically analyse the logged training data of the user and provide automated feedback or even further training plan to the trainee.

3.2. System level 3

- Replace the IPC with an internet-enabled coupler from Beckhoff Automation to connect the terminal directly to the cloud server through the internet.
- Insert the control algorithm into the cloud server and make sure that there is a seamless connection for the real time download and upload of data to enable the actuator to function accordingly.

4. Conclusion

General architecture for different levels of cloud integration for medical robots are conceptualised, developed, and explained in this paper, namely the basic cloud integration (first level), the analytics cloud integration (second level), and the cloud-based controller integration (third level). It also includes the zeroth level system which has no cloud integration as a basic reference and foundation of the building up of different level of cloud integration.

A sample prototype of zeroth level system (without cloud integration) was developed since few years ago as BITA1.0, which is a local standalone upper limb spasticity rehabilitation trainer for the domain of medical education. BITA1.0 is recently in the system-level design stage of being developed into a first level system (basic cloud integration) by enabling the connection to the cloud server, and all its function structure, behaviour, active structure, and environment diagram following the CONSENS method are developed and shown in this paper as a sample of first level system.

It is hopeful that after the full development of a fully-functioning BITA2.0, it can be further upgraded into a second level system with analytics function, and subsequently into a third level system with a cloud-based controller.

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