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Digital Twin-Based Biofeedback Controlling of Human-Cobot Interaction Upon a Manufacturing Application

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Abstract. Cobots (collaborative robots) are widely exploited in the manufacturing industry as smart assistants in proximity to human operators. The race towards mass automation brought by the fourth industrial revolution has made the safety of humans a widely discussed topic. Industrial guidelines have been introduced to accommodate this change in the manufacturing industry for better use of cobots without compromising human safety. Built-in safety is encouraged to be incorporated from the cobot programming stage itself to facilitate this safe collaborative environment. To achieve that, research is being done to train the cobots with various contact avoidance algorithms. Mitigating productivity loss while the cobots are in these trained safe operating modes, has been identified as a requirement by the researchers to take real advantage of collaborative workspaces. To address this requirement, the authors are proposing a novel cobot-controlling algorithm for human-cobot interaction by considering the biofeedback of the human operator. The proposed algorithm is part of a model workcell development which will be remotely controlled using a digital twin platform.

Keywords. Digital Twin, Cobot, Biofeedback controlling, Human safety, Manufacturing industry

1. Introduction

Since the initiation of the industrial revolutions in the 1700s, people have been inventing and innovating methods for creating productive factory environments for better manufacturing efficiencies, and labor and resource utilization [1]. Artificial Intelligence (AI) based smart manufacturing was the recent revolution that encountered, and with the 'human-in-loop' concept it is being extended towards close human-machine/robot/cobot interactions [2].

With these changes, industrial interactions are moving from homogeneous (machine-to-machine/ human-to-human) to more complex and heterogeneous interactions with the Internet of Everything (IoE). The IoE focuses on networking among people, data, processes, and machines, allowing human involvement at all levels of the system [3]. Application of these IoE tools such as Cyber-Physical Systems (CPS) and

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Digital Twins (DT) has made humans more vulnerable physically as well as cognitively due to the continuous exposure to machines and cyberspace (such as Human Machine Interfaces). Therefore, a balance between physical and cognitive ergonomics has been more important than ever.

The introduction of cobots (Collaborative Robots) came into light to facilitate this Operator 4.0 (Operator in the Industry 4.0) function for a better human-CPS interaction [4]. This has its advantages as well as disadvantages.

The advantage is that, when utilizing the cobots in a consistent manner, productivity can be enhanced. Further, fewer human interactions reduce the idling time, leading to the high productivity of manufacturing workcells. However, the downside of this can weigh more than the advantages, especially in the long term. In fact, the biology of Humans is perfectly designed for empathic interactions. When they are restricted from behaving in this natural state, they can be overwhelmed mentally. Moreover, when interacting with a machine/robot, the human's doubts about safety and unawareness of the robot's behavior can add to physical and mental dissatisfaction [5, 6, 7]. This dissatisfaction will add to the piled-up emotions of the human operator that they carry from outside work, such as family problems. In the long run, this mental overwhelm can be extended towards exhaustion and ultimately interrupt their physical well-being as well [8].

This is why, when introducing human-in-loop workcells with current automation practices, employers need to follow established occupational health and safety guidelines such as International Standard for Occupational Health and Safety (ISO), Occupational Safety and Health (OSH), etc. [9], along with the specific industrial safety standards for human-cobot interactive workstations [10].

In the manufacturing industry, human-cobot interaction can happen in assembly or non-assembly environments. In assembly workstations, the human-robot/cobot interaction is focused on the assembling task of a workpiece. The human and robot/cobot might be working on the same workpiece at the same time or in series. In non-assembly workstations, the human and robot/cobot interaction happens for any other instance such as; supervision of the work, parallel workstations, co-existence, exoskeletons/assistive robotics, etc. [10].

Cobots are meant for close human interactions, however, the safety around the cobots is relative to many factors such as; the interaction type and frequency, equipment utilization, etc. [10]. Safety-assured human-cobot collaboration types [11] can be utilized for adjusting the cobot operation (both speed and trajectory) to prevent accidental collisions in these workstations. These scalable adjustments as per human presence are currently being done in the manufacturing industry for human-cobot interactions [12, 13]. However, it cannot ensure an optimum operational environment most of the time as the productivity level of the workcell can be dropped when the cobot operation is interrupted each time a human enters the cobot's working area. Therefore, if the cobot speed can be adjusted as per the biological need of a particular operator who is in proximity to the cobot, then human safety can be ensured while maintaining the productivity of the workcell at a reasonable level. Such is known as biofeedback controlling.

These biofeedback controllers are currently being used in assembly workstations for cobot adjustment as per human needs (fatigue, stress, engagement, etc.) [14, 15, 16, 17]. In non-assembly workstations, human gaze, muscle motion, error-related brain signals, stress, etc. are used for biofeedback controlling [18, 19, 20]. The theoretical framework that has been suggested by [21] proposed the use of facial expressions, skills, personality, etc. as biodata to extract the intention, well-being, and behavior of a human in a non-assembly collaborative environment. Despite these, when it comes to non-assembly workstations, there is a gap in research done using biofeedback control and its applicative is still in its infancy.

To this end, a novel cobot-controlling algorithm for human-cobot interaction has been proposed by the authors, which is reconfigurable to mitigate productivity loss and resilient for human safety. This algorithm is part of a digital twin-based machining workcell development that is being conducted at Polytechnique Montréal. The paper is organized as follows: section II covers the methodology and current progress of the work, and concluding remarks are given in section III.

2. Methodology

The work that is being discussed in this article is to develop a biofeedback controlling algorithm for human-cobot interaction. This algorithm will be utilized in the CPS of a complex manufacturing workcell, which is currently a work in progress. This section covers the methodology that is being followed for the development of this algorithm.

2.1. Layout of the human-cobot interactive workspace

In this workcell, the human-cobot interaction happens mid-frequently every 10-20 minutes. The cobot will be the final station of a complex manufacturing workcell and will function as the quality inspector of the machined workpieces by using a cobot vision system. An image analysis algorithm will be used to train the cobot for part quality inspection and sorting. The purpose of human interaction is to occasionally monitor the workpiece that is being sorted by the cobot, and the human will be present in the workcell while attending to other available machinery. Though the human-cobot interaction is not highly frequent and not a collaborative task, as the human is present in the workcell for prolonged hours, establishing safety mechanisms around the cobot workspace for human safety is essential. This will prevent accidental/surprising collisions with the payload and will provide confidence for the humans around the cobot. Therefore, the cobot will be controlled for two safety features which fall under Safety Rated Monitored Stop (SRMS) and Speed and Separation Monitoring (SSM) [11] for human-cobot collaboration.

1. Detecting the human's need by analyzing biological data (biofeedback cobot controlling algorithm)
2. Detecting the human's presence by identifying the proximity to the cobot (human presence detection algorithm)

In safety feature one, the digital twin of the cobot will always be on alert to analyze if the approaching human has a biological need. If biosensors detect a need, then the digital twin will put the cobot to its empathic mode in real-time by reducing its operating speed. If not detected, the cobot will function at its default speed. This way, the productivity loss will be mitigated while protecting the human operator, as the cobot operation is subjected to the need of the operator and is not limited to the presence detection.

In safety feature two, the digital twin of the cobot will continuously stay on alert to detect the proximity of the human (to the demarcated cobot's workspace). If the human has reached proximity, then a sensor signal will be sent to the digital twin, and the twin will then immediately put the cobot to a stop. Through this, human safety is ensured irrespective of the human need.

2.2. Biofeedback cobot controlling algorithm development

The biological data that will be gathered in this project is human cognitive fatigue (mental clutter/ cognitive load) at a distance to the cobot, and if detected the cobot will reduce its operating speed to be an empathic coworker. The primary goal of using cognitive fatigue detection in this project is not to actively establish fatigue mitigation strategies, but to utilize it as an input for empathic cobot operation to prevent further cognitive fatigue in the human operator for a safe human-cobot interaction.

Safety and ergonomic measures can be an extra cause of cognitive load especially when using wearable sensors for fatigue detection and mitigation, as the worker has to be continuously cautious in wearing it [22]. Further, as human sensing is an essential safety feature of this DT-based workcell it has to be an adequate approach to cover even the most vulnerable operator (a worker who forgot to wear the sensor, sudden visitors who were not aware, etc.). This is why wearable sensors for cognitive fatigue detection will not be the best to use in this project, but a non-invasive non-contact biosensor will be useful.

However, on the other hand, using contactless sensors to detect cognitive fatigue seems unreal as well. This is why the authors are currently working on selecting the best possible sensor type to detect cognitive fatigue directly/indirectly. This sensor selection is currently in progress.

This cobot-controlling algorithm as per two safety features will be based on the below decision tree (Fig.1). The digital twin will be continuously listening to the external safety sensors to make this decision for the cobot operation control.

As the work is currently in progress, this article only focuses on the first safety feature, which is detecting the human's need and DT-based biofeedback controlling of the cobot.

2.3. Current progress of the digital twin-based biofeedback cobot controller

The authors are currently working on the biofeedback control algorithm (Fig. 1). The digital twin of the UR3® cobot with its Robotiq® 2F-85 Gripper is developed on the RoboDK® platform. The cobot is off-line programmed using Python® API of the RoboDK platform to perform a simple pick and place operation, imitating the workpiece sorting procedure of the workcell. This RoboDK Python API program is run on the physical UR3 cobot in real-time using RoboDK built-in Transmission Control and Internet Protocol (TCP/IP) connectivity. As the biosensor is yet to be selected, the biological data acquisition and biofeedback generation is imitated using a TCP/IP socket client created on the Python Jupyter® platform, which communicates with the RoboDK digital twin.

When in operation, the cobot's digital twin acts as the server to continuously listen to the Python socket client to adjust its speed as per the digital signal sent. For example, if the client sends '20' it interprets that human fatigue is detected and the cobot needs to slow down its default optimum speed to twenty units.

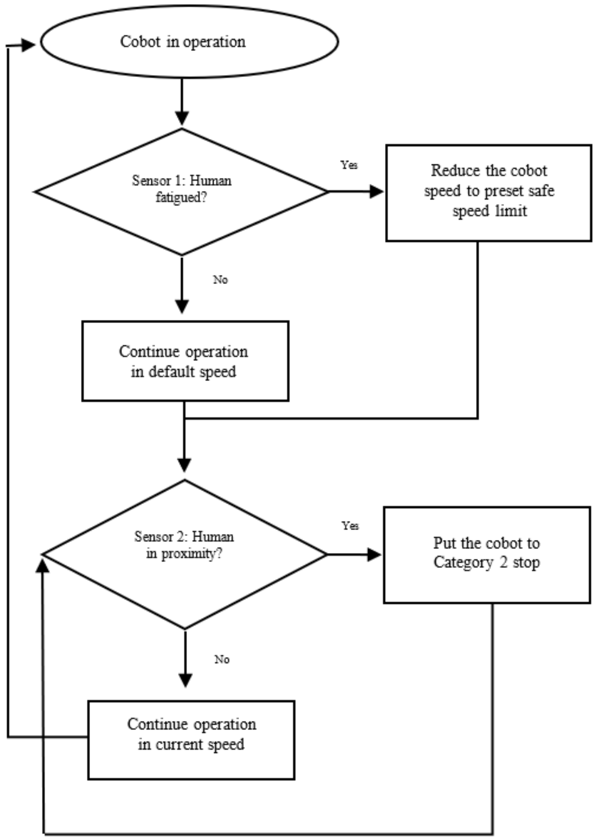

Figure 1. Decision Tree of the Digital Twin

When the project is completed, the mechanism leading to this digital input signal will be performed by the biosensor along with its connected Programmable Logic Controller (PLC) data acquisition and signal processing unit. Below Fig. 2 shows the architecture of these established and yet-to-be-established (in blue outline) parts of the layout.

Joint positions [base, shoulder, elbow, wrist1, wrist2, wrist3] cross-check between the cobot controller and digital twin data was conducted. Fig. 3 shows this comparison between the results (units in degrees) that were extracted from the cobot's online teaching pendant and RoboDK platform, respectively. The joint positions comparison (Fig.3) shows an error ranging between -0.03 to +1.16 degrees. These positions were compared by randomly stopping the cobot via the digital twin biofeedback controlling algorithm. Hence, this negligible error could be due to the minimal delays that can occur when transferring data through TCP/IP. The similarity (with mentioned negligible error) of the results affirms that the digital twin was able to correctly align all six joints of the physical cobot in real-time, emphasizing that the cobot speed and trajectory were controlled by the DT of the cobot in real-time according to the sensor data received.

Euler angles: the roll, pitch, and yaw (rotation around the x-axis, rotation around the y-axis, and rotation around the z-axis respectively) of the Tool Center Point (TCP) were also analyzed by extracting directly from the cobot controller and the RoboDK digital twin platform. TABLE I shows the comparison of these Euler angles (units in radians) of the TCP. The results are perfectly aligned without any errors. Hence it can be considered that the TCP was also correctly controlled by the digital twin in real-time.

Therefore, the usability of the developed digital twin platform is validated for its real-time reconfigurability. The fully completed biofeedback controlling algorithm will add more value to the application by establishing resilience for human safety and ergonomics as expected.

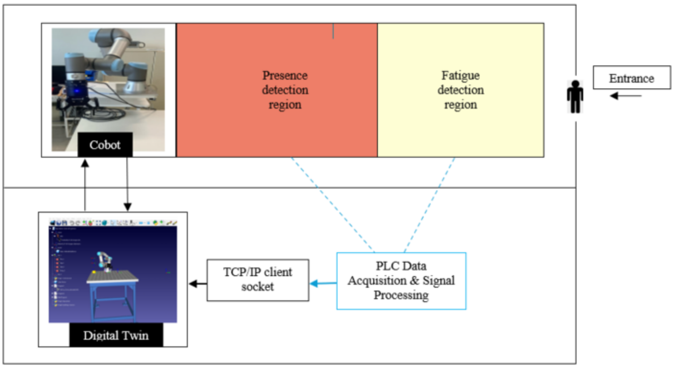

Figure 2. Cyber-Physical System Architecture

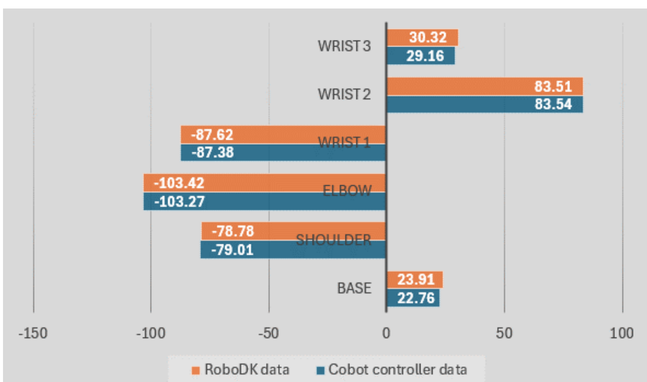

Figure 3. Joint Positions Comparison between Cobot Controller Data and RoboDK Platform Data

Table 1. TCP Euler angles comparison between cobot controller data and RoboDK platform data.

Cobot controller output			RoboDK output		
Roll	**Pitch**	**Yaw**	**Roll**	**Pitch**	**Yaw**
2.07	-2.316	0.168	2.07	-2.316	0.168

3. Conclusion

The overall idea of the proposed safety features establishment is twofold.

- By establishing safety feature 1: the human will not become the cause of productivity loss as the cobot will not reduce its speed every time the human presence is detected, but only when the humans' cognitive need is detected. Therefore, sensor tampering or incentives to bypass safety are avoided and a sense of control is given to the human [22]. Further, the human will be aware that the cobot is empathic. Hence, humans will build trust towards the cobot knowing that even when they are biologically challenged, they will be protected.
- By establishing safety feature 2: when the human is in proximity to the cobot's workspace, irrespective of the biological state, the human will be protected. This will establish a sense of belonging and trust in the humans to coexist in the workstation.

The algorithm is successfully developed and validated on the physical UR3 cobot via the RoboDK digital twin. However, the biosensor selection, PLC connectivity, and programming for signal processing are yet to be done to create the automatic digital input signal, which is currently being provided manually via a TCP/IP socket.

Upon completion of the two safety features, this workcell layout operation will be validated to analyze the sensor reliability and real-time connectivity of the digital twin-based remote controlling of the cobot. The model workcell is being established in Polytechnique Montréal and will be approved by an ethical practice panel before it is ready for the industry.

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