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Human-in-the-Loop: Literature Survey on Incorporating Human Behavior in Feedback Control

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***Abstract* —Cyber-Physical Systems (CPS) is transforming manufacturing companies through a complete understanding of information and communication technology. Today, the opportunity to use the complementary strengths of both cognitive strengths of human and machine intelligence to maximize performance and limit risk dictates that the human should remain in the loop. However, there are many issues to incorporate knowledge and human behavior into feedback control to improve decision making. An attempt is made to understand these issues from a different school of thoughts, and the corresponding literature review is presented.**

Keywords—cyber-physical system, human-in-the-loop, human behavior models, knowledge management, complex event processing, rule-based system

I. Introduction

Next generation systems contain various actuating and sensing units working together to gather and process information. The collection of systems which connect the gap between the cyber computing world and the physical objects is called Cyber-Physical Systems (CPS). Introducing human in CPS increases the productivity of the overall systems. The cognitive activity of the human is constantly monitored through body sensors. The embedded system takes the input from the human and controls the mechanism (or actuators). The human provides feedback i.e., close the control loop by giving decisions or supervising the process while observing the interactions of the physical world [1].

Earlier, the manufacturing processes were divided into the manual and automatic process. The robots lack the skill of perception of the environment. Human-in-the-Loop (HitL) systems allow the robot to complete the task while the human can support it in critical condition using his skills, cognitive capabilities and perception about the environment.

It is necessary to identify a particular system and checking whether there is a need for human intervention. If there is a need, then examine where to place the human in the entire control loop. Next select suitable sensors and machine learning techniques to gather psychological behavior of the human. Finally, combine both the human behavior models and machine intelligence to maximize the overall performance of the system.

The current article will present different school of thoughts in incorporating human behavior and further issues encountered are highlighted. The article is organized as follows. Section II introduces feedback control loops. The current trends in realizing higher value are described in Section III. Knowledge management along with different codification of knowledge is elaborated in Section IV. Section V introduces HitL and corresponding human behavior in Section VI. Finally, the article ends with suitable conclusions.

II. Feedback Control Loops

With the help of available sensors, the data is collected from a human being, processed to assume human's state i.e., his physical and psychological state [1]. Open loop systems do not need any actuation as the results produced by them have entire information, but closed loop systems actuate the human to control the loop to achieve a required state.

A. Open loop system

The input transducer converts the input to the form that is suitable to be used by the controller as depicted in Fig. 1. These systems cannot compensate for any disturbances that are added to the controller. The disadvantage of the open loop systems is it cannot correct the disturbances. They rely normally on the input. Examples of open loop system are a toaster, mechanical systems which consist of a mass, spring, and damper. In an open loop system, even though a human is in the loop, but the human does not directly control the system.

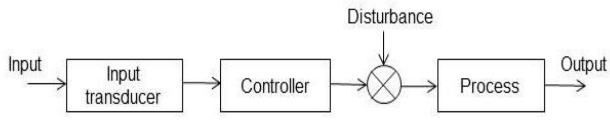

Fig. 1. Open loop system

B. *Closed loop system*

The sensor measures the output response and converts it in the form that is suitable to be used by the controller as illustrated in Fig. 2. The first summing junction adds the input and output signals which are given by the feedback path. The result is generally the actuating signal.

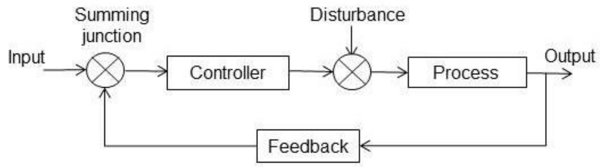

Fig. 2. Closed loop system

In closed-loop systems, the output response is measured and then fed into the summing junction via the feedback path. Here, the output is compared to input response. If there is any difference between them, then the actuating signal corrects it and then the process starts. In a closed-loop system, sensors are used to collect the information of the human and sent to the controller.

III. INDUSTRY 4.0

Manufacturing industries have seen types of industrial revolution. Industry 4.0 is the recent trend in industrial technology. Here, the machines, sensors and IT systems are connected to each other via IoT based technologies. These connected systems interact with each other and can predict failure and can adapt to changes [2]. Fig. 3 depicts the nine forms of technology that make up the Industry 4.0. With the help of Industry 4.0, there will be an increase in productivity, revenue growth, employment, and investment, among others.

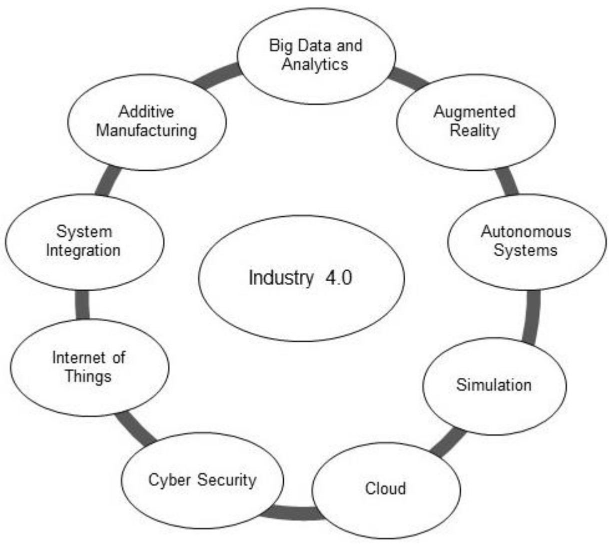

Fig. 3. Industry 4.0 and corresponding technologies

A. *Internet Of Things*

Internet of Things (IoT) is the network of physical things like sensors and smart objects, collecting data from the IoT sensors, actuators and then processing and analyzing the data which is collected. There is a need for flexible automation which provides real-time closed-loop control for optimization [3], enable collaboration between machines and provide secure and predictable service features from the cloud. The challenges related to IoT are industrial applications have large data which can be prone to information theft, data integrity and information privacy, scalability, and interoperability.

B. *Cyber-Physical Systems*

CPS comprises information and communication technologies, computer science, and IoT. It consists of embedded networks and computer to monitor and control the physical process. The feedback loops can be provided for the physical process, which alters the computation. It will support the communication between machines, human and products. A human can interact with the machine process with the help of interfaces. The applications of CPS can be found in robotics, manufacturing, transportation, communication, healthcare, military, and infrastructure. Reference paper [4] deals with the architecture of CPS in Industry 4.0 systems. Basically, a CPS consists of two main components namely:

1. Data collection from physical objects of the real world and feedback from cyberspace.
2. Cyberspace capabilities such as managing data intelligently and computation.

Cyber-Physical Production Systems consists of systems along with subsystems which are connected with each other throughout various level of automation starting from processes to production systems. For handling critical control loops, there are PLC’s placed at the field control level [5]. It will support the communication between machines, human and products. A human can interact with the machine process with the help of interfaces.

In the near future, there will arise in the intelligent manufacturing systems, biological manufacturing systems, smart factories, self-configurable manufacturing systems, holonic manufacturing systems and so forth.

The challenges related to CPS are as following:

- Handling disturbances which occur during production while scheduling,
- Need for development of algorithms for co-operative learning, detection of errors,
- Algorithms for identification and prediction of dynamical systems,
- Human-robot interaction, and
- Combination of real and virtual systems.

A digital clone of human is modeled in [6]. Cyber-I (Cyber Individual) and brain informatics work together. Cyber-I produces the cyber equivalent of each individual human and provides services in the hyper world. Brain informatics, in this case, collects brain data that is gained by electroencephalography (EEG) and functional Magnetic Resonance Imaging (fMRI).

The holons, agents and function blocks are combined together to execute CPS [7]. Multi-agent manufacturing and holonic manufacturing approaches are applied to intelligent manufacturing systems.

CPS are modeled as systems with uniform time and which are subject to unknown inputs [8]. Advanced security mechanisms are required for future power grids and mass transport networks. Prototypical attacks are stealth, replay, private and false data injection attack.

There are many challenges related to CPS. The advancements in sensors and mobile devices have led to use them in CPS to infer human states. Therefore, the human becomes a necessary part of CPS. Since human is unpredictable, introducing the human in the CPS leads to a challenge as it needs modeling of complex behavioral and psychological characteristics of a human.

IV. Knowledge Management and Codification

Knowledge management acts as a virtual repository which contains the information about the organization's products, assets and these can be made available in a usable form for future use. There exist two types of knowledge - tacit knowledge and explicit knowledge. Tacit knowledge is personal know-how which is intuitive and experience based. Explicit knowledge represents information which is codified, recorded and documented. Converting tacit to explicit knowledge is known as externalization. It plays an important role because the methods, analogies knew by a particular person should be documented well. This contains useful information for solving complex problems occurring in the organization. Internalization converts explicit to tacit knowledge as shown in Fig. 4. It converts individual experiences and knowledge into individual mental models. Once it is internalized, they reframe it within their own knowledge bases [9].

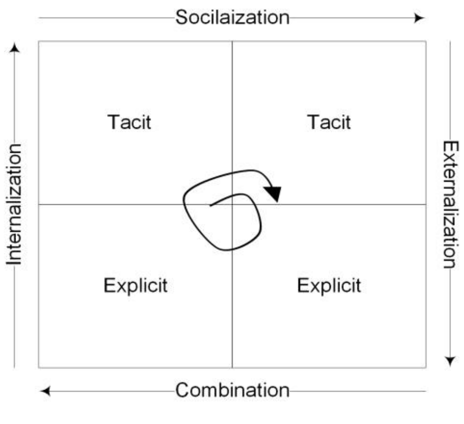

Fig. 4. Knowledge management

One of the knowledge exchange protocols for converting tacit to explicit is the SOAP (Subjective, Objective, Assessment and Plan) protocol used in the medical field. Knowledge can be captured from experts by learning from observation, learning from what they say and interviewing. The codification of explicit knowledge can be achieved using techniques such as cognitive mapping, decision trees, knowledge taxonomies, and task analysis as shown in Fig. 6.

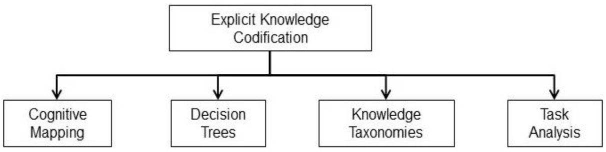

Fig. 6. Different ways of explicit knowledge codification

The explicit knowledge can be codified to a certain extent. Nevertheless, it is difficult in knowledge-based systems.

A. *Rule-based expert system*

For most of the complicated problems, heuristic solution technique is used. It has a set of rules to solve a particular problem. Earlier conventional systems used human intelligence to solve the real-world problem. Rule-based expert systems find their applications in planning, design, scheduling, diagnosis, etc. The knowledge of the human (know-how) of how to solve a particular problem is collected and then stored in the knowledge base of an expert system in the form of a code (rules) or a program (data) in the computer. The advantages of expert systems are: it can preserve human experience data; it can be used to develop a system which is more consistent than human and solve problems at a faster pace than human experts.

The expert system consists of an inference engine, knowledge base, user interface, explanation facility as shown in Fig. 5. A rule is a step by step solution (statements) or conditions which link given statements to produce outcomes. The knowledge base consists of a set of rules, data, relationships, information which shall be used by the expert system. The inference engine takes inputs from the knowledge base and provides answers, suggestions as the human operator would suggest (solve). It has to provide the right facts and information to solve the problem. It has two approaches to solve - forward chaining where the facts are considered first and then it provides the solution. Backward chaining starts with the conclusion first and then it moves to the supporting facts. The explanation facility let the users know about how the system arrived at the certain conclusion. The user interface helps the users to work with the system.

A rule-based system contains the if-then rules and related data to solve a particular problem. An interpreter considers the rules with respect to the facts. The facts are refined and the rules are written to draw conclusions based on the facts in forward chaining systems. They are driven by data. The conclusion is processed first and then the rules are considered for which the hypothesis was written and the rules would be modified if it's required in backward chaining systems as explained in [10].

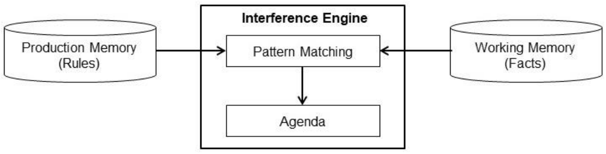

Fig. 5. Interference engine

Basically, knowledge acquisition is important in the rule-based expert system. It can be acquired by interviewing people or using symbols, letters of how they would solve the problem in a complex situation. There are a few frameworks which can help in extracting knowledge, like cognitive work analysis and cognitive task analysis. A software tool named shell is used where it has an inference engine and knowledge can be entered. CLIP is a commonly used expert system tool for development of if-then or object-oriented expert systems. It is written in C language.

As there is uncertainty in the data, there is a rise in fuzzy expert systems. The fuzzy logic can be used to model uncertainty, reasoning, etc. it uses if-then rules instead of Boolean logic.

Rule-based system poses many challenges. First, it is hard to create and maintain the rules up to date. Next, the rules cannot be in general form and the rules need to be adapted for different applications/situations.

B. Complex event processing

An event is the record of activity in a system. The main purpose of Complex Event Processing (CEP) is to detect complex event patterns from the log, sensors, and RFID (Radio Frequency Identification Technique) data [11]. It is based on semantic networks. It identifies, analyses, filters and then matches low-level events. This can be helpful where the streaming data keeps on changing. CEP has been in numerous applications.

Six rule-based classifiers are already in use where they use machine learning algorithms to replace manual rule-based patterns. They are:

1. One-R classifies the data based on the single attribute. It is adopted due to its simplicity and agility. It figures out the one rule having the lowest error rate.
2. RIPPER (Repeated Incremental Pruning to Produce Error Reduction) produces accurate and readable values from large datasets. It has two parts – 1. Growing set for building a rule set starting from an empty set. 2. Pruning set where after the rule is grown, it removes the unwanted data and modifies the rule set.
3. PART is based on partial decision trees. The algorithm is made of C4.5 decision trees and RIPPER algorithm. It is based on a separate and conquer strategy. The instances found by the first rule is removed and other rules are generated until there are no remaining instances available.
4. DTNB (Decision Tables and Naïve Bayes approaches) – the conditional probabilities are written. It depends on the forward selection procedure, where all attributes are modeled by decision tables and then sent to the Bayes model.
5. For noisy data, Ridor (Ripple-Down Rules) can be employed.

In Event-Driven Architecture (EDA), the phenomenon in which one event causes another event to activate the service. The technologies related to CEP are event stream processing where calculations are done on the streamed data. SQL contains databases to store the events and then calculations are performed [12]. There are two types of process architecture one in which the process reacts to events by entering the database values, computing and generating the events. The connectors to transport events between the activities. The languages used for CEP are RAPIDE-EPL, SASE, NFA, Cayuga and relational algebraic equivalence. The applications of CEP are HELM (Hilton Enterprise Logging Manager) - a logging infrastructure to track events and allow communication between server processes. RFID – to scan the RFID chips and provide information about the objects in which they are present. Similarly, CEP is used in Finance for stock analysis.

Pattern matching is a technique used for CEP in which patterns are matched between different events. The filtering step defines the list of relevant events followed by matching step which identifies the previous events and analyzes if it can define rule patterns. Derivation step detects the complex events using the information from matching subsets as shown in Fig. 7.

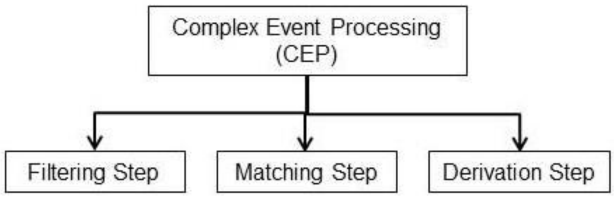

Fig. 7. Steps in Complex Event Processing (CEP)

Instead of using primitive events, base events are used as a unit for event processing and storage in [13]. Expressive Stream Language is used. The events with the same tagID and clusterID are merged into one cluster using timespan. Timed Petri Net is used for modeling application in the non-temporal and discrete system.

Writing the patterns for CEP is not easy, as the streaming of data will be continuous and the pattern should be matched.

V. Human-In-The-Loop

Autonomy is usually the repetition of the same task with minimal adaptation between the repetitions. HitL means the human is actively engaged in control decisions. A methodology is proposed for corrective maintenance in industrial automation using a HitL approach for efficient and effective maintenance. It makes use of the cyber-physical system technology, it depends on the skill level of the operator and work is assigned based on it [14]. An Automation ML (AML) model is proposed for the maintenance.

An online scheduling framework for the human system interactive decision-making process in manufacturing systems is presented in [15]. The human is part of the cybernetic loop to carry out the decision for the proper scheduling of the process.

Two forms of human control interfaces are used in [16] i.e., Xbox game controller and custom-built controller application to test how the human interaction levels with the robot would affect the performance of the robot. After testing, the results obtained were that a semi-autonomous controller performance depended on operator interaction. Continuous switching was better than discrete switching approach.

Autonomy is usually repeating the same task with minimum alteration between repetitions. Automation allows the system to adapt to changes and decide with respect to the human input. The types of autonomy are- human control, HitL, human on the loop and complete control [17]. In Human control, the human is involved in all forms of decision making. Human is actively engaged in control decisions for HitL applications. Human on the loop (HotL), in which human monitors the activity, takes control of the actions to be performed when the system fails or error, occurs. It is involved only for crucial agent decision making.

Complete autonomy is the subtask of supervisory control. The human has a minimal task for decision making.

Failures related to the autonomous control can be as following:

1. In the case of HitL, failure may occur due to panic. Also, instability may occur when there is a communication delay and if the operator takes more time to react to the situation.
2. In the case of HotL, failure may occur when autonomy fails and when the human supervisor cannot recover the performance.

Failures in the networked system may be due to cyber failure, physical failure, and human error. The risk is divided into two dimensions: 1. Impact of possible events, and 2. the occurrence of the probability of such events. Systems designed on the basis of human-autonomy integration is passivity. This helps in design methodology for accessing the stability with one or more human and one or more autonomous agents that swap between exclusive controls of the plant. Applicable to HitL performing a tracking or regulation task.

It can be concluded that autonomy can be deployed if

1. The relationship between action and consequence can be properly encoded in the impact-probability matrix.
2. Estimation of system, environment and human states in a secure way.
3. The probability of negative consequences satisfies acceptable bounds.

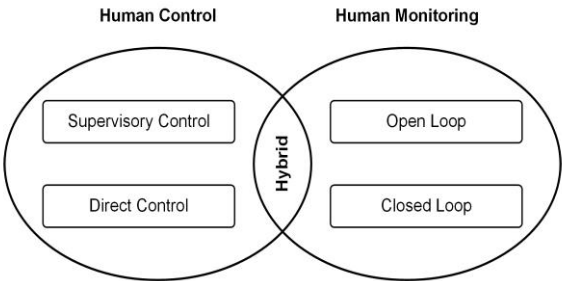

Fig. 8. Human control

David et al [1] discuss various technologies used in HiTLCPSs. Data acquisition is done through Wireless Sensor Networks (WSNs). There should be a transparent interface to infer human intent, actions, etc. Therefore, there is a need for mathematical modeling of human behavior using machine learning techniques such as Hidden Markov Model, Support Vector Machines and Fuzzy Logic. To provide actuation in HiTLCPSs, WSNs assist the robot to actuate. Fig. 8 depicts about different ways of human control and human monitoring in HitL applications [1].

Few challenges to incorporate HitL as feedback control is presented as described in [18]. Firstly, there is a need for a broad understanding of the complete range of HitL control system types. Application where human directly control the system- like adjusting the set points in the control algorithm, while the system runs autonomously. In other cases, the process accepts and carries out the command given by humans autonomously, reports the result and carries out the command.

Operations where the system monitors humans and takes appropriate action by being in the loop or on the loop. Hybrid systems monitor human behavior, takes appropriate actions and takes occasional human inputs for the control.

Secondly, extending the system identification or other techniques to derive models of human behavior. To create system models, system identification technique is used and it is applied to human behaviors. Capturing human behavior by extending system identification or other modeling techniques is very difficult due to the complex physiological, psychological and behavioral characteristics of human beings.

The third challenge is discovering the methods to incorporate human behavior models in feedback control- The challenge is how to incorporate human behavior as a part of the system itself. In some systems, even though humans are in the loop, they don't give any active feedback. The human model can be placed inside the controller, outside the loop, etc.

The fusion of semi-autonomous controller and human operator considering different criteria on how the human's involvement is in the system during safety-critical application is presented in [19].

A framework for different applications employing HitL is discussed in [20]. For example, a Brain-Computer Interface (BCI) controlled a wheelchair and wireless body area networks are used to test the physiological behavior of the human.

HitL applications have some challenges like user-specific parameters, change of human behavior over time, sensing technologies to sense human behavior.

VI. Human Behaviour Models

Considering human behavior as a dynamic process. A method for controller design by developing a mathematical model of human behavior to control a non-linear process using computer simulation is carried out in [21].

Hidden Markov Model is used for human activity recognition for semi-supervised learning in [22]. Temporal probabilistic models such as hidden Markov models and conditional random fields to test human behavior have shown to give better results to model temporal dependencies and sequential nature of human activities.

It uses audio data for offices and sensor readings for smart home and applies a Bayesian information criterion. Akaike Information Criterion for an ideal number of action states was unsuccessful, but the naturally chosen set of active states was able to outperform the models that were selected by Bayesian and Akaike information criterion.

Considering the human operator as a dynamic process in [23], a method for controller design is carried out based on the concept of mathematical models of human behavior. The human-based control system consists of the displays, the receptors, the central nervous system, and the effectors. Human operator simulator-based control loop has sensors, an input interface, a human operator behavior model and output interface.

They are divided into Observation phase - monitoring screen which has interfacing and response window. The human can operate it by pressing the 0-9 buttons from the keyboard which is directly related to a number of neurons. Modeling phase – arrays of error signals and corresponding human action are considered for mathematical modeling. It consists of weights of neurons.

Reference paper [24] proposes Scherer's Component Model of Emotion for observation, recording, and analysis of an emotional component of operator behavior. The model components are a cognitive appraisal, physiological reactions, motor expressions, and subjective feelings. The Protocol for Experimental Observation of Interaction is used for system-user interaction focusing on usability. Data collection is focused on workload, attention, emotion, and behavior.

There is a need for a reliable mechanism and mathematical modeling techniques to accurately infer human behavior. The modeling techniques will be helpful to properly model the behavior of human and use it to control the actions if there is an emergency situation.

VII. CONCLUSION

A review on Human-in-the-Loop (HitL) for automation in an industrial setting through robotics has been carried out. It is deduced that the HitL approach is the best approach in the previously mentioned setting. A human can either supervise or directly control the process so that overall performance of the system increases when prone to critical conditions. The research will be continued with implementation as a continuation of this paper. Future work includes data gathering from a controller for flying drones to improve flight dynamics. Collecting data from human experts/pilots and making use of their psychological behavior towards critical situation while maneuvering the drone.

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