A Survey on Human-in-the-Loop Applications Towards an Internet of All

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Abstract—**Our tools and appliances are becoming increasingly more intelligent and interconnected, giving birth to an "Internet of Things" that can be used to support new types of cyber-physical systems (CPSs). While many CPSs are human-centric applications where humans are an essential part of the system, unfortunately, most of these systems still consider the human as an external and unpredictable element to the control loop. In order for these systems to better serve human needs, future CPSs will need to bolster a closer tie with the human element, through Human-in-the-Loop controls that take into consideration human intents, psychological states, emotions and actions inferred through sensory data. This area is a natural confluence of multidisciplinary focus but currently lacks a general understanding of the underlying requirements, principles and theory. As far as we know, this survey is the first effort towards extending the field's knowledge through an in-depth research of the state-of-the-art and a critical overview of the current taxonomic efforts in the area of Human-in-the-Loop CPSs. On top of this research, a novel taxonomic exercise focused on the general roles of the human component together with a requirement analysis, are presented.**

Index Terms—**Human-in-the-loop, cyber-physical systems, internet of all.**

I. Introduction

A. Internet of Things and Cyber-Physical Systems

In the last few years we have been experiencing an unprecedented surge of technological advancement that culminated in many revolutionary human inventions, including personal desktop computers, portable computers and a global network of these computerized devices, aptly called "the Internet". As this inventive surge continues to develop, we are now experiencing a new sort of revolution. We humans have now achieved the power to extend our traditional tools and appliances and give them intelligence and communication capabilities. This idea began with a vision of an "Internet of Things (IoT)", where radio-frequency identification would allow the "tagging" of everyday objects to be read, identified and managed by computers. The continued advances in the miniaturization of computation allowed us to go beyond the simple tagging and identification and effectively integrate computational resources into these objects, making our tools effectively "intelligent." This means that, theoretically, everything from lightbulbs to fridges, microwaves and coffee machines can be soon connected to the Internet. In fact, some opinions, such as the one shared by Gartner, say the "Internet of Things" will soon have 26 billion connected devices by 2020 [1]. From the use of these diverse computational elements rises the concept of cyber-physical systems, which consists on the sensing and control of physical phenomena through networks of interconnected devices that work together to achieve common goals. These CPSs represent a confluence of robotics, wireless sensor networks, mobile computing and the Internet of Things to achieve a highly monitored and easily controlled and adaptable environments.

The IoT and CPSs are, therefore, closely related concepts that have been pushed by two different groups. The IoT was initially driven from a computer science perspective, mostly by the European Commission. The goal is to develop a network of connecting computers to objects with self configuring capabilities that functions on top of the current Internet. This development effort includes the hardware, software, standards, interoperable communication protocols and the languages that describe these intelligent objects [2]. Several requirements are associated with the advent of the IoT, namely the development of intelligence in devices, interfaces and services, the assurance of security and privacy, systems integration, communication interoperability and data semantization and management [3].

On the other hand, the concept of CPSs derived from an engineering perspective, being initially supported by the US National Science Foundation (NSF). CPSs concern themselves with the control and monitoring of physical environments and phenomena, through sensing and actuation systems consisting of several distributed computing devices, tightly coupled in their functions towards their physical environment [4]. In this sense, CPS require considerable interdisciplinary and a strong foundation in mathematical abstractions (algorithms, processes) that model physical phenomena, to apply technology towards solving physical problems. This also implies smart devices and services, effective actuation, security, privacy, integration, communication and data processing [5].

Thus, the IoT tended to focus more on openness and networking of intelligent devices, with CPSs being more concerned with applicability, modeling of physical processes and problem solving often through closed-looped systems. While their core philosophy and focus were initially different, their many similarities, such as intensive information processing, comprehensive intelligent services and efficient interconnection and data exchange,

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have lead to both terms being used interchangeably [6] without clearly identified frontiers [4]. Therefore, both concepts have now become inherently complementary and synonymous.

This concept of automatic monitoring and control of environments is already used by many applications. From industrial applications that monitor and actuate over several factory processes, to smartphone-based social networking applications that achieve metropolitan-wide reduction of pollution and traffic, these environments can encompass a multitude of domains. The health-care domain can also benefit from CPSs for disease management and personal health. For example, body networks may integrate the user's vital signs and activity levels with environmental information on pollutants or noise, to suggest healthier and more pleasant walking routes, restaurants and leisure activities. CPSs can also be observed in transportation, as many modern vehicles feature cruise control systems that maintain the automobile's speed or perform parking maneuvers. All these systems combine sensors, actuators and the computational intelligence of the devices to achieve the desired results.

So far, traditional embedded systems and wireless networks were designed with a specific scientific, industrial or engineering application in mind, which was usually responsible for collecting data from sensors and analyzing it for a certain task. This target-application driven development of such technologies results in a constrained applicability; that is, the systems are effective for targeted scenarios but are narrow in approach and do not explore a wider usability space. Such restriction inhibits eventual cost reductions that come with mass production and widespread use of a technology [7]. Some believe these restricted deployments, whose primary benefactors are privileged users who already know the capabilities of the network, are just the initial steps towards a future where the vast majority of intelligent devices are interconnected in massive, non-centralized networks [8]. As we approach a completely ubiquitous and pervasive technological world, ordinary people will be capable of accessing extremely rich and dynamic pools of data regarding their surrounding environments, stemming from highly heterogeneous and open CPSs. In fact, Wood *et al.* [8] argued that future CPSs will become ubiquitous and distributed, with many data streams overlaying the network, provided by large amounts of sensors. They also defended that these streams should be open for use without centrally controlled authorization, through self-advertising and discovery by nearby users. Thus, data acquisition, processing and visualization should be focused on users, not administrators or scientists.

Additionally, the data should be localized and delivered preferentially to local users, which have a greater need to know the physical constraints of interactions with their surrounding environment. On the other hand, this openness raises the need for stochastic system designs, since the demand for sensor data and actuation would be unpredictable. Heterogeneity will also need to be considered, since diverse types of sensor hardware, mobile devices, applications, user interfaces, actuators, data flows, and usage patterns already exist and the tendency is for this diversity to increase and evolve. This view of an open approach for CPSs proposed by Wood *et al.* is, however, debatable. There are obvious concerns in terms of privacy and security in face of suggested openness of these CPS deployments.

B. Humans Within Cyber-Physical Systems

While these interconnected and intelligent tools communicate with each other without any human involvement, human technology is made by humans, for humans. Thus, to promote the creation of systems that are useful to the average person, it is not enough to simply consider the openness, heterogeneity and integration of smart tools. Effective tools also require efficient and intuitive manipulation. Therefore, equally important is the discerning of how those tools can be used within a certain context. These ideas have been previously explored as *context awareness*, for Mobile and Wireless Networking [9] and the IoT [10]. Actually, increasing context awareness is a cross-cutting challenge for the design of highly optimized networking systems that support distributed autonomic decision making and reconfigurable aspects [9]. However, current trends on context awareness research encompass a broad definition of context. "Context" can be defined as any information that can be used to characterize an *entity*, that is, a person, place or object [11]. Thus, several works in the area attempt to predict context [12] and use this information to achieve several ends, such as mobility management [13] or energy efficiency in ubiquitous environments [14]. There are also remarkable proposals for frameworks that manage and distribute this contextual data [10], [15].

Yet, outside of the area of e-health, whose primary objective is the monitoring of patients [16], there is still scarce scientific work that focuses on the actual effects of this human "context" in the control-loop of CPSs powered by the IoT. Indeed, one important element often left out of current cyber-physical research is the human user [8]. On the other hand, nowadays humans are, by themselves, walking sensor networks. They use smart-shirts, carry a smartphone with several sensors and network capabilities (GSM, Bluetooth, LTE), use Google glasses, iPods, smart watches and shoes with sensors. In particular, smartphones have become personal portable computers, representing a versatile computational resource; nowadays, even the most basic and cheap mobile phones are capable of processing considerable amounts of information and are equipped with a few sensors (microphone and camera) and basic programming platforms. Modern smartphones are actually more powerful than desktop computers from a decade ago. For example, an iPad 2 tablet, introduced in 2011, has a peak calculation speed equivalent to that of the Cray-2 supercomputer, introduced in 1985 [17]. However, tablets and smartphones also possess advanced sensors such as gyroscopes, accelerometers and digital compasses, feature quad-core processors and up to 2 Gigabyes of RAM. In a very real sense these devices have brought us pocket-size supercomputer-like computational power in a matter of few years. They also brought us incredible mobility, not only for our telephone calls, but also in our Internet access, allowing us to communicate with remote devices almost anywhere. While possibilities of such advanced mobile platforms are already apparent in the diversity of existing applications made available for them, we believe these are only primordial examples. When we begin using all of these sensors and mobile devices to monitor and evaluate human nature, humans become an integral part of CPSs and we are now in the realm of Human-in-the-loop Cyber-Physical Systems (HiLCPS), that is, cyber-physical systems that take human interaction into consideration. Human presence and behavior is no longer seen as an external and unknown factor but becomes a key part of the system instead. Thus, current CPSs that involve control loops will begin to include humans as inherent elements of this control. For example, today's aircraft pilots still decide for themselves when to engage the autopilot or assume manual control of the plane, and cruise control systems for automobiles simply maintain the desired speed without taking the driver's behavior into consideration. Future HiTLCPSs will bolster a stronger tie between humans and control loops. By inferring the user's intents, psychological states, emotions and actions through sensors, a control-loop's performance and accuracy can be vastly improved. For example, cruise control systems could take into consideration the driver's psychological state (e.g., fatigue, attention-levels, etc.) to emit signal alarms and suggest the activation of cruise control [18]. HiTLCPSs also include brain-computer interfaces (BCIs), controlled assistive robots, intelligent prostheses, monitoring systems, among others [19]. In order to improve the accuracy and timeliness of the system by considering the human element, it is essential to integrate reliable and accurate modeling techniques that attempt to learn and predict human behavior. Since humans are often considered unpredictable, bringing them into CPSs is a colossal challenge, as it requires modeling of complex behavioral, psychological and physiological aspects of human nature. Within these aspects, a multitude of variables regarding the person's status may be measured, including movement, vital signs, attention level and any other facet that may be interesting to control the task at hand.

The maturing of HiTLCPSs' design requires a general understanding of their underlying requirements, principles and theory. As HiTLCPSs have a wide spectrum of applicability, it is necessary to amass examples of HiTL solutions from multiple domains before such an understanding may be achieved [18]. This need drives us to ask questions such as why do current IoT solutions still leave behind the human? Why have we yet to integrate the human component into CPSs? In particular, we also want to discover how we can take advantage of these new ubiquitous sensing platforms known as smartphones, personal devices used massively by people throughout their days, to build not an Internet of Things, but an "Internet of All": an Internet that includes the emotions, psychological states, actions and drives of the ordinary user—the Human, as part of larger scale systems. Pondering on these questions, our research paper makes the following contributions to the further development of the field of HiTLCPS:

- An analysis of the state-of-the-art of the field of HiTLCPSs.
- A critical overview of current taxonomic efforts.
- An extension to current taxonomies that considers the perspective of the possible human roles in HiTLCPSs.
- An analysis of the requirements and challenges for these types of systems.

While there are previous articles that discuss the field of HiTL and its unresolved challenges [19], [20], as far as we know this is the first effort towards a general overview of the existing solutions, projects and taxonomic analysis in the field of HiTLCPSs. The only previous taxonomic classification of the field of HiTLCPS [20] is limited in the sense that it only classifies the different types of HiTL applications. We intend to provide an alternative point of view of HiTL process by performing a taxonomic exercise in the perspective of the different processes of the HiTL control.

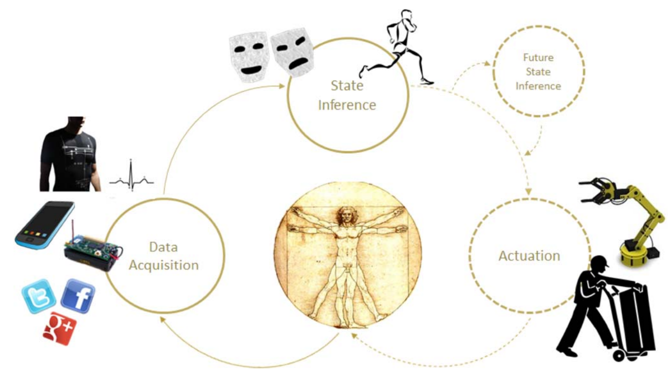

Fig. 1. The processes of human-in-the-loop control.

The rest of this paper is organized as follows: Section II is dedicated to a introduction to the major concepts and evolution of current HiTLCPSs, where the main associated technologies are identified and where several relevant research works, including those with a social networking component, are described; in Section III, taxonomic overviews of HiTLCPSs and the human roles within them are presented; Section IV attempts to identify several requirements that need to be addressed in future HiTLCPSs; Section V represents an overview of our research, including a chronological exposition and the main lessons learned; we finalize our paper in Section VI with a few concluding remarks and possible future research directions.

II. Evolution of HiTL Systems

Emerging research in HiTL control systems based on the IoT and in CPSs offers a tremendous range of opportunities.

Fig. 1 presents the various processes associated with HiTL control. On an initial phase, data related to the human individual is gathered from the available sensors. This data is then processed in order to infer the human's state, that is, his physical and/or psychological condition. Some approaches may also attempt to predict future states based on historical data and the current state. Finally, the system may or may not perform a certain action based on current determined conditions. Some "open-loop" systems do not affect the system *per se*, that is, their results are merely informative, without direct actuation. However, "closed-loop" systems actuate directly on the environment or the human in order to influence the loop and achieve a desired state.

Introducing HiTL concepts into CPSs is still a challenge currently scarcely addressed by the academia. In the paper written by Stankovic *et al.* [20] three main challenges were identified for HiTLCPSs. Firstly, there is a need for a comprehensive understanding of the spectrum of HiTL applications, which requires a study of a large number of solutions so that common underlying principles, requirements and models may be found. Secondly, it is necessary to improve the techniques that derive models of human psychological states, emotions, physiological responses and actions. In order words, we need reliable mechanisms for modeling, detecting and possibly predicting human nature, such as advanced mathematical models or machine learning techniques. Current state-of-the-art techniques are either very generic or too application-specific and the development of dynamic human-behavior models that are both accurate and general enough remains an enormous challenge. Finally, these human behavior models need to be incorporated into the formal methodology of feedback control, either outside or inside of the loop, within the system model or at any other level of the hierarchical control.

A. Technologies for Supporting HiTLCPSs

In an effort to gain an understanding of the existing types of solutions and methods, we will begin by analyzing the scope of HiTLCPSs through a practical perspective, first delving into the processes of data acquisition, then considering different solutions for inferring state and finally, different techniques for actuation.

1) Data Acquisition in HiTLCPSs: The acquisition of data through which the human's state may be inferred is a complex process with a multitude of possible sources of information. HiTLCPSs have previously used physical properties, such as localization (e.g., GPS positioning), vital signals (heart rate, ECG, EEG, body temperature…), movement (accelerometers), sound (voice processing), among many other types of information that can be acquired directly from physical reality. There are also many non-physical properties that may be derived, such as communication behaviors (e.g., phone calls, SMSs), or socialization habits. Most of this raw physical data comes from distributed sensor architectures, which are critically important for HiTLCPSs since they allow the measurement of changes which may be processed to infer current environmental conditions and human activities, psychological states and intents. On this regard, several types of architectures and technologies have been proposed.

One of the most important technologies for the process of data acquisition in HiTLCPSs are Wireless Sensor Networks (WSNs). These are networks of small battery-powered devices with limited capabilities, wireless communication and various sensors that have been applied in countless application scenarios worldwide. One highly debated challenge for applying WSNs to CPSs is the integration of these tiny devices into the worldwide Internet of Things. This ease of integration is of particular importance for HiTLCPSs, since it would make these systems more distributed, open, interactive, discoverable and heterogeneous, as previously envisioned in [8]. In WSNs, the use of the IP protocol has always been considered inadequate due to the fact that it does not minimize memory usage or processing. Moreover, the use of the full TCP/IP stack is not possible because it requires more resources than what most of these devices can offer. However, the integration of IP has the advantage of offering a transparent communication between nodes while using a well-known protocol, providing interoperability and even Internet connectivity. While working towards employing IP in WSNs, the IETF created the 6LowPAN group that has been working on standards for the transmission of IPv6 packets over low capability devices in wireless personal areas, using IEEE 802.15.4 radios. New drafts were also proposed for adapting 6LoWPAN to other technologies like Bluetooth. Unfortunately, 6LowPAN cannot be applied to devices devoid of processing or memory capabilities, such as RFID tags. Gateway-based approaches are a possible solution to support IP functionalities on these scenarios. The main advantage of these approaches is that terminal devices do not require any processing or communication capabilities. Moreover, they make the sensor and device networks transparent to external environments and developers can use any protocols that are most suitable. However, one inherent problem of gateway-based approaches is that they become a single point of failure. This problem is exacerbated in environments where devices present some type of mobility, i.e., moving from place to place while maintaining connectivity. In these mobile environments, all of the communication processes are more fragile and failure of fixed gateways can compromise the integrity of the HiTLCPS. Another problem of gateway-based approaches is that sensor nodes are often required to format the data according to a specification defined by the provided drivers of the gateway, forcing the developer to create a software driver or analyzer for each specific data frame format, further reducing their interoperability for HiTLCPSs.

Some research works focused on some of these architectural issues for including WSNs into HiTLCPS. SenQ [21] is a data streaming service for WSNs designed to support user-driven applications through peer-to-peer in-network queries between wearable interfaces and other resource-constrained devices. It introduced the concept of "virtual sensors", user-defined streams that could be dynamically discovered and shared. For example, in assisted-living scenarios for elderly people, a doctor could combine information from mobility speed, movement and location (e.g., nearby stairs) to create a virtual sensor that alerted nearby healthcare staff of an elevated risk of falls. SenQ took into consideration several requirements that were not satisfied by existing query system designs at the time, such as heterogeneity of sensor devices, dynamics of data flow patterns, localized aggregation of sensor data and in-network monitoring. The system supported hierarchical architectures but predominantly favored *ad hoc* decentralized ones, as the authors defended that *ad hoc* architectures with neighborhood device and service discovery are better suited for supporting large-scale and open systems with many users and sensors [8]. Data and control logic was also kept close to the concerned devices, in order to save energy and preserve scalability by providing a stack with loosely coupled layers that were placed on devices according to their capabilities and by enabling in-network peer-to-peer query issue for streaming data.

Another type of communication paradigm that may benefit HiTCPSs is body-coupled communication (BCC) [20] for supporting low-energy usage, heterogeneity and reduced interference. BCC leverages the human body as the communication channel, that is, signals are transmitted between sensors through electrical impulses directly through human tissue to a point of data collection. Through a circuit-equivalent representation of the body channel, different types of body tissue (skin, fat, muscles and bone) are modeled with variable levels of impedance

[22]. In particular, in "Galvanic coupling" the signal is applied differentially over two coupler electrodes and received differentially by two detector electrodes. The coupler establishes a modulated electrical field, which is sensed by the detector. Therefore, a signal transfer is established between the coupler and detector units by coupling signal currents galvanically into the human body [23]. There are several motivations propelling the support this paradigm. Firstly, the energy consumed in BCC is shown to be approximately three orders of magnitude less than the low-power classic RF-based network created through IEEE 802.15.4-based nodes. This technology is also bolstered by a high bandwidth availability of approximately 10 Mbps, which accommodates the needs of multiple sensor measurements. Finally, it offers a considerable mitigation of fading phenomena and overcomes typical interference problems of the ISM band, which are usually affected by nearby devices (e.g., Bluetooth, Wi-Fi or microwave ovens) [20].

In a different perspective, we argue that much of the computational power and sensing capabilities for future HiTLCPSs will come from devices already existing in the environment. In particular, we believe that near-future HiTL systems will be heavily based on smartphone technology, due to their rapidly expanding dissemination and their powerful computation and sensing capabilities. Current low-end smartphones capable of basic sensing and processing functions are widely available even in many low- and middle-income countries that lack a much needed basic infrastructure, such as paved roads and electricity, diminishing the need for fixed Internet deployment [24], [25]. The International Telecommunications Union found that, by the end of 2011, the number of mobile phone subscriptions reached 5.9 billion, representing a penetration of 87% of the entire world and 79% of all developing countries [26]. Thus, smartphones are extremely common, increasingly cheap, and provide mobile Internet connectivity almost everywhere, making them excellent candidates for sensing and processing nodes in future HiTL applications. In fact, smartphone sensors such as accelerometers, GPS, microphones or cameras can be used by simple inference mechanisms to evaluate a human's psychological and physiologic states and integrate this information into HiTLCPSs. Several mechanisms to support this continuous sensing have been proposed. Jigsaw [27] is a continuous sensing engine that supports resilient accelerometer, microphone and GPS data processing. It comprises a set of plug-and-play sensing pipelines that adapt their depth and sophistication depending on the quality and information of data as well as the mobility and behavioural patterns of the user to drive down energy costs. This reusable and application agnostic sensing engine proposed solutions to problems that usually arise in smartphone sensors, such as performing calibration of the accelerometer independently of body position, reducing computational costs of microphone processing and reducing the GPS duty cycle by taking into account the activity of the user. Focusing more specifically on the microphone, as one of the most ubiquitous but least exploited of the smartphone sensors, SoundSense [28] is a scalable sound sensing platform for people-centric sensing applications which classifies sound events. It is a general purpose sound sensing system for resource limited phones that uses several supervised and unsupervised sensing techniques to classify general types of sound (music, voice) and discover novel sound events that are specific to individual users. These are two examples of sensing architectures that could be exploited to enable future continuous and ubiquitous smartphone sensing in HiTLCPSs.

2) State Inference in HiTLCPS: A recurring premise behind powerful HiTL systems is transparent interfaces that can infer human intent, physical and psychological states, emotions and actions. While traditional interface schemes such as the mouse and keyboard have long been used to transmit human desires, they are unpractical, involving series of key combinations or sequences of mouse clicks that are unintuitive and require practice and repetition in order to learn and master. On the other hand, HiTLCPS applications are meant to react to natural human behavior and do not necessarily require direct human interaction. However, deriving advanced mathematical models or machine learning techniques that can reliably classify and possibly predicting human nature is a colossal challenge.

Many different methods and types of signals are used to perform human activity classification in the literature. One of the most successful and popular techniques is the use of Hidden Markov Models [29]–[31], but some approaches also use naive-bayes classifiers [32]–[35], Support Vector Machines [36], C4.5 [34], [36] and Fuzzy classification [37]. Research also uses different kinds of sensory data for activity detection: wearable sensor boards with many different types of sensors [29], [30], wearable accelerometers [31], [34], [36], [38], gyroscopes [38], ECG [36], heart rate [34], to smartphone accelerometer data and sound [39] and even RSSI signals [40]. The application of activity recognition is present in many areas, from sport solutions to social networking and health monitoring. The state-of-art is very active and presents very good results, some works achieving accuracy levels in the order of 90–95%.

The detection of a user's psychological state has also been previously attempted. Smartphones have been used in Experience Sampling Method (ESM) studies, where participants respond to short questionnaires that give insight into their moods and behavior [41]. Through a prototype smartphone-based ESM system, named EmotionSense, it was possible to study the influence of different sampling strategies on the inferred conclusions about the participants' behavior. Their prototype system was based on an Android application that used both "physical sensors" (including the accelerometer, microphone, proximity, GPS location and the phone's screen status) as well as "software sensors" (capturing phone calls and SMS activity). These sensors were used to evaluate the context of users and to trigger survey questions about their feelings, namely how positive and negative they felt, their location and their social setting. The application could be remotely reconfigured to vary the questions, sampling parameters and triggering mechanisms that notified users to answers a questionnaire. The results were used to empirically quantify the extent that sensor-triggered ESM designs influence the breadth of behavioral data captured in these kinds of studies.

EmotionSense was also used to enhance Behavior Change Interventions (BCI) by using the devices capabilities to positively influence human behavior [42]. Traditional BCIs involve advice, support and information relevant to the patient's daily activities that are given during sessions by therapists and coaches. Smartphones with their powerful sensing and machine learning capabilities, ubiquity and presence, allow for behavior scientists to use directed, unobtrusive and real-time behavior change interventions to induce lifestyle changes that may help people coping with chronic diseases, smoking addiction, diets or even depression. Information can be delivered and measured in the moments when the users need it the most; for example, people addicted to smoking usually suffer from detectable stress when feeling the need to smoke, allowing an opportunity for the system to send a notification urging them not to do so. Thus, detecting the user's context and emotions allows for interventions to be delivered at the right time and place. The EmotionSense application uses the Gaussian Mixture Model (GMM) machine learning technique to detect ongoing conversations and their respective participants. An emotion inference component was also developed using a similar approach, training a background GMM representative of all emotions through the Emotional Prosody Speech and Transcripts library [43]. This component allowed the application to infer five broad emotional states from the smartphone's microphone: anger, fear, happiness, neutrality and sadness. The authors reported an accuracy of over 90% for speaker identification and over 70% for emotion recognition. With the same objective of providing positive behavioral change, the authors also developed SociableSense [44], a platform that monitored the user's social interactions and provided real-time feedback to improve their relations with their peers. In this work, the authors attempted to measure the "sociability" of users, which is an important factor in many behavioral disorders, ranging from autism to depression. The system then closed the loop by providing real-time feedback and alerts that aimed to make people more sociable. The sociability measurement was divided into two factors, collocation and interaction. Collocation was defined by the proximity between users and it was inferred by a coarse-grained Bluetooth-based indoor localization mechanism. Interaction was derived from the speaking between users and it was inferred via the microphone sensor and a speaker identification classifier, in a fashion similar to EmotionSense. Active socialization was promoted through a gaming system which classified the most sociable persons as "mayors" of the social groups. Their results showed that such feedback mechanisms influenced users and increased their sociability.

Several ongoing challenges for mobile sensing were also identified in [42], including:

- Energy constraints associated with continuous sensing, which require intelligent mechanisms that dynamically adapt sampling rates depending on the user's context.
- Data processing and inference mechanisms that can accurately extract information on human behavior from raw sensor data and the importance of balancing the distribution of this computation through the smartphone sensors and cloud-based back-ends.
- Generalizability of classification mechanisms that need to make uniform inferences regarding widely different populations of users.
- Privacy concerns about the acquisition of sensitive data (locations, activities) and the recording of data without people's informed consent (e.g., inadvertently capturing the voice of an external person through the microphone of a smartphone user).

The detection of emotion is not restricted to voice pattern recognition, however, and other interesting ways of inferring the user's psychological state have been proposed. The touch interface and movement of a smartphone were used in [45] as a way for infering emotional states. The proposed framework consisted on a emotion recognition process and an emotion preference learning algorithm which were used to recommend smartphone applications, media contents and mobile services that fit the user's current emotional state. The system collected data from three sensors, the touch interface, accelerometer and gyroscope, classifying it into types (e.g., touch actions could be divided into tapping, dragging, flicking and multi-touching). The processed data was used to quantify higher level emotions, such as "neutral," "disgust," "happiness" or "sadness," through decision tree classification methods. By analyzing communication history and application usage patterns, MoodScope [46] also inferred the mood of the user based on how the smartphone was used. The system passively ran in the background, monitoring application usage, phone calls, email messages, SMSes, web browsing histories, and location changes as user behavior features. With daily mood averages as labels and usage records as a feature table, the authors applied a regression algorithm to discern a mood inference model.

3) Actuation in HiTLCPS: Actuation is a very broad definition in the field of HiTLCPSs. For example, applications that passively monitor a human being's sleep environment to give information about potential causes of sleep disruption [47], or that record a human's cardiac sounds to detection of possible pathologies [48] do not directly influence the associated environment to attempt to achieve a certain goal and yet, they still "actuate" by providing information. A more direct actuation with the physical world can be achieved through specialized device, such as robots [19]. Future generation of advanced robots are envisioned to be mobile and operating in unstructured or uncertain contexts. The world has seen a gradual increase in the number of robots installed annually, from about 65.000 in the early 2000 to 105.000 in 2007, according to the United Nations Economic Commission for Europe [49], and to about 120.000 predicted for 2015. The sector is expected to grow at a rate of 4–5% per year, from a value of \$5.4B in 2005 to a projected value of \$52B by 2025, according to the U.N. Economic Commission Study. Considering these factors, robotics will also play a huge role in future HiTLCPSs.

Interestingly, in recent years there has been a combination of two important technologies—robots and WSNs—that complement each other. WSNs assist in the process of discovering the environment where robots actuate; the detailed level of information provided by their sensors may be essential for the tasks to be undertaken by the robot. On the other hand, robots can be used as mules that collect and forward information from several sensor nodes spread in the environment. Thus, the excessive energy needed for long distance or multi-hop transmissions is reduced. Robots can also perform the calibration of sensors and support their recharging process when energy levels are low.

Robots and wireless sensor technologies can be exploited to support remote monitoring in dangerous environments under maintenance, using a set of sensors to measure, for example, gas levels. They can also be applied in the monitoring of environmental impact, such as in waste-water treatment facilities or for measuring air emissions, allowing a proactive implementation of a social responsibility culture. Using wireless technology and robotic mobile inspection for the monitoring and surveillance of wide areas, where diagnosis and intrusion detection are critical, is also a more reliable cost-efficient solution than traditional methods.

While WSNs offer the sensorial capabilities necessary for robots to perform the desired tasks, humans provide the necessary management of the operation. Thus, robots are capable of performing missions in hazardous environments in cooperation with humans, taking in consideration the psychological state of humans, while using data from WSNs to scan both humans and the environment. In fact, the combination of Human-WSNs-Robots has a huge potential in the perspective of actuation in HiTLCPSs, since advanced industrial automation can strongly benefit from distributed sensing capabilities. Robots, humans and WSNs can be deployed to support personnel safety, by complementing human work in hazardous contexts, with wireless sensor networks collecting and processing information. Mobile workers and robots can be equipped with multiple sensory systems that send information to a control center, accessible and monitored by safety and personnel health-control staff. This allows workers to safely and remotely control operations and to make decisions faster. Such combination of these technologies allows us to envision highly advanced HiTLCPSs applied to many different scenarios. As an example, flying inspection robots could be used to navigate interactively and inspect power plant structures (including various components within and around boilers, environmental filters or cooling towers) and structures within the oil and gas industry (inside and outside large scale chimneys, inside and outside flare systems, inside button part of refining columns, as well as pipelines and pipe webs). On the other hand, workers in the field may collaborate with these robots in their inspection tasks, in the management of the whole operation and in the deployment and collection of sensor networks. HiTL controls allow for this collaboration to be safe for humans, since their presence, actions and intentions are made known to the individual robots, as well as the entire system.

There are several projects that specifically study and evaluate the integration of WSNs with Robots. For example, the Robotic UBIquitous COgnitive Network (FP7-ICT-269914) [50] is an on-going project that aims to create autonomous and auto-configured systems by combining WSNs, multi-agents and mobile robots. The proposed mechanisms reduce the complexity and the time needed in deployment and reconfiguration tasks. However, the main objective of this project is to remove, as much as possible, the Human from the configuration and maintenance processes. According to the authors, this means that the quality of service that is offered by the Robot-WSNs intends to be significantly improved, without the need for extensive human involvement. Considering that these technologies are meant to co-exist with human beings, why are humans excluded from control loop decisions? Why not take advantage of the Human potential to create immerse HiTLCPSs?

Other research venues focus more this human-robot cooperation. Projects such as NIFTi: Natural human-robot cooperation in dynamic environments (FP7-ICT-247870) [51], an European FP7 project that ran from January 2010 until December 2013, proposed new models for co-operation between robots and humans when they work towards a shared goal, performing tasks together. However, this project required a lot of direct instructions from human to robots and WSNs were not used to dynamically contribute and adapt these systems. PHRIENDS: Physical Human-Robot-Interaction—Dependability and Safety (FP6-IST-045359) [52] was a project that aimed to propose the coexistence of robots and humans. One of its main objectives was to find the strictest safety standards for this co-existence. Later, this project resulted in a new PF7 project, SAPHARI [53], which maintained its main objective but now used soft robotics, combining cognitive reaction and safe physical human-robot interaction. In contrast with its precursor project, SAPHARI intended to provide reliable, efficient and easy to use functionalities. There are also other projects on the topic of safety in interactions between humans and robots. CHRIS—Cooperative Human Robot Interaction Systems (FP7-ICT-215805) [54] evaluated a mapping mechanism between robots and humans. This project also aimed to study the safety of cooperative tasks between humans and robots when they work for the same purpose. However, once again, these environments did not assume the existence and the participation of WSNs. On the other hand, Humans were seen as just end-users and they were not integrated in the system. SWARMANOID—Towards Humanoid Robotic Systems (FP6-IST-022888) [55] and SYMBRION: Symbiotic Robotic Organisms (FP7-ICT-2007.8.2) [56] were two similar projects that aimed to find strategies to achieve a collaborative work between robots. SWARMANOID proposed joint mechanisms both by air and land to achieve search tasks. The latter project intended to optimize energy by sharing policies. Robot-Era [57] is a project that started in 2012 and it will finish in 2015. It intends to implement and integrate advanced robotic systems and intelligent environments in real scenarios for the aging population. Some of these intelligent environments are based on WSNs and their role is to support the quality of life and independent living for elderly people.

Despite all of these efforts, much work still has to be done, in particular for robotic actuation that considers the human-state. Thus, the role of robotics in future HiTLCPSs cannot be yet fully understood. In addition to the unsurpassed technical challenges, there are also questions of an ethical nature that will also need to be considered. We will identify some these matters further in Section V-B2.

B. Applications of HiTLCPSs

There is a need for a comprehensive understanding of spectrum of HiTL applications, which requires a study of a large number of solutions so that common underlying principles, requirements and models may be found. In this section, we will analyze several works in the area of HiTLCPSs that apply the different processes discussed in Section II.

To contribute to this need for understanding spectrum of HiTL applications, the work in [18] provided its own implementation of a human-in-the-loop system that attempted to reduce the energy waste on computer workstations by modeling human behavior to detect distractions. Current practices for reducing energy consumption are usually based on fixed timers that initiate sleep-mode after several minutes of inactivity. However, this distraction detection system used adaptive timeout intervals, multi-level sensing and background processing to detect distractions (e.g., phone calls, restroom breaks) with 97.28% of accuracy and cut energy waste by 80.19% [18]. The proposed "distraction model" enclosed two main sources of information, user activities and system activities. At the user-activity level, the authors used a "gaze tracker" which evaluated the user's gazing at the computer's screen through a webcam. At the system-activity level, the system evaluated keyboard and mouse events, CPU usage and network activities to infer the machine's level of use. The control loop combined both types of information to determine the distraction status of the user, with some self-correcting measures; e.g., if the user resumed the system shortly after it was put to sleep, the control loop took this as a negative feedback event, and subsequently adjusted the timeout interval.

The area of Human Computer Interaction (HCI) has long studied the concept of HiTL. Humans prefer to attend to their surrounding environment and engage in dialog and interaction with other humans rather than to control the operations of machines that serve them. Thus, in [58] it is suggested that we must put Computers in the Human Interaction Loop (CHIL), rather than the other way around and a consortium of 15 laboratories in 9 countries has teamed up to explore what is needed to build usable CHIL computing services. The consortium developed infrastructure used in several prototype services, including a proactive phone/communication device, a Memory Jog system for supportive information and reminders in meetings, collaborative supportive workspaces and meeting monitoring and a simultaneous speech translator for the lecture domain. These projects led to several advances in the areas of audio-visual perceptual technologies, including speech recognition and natural language, person tracking and identification, identification of interaction cues such as gestures, body and head poses and attention, as well as human activity classification.

A communication framework for human-machine interaction that is sensitive to human affective states is presented in [59], through the detection and recognition of human affective states based on physiological signals. Since anxiety plays an important role in various human-machine interaction tasks and can be related to task performance, this framework was applied in [60] to specifically detect anxiety through the user's physiological signals. The presented anxiety-recognition methods can be potentially applied in advanced HiTLCPSs.

HiTL concepts have also been applied to smartphone data usage. In fact, HiTL has previously been proposed as a solution for addressing the increasing demand for wireless data access [61]. Since the wireless spectrum is limited and shared, and transmission rates cannot be improved anymore solely with physical layer innovations. Thus, a "user-in-the-loop" mechanism was proposed that promoted spatial control, in which the user was encouraged to move to a less congested location, and temporal control, in which incentives, such as dynamic pricing, ensured that the user reduced or postponed his current data demand in case the network was congested. This closed-loop controlled user activity itself through suggestions and incentives, influenced by the current location's signal-to-interference-plus-noise ratio and traffic situation. The authors proposed that users receive control information on the form of a graphical user interface, showing a map and directions towards a better location and a better time to start his traffic session (e.g., outside of busy hours).

Schirner *et al.* [19] have previously stressed the existing multidisciplinary challenges associated with the acquisition of human states in HiTLCPS. For example, embedded systems are key components used for these systems and, as such, they proposed a holistic methodology for system automation in which designers develop their algorithms in high-level languages and fit them into an electronic system level (ESL) tool suite which acts as a system compiler, producing code for both the CPU and the field-programmable gate array. This automation allows for researchers to more easily test their algorithms on real scenarios and to focus more exclusively on the important task of algorithm and model development. Schirner *et al.* also used an EEG-based brain-computer interface for context-aware sensing of a human's status, which influenced the control of an electrical wheelchair. To improve the intent inference accuracy, the authors suggested that inference algorithms should adapt to the current application as well as the user's preferences and historical behavior, that is, use application-specific priors and contextual information. The field of robotics is also addressed, as robots are the primary means for actuation and interaction with the physical world in CPSs. Their semiautonomous wheelchair interpreted brain signals that translate high-level tasks such as "Navigate-to-Kitchen" and then executed path planning and obstacle avoidance [19]. However, important research questions are still unresolved, namely the problem of dividing control between human and machine, as well as the modularity and configurability of such systems. Distributed sensor architectures are also very important for HiTL since they allow the measurement of physiological changes which may be processed to infer current human activities, psychological states and intent. On this regard, BCC was presented as a means for supporting low-energy usage, high bandwidth, heterogeneity and reduce interference.

At the Worcester Polytechnic Institute [62], a prototyping platform and open design framework for a semi-autonomous wheelchair to realize a HiTLCPS was developed. The authors considered disabled individuals, namely those suffering from "Locked-in syndrome," a condition in which an individual is fully aware and awake but all voluntary muscles of the body are paralyzed. To improve the life of these individuals, they created a HiTL wheelchair system which used IR and ultrasonic sensors to navigate through indoor environments, enabling the user to share control with the wheelchair in a HiTL fashion. This allows handicapped individuals to live more independently and have mobility. The resulting prototype used modular components to provide the wheelchair with a degree of semi-autonomy that would assist users of powered wheelchairs to navigate through the environment. This work was extended in [19], where the user could interface with the wheelchair through a brain/computer interface based on using steady-state visual evoked potentials induced by flickering light patterns in the operator's visual field. A monitor showed flickering checkerboards with different frequencies. Each checkerboard and frequency corresponded one of four desired locations. When operator focused on a desired checkerboard on the monitor, his visual cortex predominantly synchronized with the checkerboard's flickering harmonic frequencies. These frequencies were detected through an electrode on the scalp near the occipital lobe, where the visual cortex is located.

Other projects also focused on the development of HiTL wheelchairs to assist disabled people. The work "I Want That" [63], proposed a system that controlled a commercially-available wheelchair-mounted robotic arm. Since people with cognitive impairments may not be able to navigate the manufacturer-provided menu-based interface, the authors improved it with a vision-based system which allows users to directly control the robotic arm to autonomously retrieve a desired object from a shelf. To do so, they used a touchscreen which displayed a shoulder camera view, an approximation of the viewpoint of the user in the wheelchair. An object selection module streamed the live image feed from the camera and computed the position of the objects. The user can indicate "I want that" by pointing to an object on the screen. Afterwards, a visual tracking module recognized the object from a template database while the robotic arm reached towards it and brought it back to the user.

A vision-based robotic device to facilitate activities of daily living for spinal cord injured users with motor disabilities was also proposed in [64], through a HiTL control of an assistive robotic arm. The objective of the research was to reduce time to task completion and cognitive burden for users interacting with unstructured environments via a wheelchair mounted robotic arm. Users could indicate the approximate location of a desired object in the camera's field of view using one of diverse user interfaces, including a touchScreen, a trackball, a jelly switch and microphone. Afterwards, they could order the robotic arm to center the object of interest in the visual field of the camera and then, grab the desired object.

A model-driven design and validation of closed-loop medical device systems was presented in [65]. The safety of a closed-loop control system of interconnected medical devices and mechanisms was studied in a clinical scenario, with the objective of reducing the possibility of human error and improve safety of the patient. A PCA pump delivered a drug to the patient at a programmed rate while a pulse oximeter received physiological signals and processed them to produce heart rate and SpO2 outputs. A Supervisor component got these outputs and used a patient model to calculate the level of drug in the patient's body. This in turn influenced the physiological output signals through a drug absorption function. Based on this information, the Supervisor decided whether or not to send a stop signal to the PCA Pump. The main contribution of the paper was the methodology for the analysis of safety properties of these types of systems.

Heating, ventilation and cooling (HVAC) systems have also been endowed with HiTL controls. For example, in [66] the authors implemented a system that used cheap and simple wireless motion sensors and door sensors to automatically infer when occupants are away, active, or sleeping in a home. The system used these patterns to save energy by automatically turning off the home's HVAC system as much as possible without sacrificing occupant comfort, effectively creating a HiTLCPS. Another example can be found in [67] where a occupancy sensor network was deployed across an entire floor of a university building together with a control architecture that guided the operation of the building's HVAC system, turn it on or off to save energy while meeting building performance requirements.

C. Social Networking and HiTLCPSs

Despite being in their infancy, the IoT and CPSs are already transforming the way our world and society work, at a very fundamental level and at an incredibly fast pace. As our Internet-connected devices evolve so do the means we use to communicate and interact with the people we deem close. In the past, people's interactions were mostly face-to-face amongst their peer groups, with occasional long-distance relationships through letters or telephone calls. In today's world, we see a social revolution where people share, in real-time, funny stories, thoughts, feelings, photographs and other pieces of their lives with their family and friends, some of which they have not been in physical contact with for a long time, and in some cases, not even ever seen in "real life." Social networking is a phenomenon that bloomed and continues to connect an astonishing number of users, becoming fastest-growing active social media behavior online. The sheer scale at these changes are happening is astonishing: a statistical analysis by Browser Media, Socialnomics and MacWorld suggest that Facebook, one of the largest social networks, has around 1.4 Billion users worldwide and that 98% of 18–24 year olds already use social media websites [68]. Another study claims that 42.6% of the global online population uses Facebook [69]. This social networking tendency shows no indications of slowing down, as the number of Facebook users increased 22% from 2012 to 2013 [70].

Since social networks are becomming so important in the interconnections between humans, it is expected that they will play a prominent role in HiTLCPSs. This already evidenced when we take into consideration the pervasiness of social networking, made possible through the use of dedicated smartphone applications. Of the 1 310 000 000 monthly active Facebook users, around 680 000 000 use a mobile app [70], representing a percentage of use of 69% by the global smartphone community [69]. Despite these advancements and the general public's interest in these social services, their current functionality does not yet reflect the true dynamic of people's relationships and personal lives. Instead of being pre-determined and unique events in time, social group activities can, in fact, happen very frequently and, most of the time, spontaneously. Current systems are not capable of providing this "real-time" component to social networking, which diminishes its true potential. In a sense, we can classify current social networks as still very "static" when compared to a more complete system capable of truly following the extent of human social interactions. While the use of collaborative contributions is still an important part of social applications and can provide meaningful and useful data, sensing systems can provide a more reliable and responsive feedback that may crucial in achieving this "automatic real-time" social-networking. In fact, a HiTL approach to social networking may well come to prove a technological leap over current social-networking of the same magnitude of the one provided by mobile phones over traditional telephones.

We can already see an increase in the number of social applications available for mobile devices that are beginning to touch the border between the virtual and the physical worlds. Although most of them do not depend on the use of sensors or actuators, many applications fetch environmental data from collaborative feedback provided by their users. Users can provide feedback on the weather conditions in a city, the environment of nightlife establishments or even traffic congestion. Waze [71] is a community-driven GPS navigation software that learns from user's driving times and from user reports on accidents and traffic jams to provide routing and real-time traffic updates. Foursquare [72] is a highly popular mobile social networking application that allows users to "check in" at various locations. Location is based on GPS hardware in the mobile device or network location provided by the application, and can also be selected using a mobile website or from a list of venues located nearby.

Highlight [73] is a social application that allows users to learn more about the people around them. People using Highlight can have the profile of other users, within a football field or so of their location, show up on their phone. The application presents several types of data, namely names, photos, mutual friends and other information users have chosen to share, as well as a tiny map that shows their recent location. The closer a person is to the user (the more interests, friends or history they have in common) the more likely the user will be notified of their presence. Thus, Highlight hopes to increase synchronicity and reduce the friction in meeting new people, allowing users to know a few things about one another in advance.

The SceneTap [74] application is another example of an even more flexible and complex detection of people for social networking purposes. The application uses anonymous facial detection software to approximate the age and gender of people entering a nightclub environment. By counting the number of people entering and leaving a venue, the application can estimate and report crowd size, gender ratios, and the average age of people in a given location. This information is shared among users, allowing them to better plan their night outs and decide which nightlife establishments are a better fit for their desires.

While the previous examples show how mobile applications are becoming increasingly more pervasive, we still have not reached a stage where HiTL and social networking have been successfully joined. Nevertheless, the large interest in social networking by the masses, the increasing sharing of personal information and the surge of mobile social applications mark a very pronounced trend that points out to a future where sensing and mobility will most likely become more important and well-accepted. This line of thought has been present in research as early as 2008, with an important research work that has considerably shaped research in the area. CenceME [75] was an innovative people-centric sensing framework where sensors embedded in commercial smartphones were used to extrapolate the user's real-world activities that in turn were reproduced in virtual settings: the long term goal was to provide virtual representations of humans, their surroundings and social interactions, sharing this information amongst groups of friends in order to facilitate social activities and to introduce a real-time component to social networking. The user's smartphone ran activity recognition algorithms that extracted patterns from the obtained data, such as the current user status (e.g, as sitting, walking, standing, dancing, meeting friends) while GPS was used to detect a user's logical location (e.g, the gym, coffee shop, work or other significant places). This information was reflected on a virtual world, Second Life [76], where the user's friends could see what activities he was performing at any given moment as well as his current geographical position. The use of smartphones as means of sensing and communicating with virtual realities is an important aspect of this work, as relying on common and easily accessible technologies foments the adoption of these new systems by more users.

Despite the innovation and potential shown by these HiTL social-networking applications, they have also been met with a considerable amount of skepticism. In regards to Highlight, it has been argued that encounters between people are sometimes best "left to fate" and that the application "may tell others too much about you" [77]. As for SceneTap, skeptics advocate privacy concerns and have raised questions around the facial detection technologies used to collect information, since they are employed without people's consent. The application met a troubling launch in May 2012, where it was supposed to be supported by twenty-five San Francisco bars, of which ten dropped out after angry calls and an editorial that called the service "creepy". The app has also been criticized for its gender filtering options, letting people find bars with a larger proportion of men or women in a certain age range [78]. Accuracy problems in the facial recognition software have also been pointed out, resulting in several bars showing high capacity percentages when in fact they were "as dead as can be" [79].

CenceME's implementation and release was also met with some reservation. As the authors themselves admit, user reviews can be brutal and the impact of such reviews may be negative for the application reputation [80]. While several users praised CenceME claiming it was "something fresh and new" and "the best way to keep up with your friends," many saw it merely as a quirky application that, albeit interesting, was slow and filled with bugs. Other users were unsure if it was "very cool or useless," showing some apprehension towards a "Big Brother scenario," seeing it as an "invasion of privacy" and questioning the usefulness of letting others "know if you're running or walking or not" [81].

III. Taxonomic View of the HiTL Paradigm

The previous sections have shown that the field of HiTL has immense potential and yet, it is still mostly unexplored and there are massive challenges to be surmounted. As proposed by [20] there is a need for attaining an understanding of the

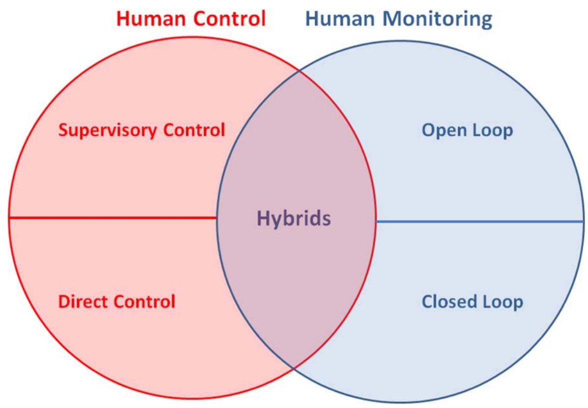

Fig. 2. Taxonomy of human-in-the-loop applications.

spectrum of HiTL applications, their underlying principles, requirements and models.

In order to better comprehend the dimension of such an expansive field as HiTLCPSs, it is important to perform taxonomies that allow us to better structure our ideas and concepts. Stankovic *et al.* [20] have already begun to establish a taxonomic foundation for HiTLCPSs applications, presented in Section III-A. In this document, we will expand this taxonomic exercise to also consider the possible roles of humans in these systems, as well as their general requirements. We believe such a distinction is important, since it will allow us to better answer some of the previously proposed challenges, such as determining how to incorporate human behavior into the methodology of feedback control [20].

A. Taxonomic View of Current HiTL Applications

According to Stankovic *et al.* [20], it is possible to organize existing HiTL applications into three types as shown in Fig. 2: (*i*) applications where humans directly control the system, (*ii*) applications where the system passively monitors humans and takes appropriate actions, and (*iii*) a hybrid of (*i*) and (*ii*).

Human Control: There are two main scenarios where humans directly control the CPS. In supervisory control scenarios, human operators oversee an otherwise mainly autonomous process. The operators are responsible for adjusting certain set points that may influence the system. This is the case on, for example, industrial scenarios where operators mainly set or adjust certain target metrics that are then accomplished by the autonomous robotic CPS. If the human has a more direct command over the process, we are in the presence of direct control scenarios. These are typical master-slave scenarios where humans issue commands to the cyber-physical system, which then carries the necessary actions and reports back the results. An example of such a system can be seen in the previously introduced [63], where a wheelchair-mounted robotic arm is controlled by a disabled person to retrieve objects.

Human Monitoring: Applications that passively monitor humans, also known as "people-centric sensing" applications, use their monitoring data to take appropriate actions. In the scope of CPSs, these can be of two types: open-loop and closed-loop systems. Open-loop systems monitor information about humans regarding several aspects (e.g., sleep quality, physical activity, attention-level) and report these results. One example is Look4MySounds, a remote monitoring platform for auscultation of cardiac sounds and automatic detection of pathologies [48]. The platform uses an integrated stethoscope with which auscultation sounds are recorded and processed to automatically detect pathologies. The sound samples and obtained diagnosis are thereafter remotely sent to a clinician. Despite the human being in the loop, the system does not take any proactive actions and simply relays the results to a specialized medical practitioner. On the other hand, closed-loop systems use their sensory data and processing results to actively contribute towards a specific goal. For example, a smartshirt may monitor a human's exercise levels on a gym, while a sensor placed on the wall monitors room temperature. When the human is exercising, the HiTL control may signal the HVAC system to reduce the room's temperature in order to make the exercise more pleasurable.

Hybrid Systems: Hybrid systems take people-centric sensing information as feedback to their control-loops while also taking direct human inputs into consideration. Let us expand our smartshirt example to include a smartphone application that allows the user to keep track of their exercise and also to set a desired room temperature. The hybrid system could take the user's desired temperature as input while using the activity information to fine-tune the absolute temperature value, or to control the rate of temperature change.

B. Taxonomic View of Human Roles Within the HiTL

The goal of this section is to contribute to the establishment of a reference for the classification of the role of a Human in the future IoT as we envision it: using a HiTL paradigm. We also want to define a set of requirements that fully characterize this new type of systems. From now on we will call this reference model the Internet of All (IoA), meaning that it includes not only the (traditional) IoT but also the Human as a fundamental element. This way, we emphasize that this Internet is made by Humans, for Humans and with Humans. IoA is built from spatially distributed devices that are considered by standard IoT, like laptops, mobile phones, computers, sensors, actuators, "classical" network elements (we mean all passive elements like routers, switches, access points, etc.), RFID tags, readers, cars, intelligent clothes, wearable devices, furniture and home machines… the possibilities are endless. As previously inferred, IoA also includes robotics and its interaction with intelligent devices and sensors into its scope. However, on top of these man-made devices, we also consider human beings themselves as part of the system: their actions, drives, desires and emotions.

Stankovic *et al.* [20] have identified the incorporation of human behavior into the methodology of feedback control as a crucial challenged to be addressed by future research in HiTLCPSs. This is a difficult challenge since human presence manifests in different ways in various HiTL scenarios. For example, in open-loop monitoring systems, humans are in the loop but are not giving nor receiving any active feedback, while in more sophisticated systems, humans may directly influence control-loop parameters and even actuate on the system. We would like to reflect on this challenge through a different perspective, evaluating not simply where to place the model of human behavior on the control loop, but considering where to place the human as a whole on the entire HiTLCPS.

1) Data Acquisition: Human as a set of sensors—taking advantage of the sensors that he carries, the human becomes an integral part of the sensing network. As we explained before, in today's world the mobile phone is an indispensable element of everyday life that is progressively becoming richer in terms of processing power, memory and sensing capabilities. Other wearable devices, such as intelligent clothes and shoes, can also become important elements in the future Internet. Nanotechnology is also an important element in this aspect; in the near future, it will also bring intra-body elements to this IoA [82]. Nano-networks have been receiving a lot of attention from the scientific community and very soon, new studies and prototypes will emerge that will result in very advanced applications in the biomedical area. However, the different types of communications for these technologies, most of them based on nano-machines and nano-tubes, are out of the scope of this document. Another source of data is present in the world of social-networking. Sensor nodes placed in a major shopping center can help and support the shopping of human beings who use Google glasses by, for example, overlaying price-tags on the products of their interest (e.g., that they "like"). However, some people might find this intrusive and, therefore, disable the sharing of social information.

Human as a communication node—multi-hop is a very common technique used by tiny devices to save energy. Intermediate nodes can be used in a communication process between a sender node and a receiver node to reduce the required signal power. In this context, human devices such as smartphones and body-area-sensors may also be used as intermediate nodes in the "hopping" process, taking advantage of human mobility and intelligence to more effectively distribute information in the network. This may be particularly useful in, for example, metropolitan-wide collaboration systems where human presence and mobility may be crucial in re-passing non-critical information about the environment. Instead of using multi-hopping or long-distance communication between sensor nodes to, for example, monitor temperature, this information might be aggregated and stored by human-carried devices as people move around the city, opportunistically forwarding it when appropriate, thus, reducing the amount of energy required for communications.

2) State Inference: Human nature—The combination of sensors in the human's body-area-network is capable of measuring several different aspects of human nature, including his vital signs (heart rate, ECG, EEG, movement, etc), but, more interestingly, characterize his actions, detect his activities and even psychological states and emotions. These "human nature" phenomena are an integral part of the control loop in IoA scenarios: the attention level of a driver affects the cruise control mechanisms of an automobile, the user's exercise levels affect the air conditioning of his house, a human's emotional state may affect the UI of his smartphone application… humans are no longer an external entity that simply benefits from the system. Their presence, actions, and emotion states strongly affect how IoT things react.

Human as a processing node—although most devices carried by a human are very simple and have limited processing capabilities, if we use distributed algorithms we can take advantage of the huge number of processing elements and enable collaborative tasks that could not be fulfilled by any particular node by itself. Smartphones, which are becoming increasingly more powerful, can be major participants in this processing, so the human and his appliances can be an interesting powerful node, comprising sub-nodes, in the new IoA. Human choices should also play an important role in this processing.

3) Actuation: Human as actuators—nowadays humans already act as actuators and as a function of the medium. If a gas leak is detected in a factory, the responsible employee quickly goes to the control room to close the respective valve. If, in a hospital, the blood pressure of a patient reaches a prohibited value, the nurse on duty, hearing the alarm signal, goes directly to the patient room to administer a new drug. In HiTLCPSs, human actuation remains extremely important, since human conceptualization will continue to be unmatched by artificial intelligence for, most likely, many years to come. However, the IoA paradigm takes human action into consideration in the control-loop, in the sense that these systems are made for humans, with humans. Examples of this human role are industrial systems that may use WSNs and robots to monitor and detect problems, and then require specialized actuation of humans to fix the problem. On our social-networking shopping mall example, users may consider product suggestions from other clients with similar interests and psychological states, who collaboratively suggest products of their own interest. In this way, IoA systems are not "devoid of human soul," but make human actuation as an integral part of their functioning.

IV. Requirements for IoA Applications

In this section, we will attempt to identify several requirements that need to be addressed in future HiTLCPSs, in the same perspective of the several processes associated with HiTL control.

A. Resilience

It is important to extend current research by providing resilient and performance controlled solutions for IoA environmental interactions. Performance controlled solutions have been previously achieved through planned and controlled deployments, even in critical scenarios such as oil refineries [83]. For HiTLCPSs, instead of targeting previously planned, static deployments, new performance controlled systems will need to be designed in an adaptable way, in order to operate in dynamic environments and to enable coordinated HiTL control, while keeping the system performance under acceptable levels, even in the presence of mobility and a diversity of faults. These requirements raise a number of new challenges that must be addressed to enable the successful implementation of the underlying paradigm in critical environments.

As some recent works have suggested, for enabling performance controlled systems to meet dependability targets, it is necessary to incorporate fault tolerant and self-healing mechanisms into the design, deployment and execution tasks [84].

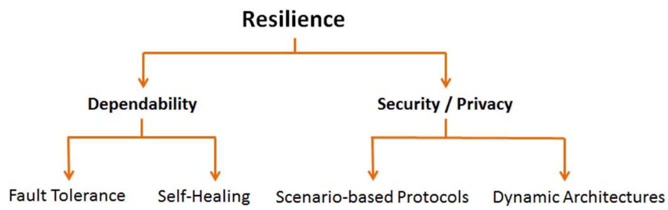

Fig. 3. The resilience paradigm.

These mechanisms will ensure end-to-end performance control in HiTLCPS environments where that control is an important feature. Key innovations need to be produced on performance-aware models and mechanisms for enhancing the performance and management of the system. The inherent ability of handling faults in a distributed environment also needs to be considered. When sensitive data retrieved by sensors is transmitted through critical environments, security challenges are also raised. If not protected, transmission of data may be accessed, corrupted, or even destroyed, reducing the safety required [85]. Consequently, security mechanisms should also be investigated and added to the design. We consider resilience as a combination of a number of features, as shown in Fig. 3, which include dependability, security and privacy, as well as the required means to provide overall robustness and performance to the system.

Dependability is achieved by integrating, during development-time, static approaches based on fault tolerance mechanisms and techniques and by providing, at run-time, dynamic approaches based on self-healing. Security and Privacy are also important aspects in the IoA. Security has long been addressed in academic research, with several secure protocols having been proposed over the years [86]. Most of these protocols have only been evaluated in an isolated fashion and not in the context of HiTL application security, often because of the lack of concrete applications or deployment scenarios. Therefore, most of the current state-of-the art IoT security protocols are purely academic, as they are based on theoretical or simulation results. Thus, security in the IoA can be achieved by developing new protocols that cater to the specific needs of HiTL scenarios and applications. As for privacy, there is a need to define models and architectures for HiTLCPSs for supporting dynamic policies that are adapted and tailored to each individual. As different applications of IoA have different security and privacy requirements, an architecture should be able to guarantee distinct desired levels. As the desired level might change even during the deployment of an IoA system, it should be possible to configure and control both the security level and the privacy dynamically. Thus, we believe the major challenge security and privacy is to define an adaptable and manageable architecture for use in real-time scenarios that combine humans, robots and IoT. Instead of an isolated analysis of different protocols or communication layers, this architecture should consider the security and privacy of real application deployments.

Future work should, therefore, to define, implement and evaluate a set of resilient protocols, techniques and tools for performance-controlled supervision of cooperating robots, humans and environments based on WSNs with HiTL control. The devised resilient supervision based on WSNs should be designed for providing safe and mobile HiTL interaction and cooperation in various scenarios, including safety-critical environments. This work should rely on the complementary use of design-time and run-time approaches for obtaining compliant solutions that enable the provision of performance controlled services even in the presence of changes that may occur to the system, its environment or its requirements.

B. Standard Communications

In the current Internet there is a high heterogeneity in devices and communication protocols. This heterogeneity will be more pronounced if we consider all the human elements (Human as a set of sensors, Human nature, Human as actuators, Human as a communication node and Human as a processing node) described in the previous section. In fact, it is important to find processes and protocols that would support communication between all these elements, human and otherwise. These heterogeneous processes and protocols must be able to allow communication between devices that are highly different in processing capabilities, size and function, such as robotic elements, wireless sensor nodes, body-coupled sensors, smartphones, etc. [87]. Additionally, this communication must remain reliable even in face of the highly crowded wireless spectrum, where different kinds of communication technologies (e.g., Wi-FI, 3G, LTE, ZigBee, Bluetooth) co-exist. Supporting persistent and reliable connections while supporting mobility, and different kinds of wireless mediums is a very demanding challenge [88].

Therefore, future research works will need to consider the existing communication processes and protocols at the different OSI layers to evaluate their feasibility into real HiTLCPSs. If existing solutions are unable to support seamless interfacing between robots, WSNs, Humans and smartphones while supporting reliability and mobility, new kinds of protocols and communication paradigms might have to be considered.

C. Localization

Determining the positions of elements of the CPS, especially mobile nodes or humans, is critical for some types of applications in the IoA. Indeed, many types of data are meaningless without knowing the location where they were generated. Thus, localization supports HiTL control-loop decisions by allowing the identification of the location of collected data, coming from both people, animals, robots or vehicles. It plays an important role in many types of HiTLCPS scenarios, ranging from healthcare patients' monitoring, people-centric sensing mobile applications, monitoring of workers within hazardous environments, robotic drones' positioning, smart homes, etc. The localization problem has long been considered since the 1960s resulting in a location system that is widely in use today, the Global Positioning System (GPS) [89]. While GPS is an excellent solution for outdoor localization, it is not adequate for many types of devices. For example, cost and energy consumption constraints in wireless sensor nodes makes localization using GPS inefficient in most WSNs. In addition, there are some cases in which GPS is not feasible such as indoor locations, underground tunnels or places with a lot of obstacles. The accuracy of civil GPS units may also not satisfy the requirements of HiTL applications. Despite some previous attempts at embedding GPS receivers into constrained devices [90] by offloading processing to the cloud, the accuracy achieved is still low (35 m). Numerous other approaches for achieving localization have previously been proposed, notably those based on the "closest beacon principle" [91], Wi-Fi-based positioning systems [92], Kalman Filters [93], multilateration [94] and even machine-learning techniques [95], [96].

A critical problem in localization is the accuracy and the stability of the measurement methods, which is even more exacerbated in HiTLCPSs since these values may influence the result of the entire control-loop decision. Consequently, it is necessary to have scalable, low cost, and near real-time localization systems which can produce an acceptable accuracy using measurements commonly available to control HiTLCPSs. Thus, future research will need to study current localization methods in order to find appropriate solutions for measuring location in different situations (outdoor, indoor) and for different elements (humans, robots, smartphones, sensor nodes).

D. State Inference

The accuracy and reliability of the inference of human states is critical for HiTLCPSs [20]. This is a very broad requirement that includes the detection of all states related to the human, be it activities or actions, commands, intents, attention level, physiological parameters, psychological states or emotions. Some of these aspects of human nature are more challenging than others. For example, the detection of physiological parameters is a topic that has long been debated in research and we have plenty devices that are capable of detecting a wide range of parameters, ranging from the heart's rate to the electromagnetic waves resultant from brain activity.

On the other hand, the quantitative detection of more abstract aspects of human nature such as activities and emotions is less established. In terms of activity detection, current approaches can achieve high levels of accuracy for narrow ranges of activities in specific scenarios, such as medical environments or daily activities [29], [36]. However, despite many activity detection solutions reaching high levels of accuracy, these results are only valid for a limited number of activities and for a limited audience. The standard practice in most sensing systems is the use of unchanging classification models trained prior to deployment. When dealing with large-scale HiTLCPSs, this poses a big problem, since the target audience is highly heterogenic: an old person walks in a very different way than a younger person. Recent research has attempted to address these issues by personalizing existing classification models through manually provided training data [97], and by incorporating inter-person similarity into the process of classifier training, allowing crowd-sourced sensor data to personalize classifiers [35]. Another gap in current activity recognition research is the problem of flexibility of activities. The way a certain activity is performed may change over time: a person may develop quirks or get more efficient without even realizing it. From a usability and pervasiveness perspective, the personalization of existing classification models should not depend on manually provided training examples or labeling: it should be a transparent process that happens during daily life. Additionally, most research focuses on achieving high accuracy rates for a limited number of activities. In HiTLCPSs the number of activities of interest may be very high and change over time: it is limiting to develop a system that only handles few activities. A more interesting solution would allow the collaborative identification of new activities by users. This requires HiTL control to detect new types of activities that are not envisioned at the time of deployment. On the other hand, this brings a number of challenges yet to be addressed: how to scale the introduction of activities? How to avoid redundant labeling? How to perform lightweight classifier training in a fashion not too taxing on mobile hardware? These are important challenges that need to be addressed to achieve good contextual analysis in future HiTLCPSs.

The emotions and psychological states are crucial aspects for improving relations, learning, health and quality of life of human beings. These emotional processes have a crucial value for determining humans' behavior in HiTLCPSs because they are a primary source of human motivation [42]. Literature in emotion is very extensive, and there have been controversies even in it definition. The word emotion has its foundations in Latin *emovere*, a word that derives from *movi*, which means to "put in motion". Thus, emotion means first of all movement and without emotions nothing progresses. A more scientific definition of emotion can be that it is a psychological construction where cognitive, physiological and subjective components interact. Several psychology researchers focused on this problem of emotion definition. Early researchers proposed various models that grouped emotions into several categories. For example, Ortony *et al.* [98] established an architecture of conditions and variables which influenced emotions. On another attempt of emotion classification, Ekman studied human facial expressions and associated them with a set of six basic emotions, through the Facial Action Coding System (FACS) [99] which is now widely used in the field of psychology, animation and robotics. A circumplex model of emotion was first proposed by Russell [100], where emotions were distributed in a two-dimensional circular space, ranging from "miserable" to "pleased" and from "sleepy" to "aroused." The work of psychologist Magda Arnold, then followed by Richard Lazarus [101] resulted on the "appraisal theory", which states that emotions derive from our own evaluation of physical events, which then cause different reactions in different people. For example, if a certain event is perceived as positive, that event will manifest a response that will evoke positive emotions; on the other hand, negative perceptions of reality will result in negative emotions.

The area of HiTLCPSs will have to consider these fundamental works in psychology as a basis for accurate and reliable emotional classification, relating each emotion to associated physiological signals such as skin conductivity, blood pressure, heart rate, breathing rate, etc. Such areas are currently very active in computer science and engineering. Body and wireless sensors that measure these vital signs, video-cameras for facial recognition, and several other devices are normally used to capture the emotion of a person. Nowadays, even the use of EEG sensors in a non unobtrusive way is a realistic possibility for measuring emotions, thanks to portable EEG devices such as the Emotiv [102]. Unfortunately, associating quantitative emotional states to these physical parameters is a considerably complex task, being, in fact, one of the most demanding challenges for future HiTLCPS research.

E. Safety

Historically, robots are designed and programmed for relatively static and structured environments. Once programmed, it is usually expected for the robot's environment and interactions to remain within a very constrained range of variance. Anything unaccounted for in the robot's configuration is essentially invisible and only minimal feedback is traditionally available, such as joint position measurements. These primitive sensory capabilities require robots to operate in isolated "work cells," free from people and other interferences. Thus, current robots, including mobile and manipulator ones, are far away from being integrated in HiTLCPSs, still mainly using collision sensors that halt operation whenever something unaccounted for happens or whenever somebody enters their workspace, to prevent accidents. This continues to enforce the need to have areas for workers and areas for robots which are mutually exclusive and preclude any type of human-robot cooperation, typically found in HiTLCPSs [103]. Apart from safety reasons, there is also the lack of trust that workers put on robots. People prefer to work along with teleoperated robots than with autonomous ones [104]. The reason for this mistrust is that people cannot predict the robot's intentions or behavior due to the lack of body language signs, common in humans. A second reason for mistrusting robots is that people do not know if the robot "sees them" (lack of presence awareness). Without HiTL behavior modeling, robots of many automated factories remain isolated in both physical and sensorial senses [105].

While robots were initially used in repetitive tasks where all human commands are given *a priori*, they are becoming progressively integrated in HiTLCPSs and involved in increasingly more complex and less structured environments and activities, including interaction with people for task execution. This means that there is a critical need for novel safety mechanisms that can ensure a safe and effective cooperation between human elements and robot elements, that is, robots need to start considering the "human-in-the-loop" of working tasks.

V. Towards an Internet of All

Now that the major concepts and current trends of HiTLCPSs have been explored, we would like to provide a chronological overview of the development in the field as well as summarize the learned lessons to help the reader avoiding pitfalls in his own work.

A. Chronological Overview

Our exposition of the area has shown how the concept of Cyber Physical Systems has evolved together with the Internet of Things and how these are closely related. It is possible to observe a certain "direction" of these types of systems, in terms of sensing, state inference and actuation, that has begun in the scope of simple "things," to large environments and, more recently, human beings.

In fact, early works began by proposing the use of physical tokens (such as barcodes or electronic tags) to relate objects to the web [106]. For example, the Cooltown project [107] provided an infrastructure for human interaction with mobile and ubiquitous devices, pushing web technology into common digital appliances such as printers, radios and automobiles, and also to non-electronic things like CDs, books and paintings. The idea was to extend the concept of a web page to every physical entity, creating a "web presence" with information and services for every entity of the physical world. In their "Cooltown Museum" test environment, both infra-red beacons and tag identifiers supplied user PDAs with the URL of the "web presence" of each work of art.

Sensing and actuation in environments, namely through WSNs, has also long been considered. The work in the Economic Weather Map project [108], for instance, supported the concept of "reality mining," the data mining of sensor streams that monitor specific environments. The manipulation of massive amounts of sensory data was used in detection and action systems, allowing users to use sensor data in valuable ways. The authors designed a prototype of a sensor information system that used geographic information software, mission planning/terrain visualization systems and sensor networks in conjunction with a photo-realistic, 3D visualization of the prototype's environment. One of these prototypes consisted on a fire-detection system, which used sensors to monitor temperature in order to help anticipating the initial spread of fires and promote a more effective actuation of firefighters.

Only more recently did research began to focus on the human-side of sensing, inference and actuation, often within a social networking context. Sensor nodes have been used as means of transmitting mobility into virtual worlds. In [109] a framework was proposed which mapped a sensor node to an object in the popular social network, Second Life [76]. The location of the sensor mode, which was calculated from the RSSI values from three or more fixed reference nodes, was reflected on a virtual avatar, which moved according to the real-world movement of the node.

CAALYX [110] was a research work that intended to develop a wearable light device directed towards the monitoring of elderly people. The device was able to measure specific vital signs, detect falls and communicate automatically, in real-time, with assistance services that would actuate in case of emergency. The CAALYX project also developed an initial simulation of its workings in the Second Life virtual world, as a means of disseminating and showcasing the project's concepts to wider audiences. There are two interesting aspects of this work, its use of mobile phones as gateways for anywhere communication and its early attempts at integrating health monitoring with virtual environments.

The work of Lifton *et al.* at the MIT media laboratory coined the term "dual reality" to indicate the ability to merge the real and virtual realities through sensor networks. They designed several prototypes where they performed experiences in merging a real world location, the Media Lab's third floor, and virtual worlds, in this case Second Life. One of these prototypes is described in [111], where the authors present the ShadowLab, a Second Life map of the Media Lab's third floor animated by data collected from a network of several sensor/actuator nodes. A two-way cross-reality experience and communication was also achieved, from the user's environment to ShadowLab, and from ShadowLab into the real world, through a monitor display and a controllable camera, giving the virtual world control of a gaze into the real one and vice-versa.

This awareness of the human condition has also become an increasing concern for corporations, in particular with the well-being and happiness of their employees. In [112] it is discussed how technological advances in computers and telecommunications have brought about tremendous gains in productivity but also made the work lives of professionals highly saturated with distractions. Based on the premise that a happy employee is a more productive one, this work explored how technology might be applied to increase overall their happiness and reduce stress. Through a small wearable badge the wearer's body movements, voice level, location as well as the ambient air temperature and illumination, were measured. When these transceivers detect another badge within 2 meters, the two badges exchange IDs and each badge then records the time, duration, and location of the interaction. This allows the collection of data about the type of social exchanges that took place in the workplace. This data was then used in conjunction with studies from the field of positive psychology, which focuses on desired mental states (including happiness), to improve people's personal and professional lives. One advantage of measuring activity is that once people become aware of their daily patterns, they can better schedule their work to take advantage of times when they can most easily achieve a focused mental state. Documenting social interactions can also help in identifying the areas in an office which tend to host the most frequent and active discussions, helping in the restructuring of office layouts to foment more fruitful collaborations.

The summarized exposition of the previous illustrative research shows us a certain evolution in terms of the IoT and CPSs. While real-world objects began as the initial targets for the extension of the web into the physical reality, the development of WSNs later permitted CPSs to monitor wide geographical locations. Only very recently did we achieve the necessary advancements in the miniaturization computational power, sensing and machine-learning techniques that allow us to focus on the most complex aspects of our reality, including ourselves. People-centric sensing systems arose from the dissemination of smartphones to create a whole new world of possible applications, from the sharing of activities and location in social-networks [75], to the management of traffic congestion [71], and even location-based healthcare [110].

Throughout this paper, we intended to acquaint the reader with yet another step in our technological evolution. HiTLCPSs will be built on each of these previous ideas to, not only build systems that monitor humans, but to create intelligent systems that are aware of their needs, moods and intents. Our research has led us to expect the next few years to yield considerable advancements in the areas of smartphones, robotics and WSNs that will bring our tools and appliances closer to us and make their use progressively more intuitive and natural. This has, in turn, the potential to bring considerable gains in both work productivity and general quality of living.

B. Lessons Learned

As suggested in the previous section, while many of discussed developments happened in parallel and are overlapped with each other, it is quite possible to delineate a certain convergence. We believe that the technological progress will always revert back to its origins: the adaptation of the environment to the human being, may this environment be an ancient terrain that became a cultivated field, or a world filled with intelligent devices that begin to work together to accommodate human needs.

Throughout our exposition, we have observed many limitations existing in the current state-of-the-art. There are several limitations of a technical nature, that require additional research efforts in order to be overcome. However, there are also limitations of a more ethical nature that relate with the public's acceptance of these new types of technological paradigms. Therefore, we dedicate this section to the identification of these lessons learned during our study.

1) Technical Limitations: Despite all of these advances only now are we beginning to observe how sensing, state inference and actuation can be combined together in HiTLCPSs, as it is evidenced by all the research projects described in Section II-B and C. In general, most of these projects still assume deliberative robot architectures within environments that are well known and static. These architectures rely on techniques such as path planning, in which conditions are known in advance. We believe that future IoT environments will be mobile, dynamic and reactive, where robots and humans will have to react to stimulus from the environment in real time, to guide their actions [113]. On this end, WSNs allow for the monitoring of environmental conditions, helping both robots and humans to react much more effectively to changes.

Additionally, most of current scenarios do not fully consider the Human, his behavior and psychological state as an integral part of the system. Humans are still mostly seen as an external final user and rarely directly interfere in the control loop of working tasks. As far as we know, there is no significant work that fully utilizes the potential of the human element to support the control-system itself. In all previous projects there is a very well defined border between Humans and the system, instead of a tightly coupled integration. In fact, humans can play various roles ranging from actuators, co-helped by robots and acting on information collected by the sensor networks, to intermediate nodes in multi-hop communication processes. They can also become an element of environmental monitoring (through the sensors carried by them, e.g., on smartphones or smartshirts). While the works presented in [19], [62], and [63] are more complete demonstrations of the potential of HiTLCPSs, we believe that their approaches are not feasible for widespread deployment. The use of vision-based systems is very prone to noise and limitations in image processing, only working for very controlled and limited environments (e.g., objects detected are limited to those programmed into the system). Brain/computer interfaces based on EEG signals are difficult for practical use, since electrodes are usually very cumbersome to wear and thus, not suitable for day-to-day HiTL applications. Future HiTLCPSs need to be based on more pervasive and mobile technology. There is, however, a ubiquitous sensing

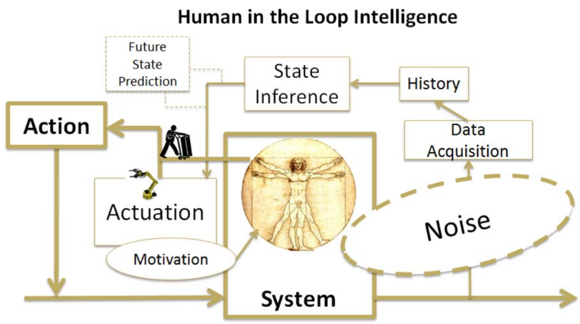

Fig. 4. Lessons learned towards human-in-the-loop control.

platform that is already used by millions of people around the globe, everyday. Smartphones are devices that give us the sensing power and computational capabilities that might be key for massive HiTL deployments in the next few years. Still, we still have very few actual applications of smartphones and HiTLCPSs. While [61] did use HiTL concepts to limit current mobile data demand, the actuation aspect was limited to suggestions and incentives on a smartphone's graphical user interface and aspects such as robotics and direct actuation are not considered.

We attempt to condense all of these technical limitations and challenges in a model, shown in Fig. 4.

This model presents the various processes associated with HiTL control. According to our research, a human is integrated into a CPS through **"Human-in-the-Loop Intelligence**," responsible for receiving input from the human sensors and also for influencing the system's control loop depending on the inferred context. This intelligence's specific implementation should follow the general principles and requirements introduced in Section IV, to guarantee reliable and secure human-context monitoring. In particular, we consider the issues of privacy and reliability as two of the most important requirements responsible for the current lack of HiTLCPSs in real scenarios.

On a first step, determining a human's state requires the **acquisition of data**, through sensors or even information gathered from social networks. This information can relate to several aspects of physical reality, such as the human's thought patterns through EEG, who their friends are, their heart-rate, movement through accelerometers, positioning through GPS, facial expressions through video-cameras, among others. Seeing physical reality through sensory data is the cornerstone of HiTL control, since every other aspect of the system is related to the raw data acquired from the sensors.

The **history, or memory**, is another important aspect that closely relates to the acquisition of data. In fact, research has shown how previous human states may offer important insights for inference mechanisms [114]. This historical data can also be used by delay tolerant mechanisms in non-critical applications, setting a meaningful state whenever the real-time connection to sensory data is interrupted.

Perhaps one of the most critical aspects of HiTLCPSs is the reliable **inference of human state**. State inference mechanisms need to adapt to the current context as well as the human's preferences and historical behavior, integrating this information into the control-loop as feedback to determine the actions of the HiTLCPS. This is incredibly difficult and implies a need for reliable and secure mechanisms for modeling, detecting and possibly predicting human nature, as discussed in Section II-A2.

There are two types of **actuation** in HiTL controls. A system actuation is based on the system's current status and the inference of human state. For example, a HiTL-enabled HVAC system may only adapt room temperature in the presence of humans. Human actuation relates to the actions of humans within the HiTL system, since they can themselves actuate whenever necessary. Motivation is a crucial aspect of this type of actuation and one of the most important research challenges. Future HiTLCPSs need to provide the necessary motivation and benefits for humans to act in a way that benefits the overall system and refrain from adopting greedy or prejudicial attitudes.

Finally, **noise** shows how real world environments are far from idealized academic-controlled testbeds. For example, HiTLCPSs based on speech and video-captured gestures have to deal with challenges such as ambient noise, moving background clutter or object segmentation. The acquisition of human vital signs is also prone to problems in terms of signal-to-noise ratios, where many signal frequencies are resultant from internal physiological functions that have nothing to do with what needs to be acquired.

Another source of noise is related to human variability. The human species has a high genetic variance and thrives in many different environments with highly disparate cultural backgrounds, which results in many possible phenotypes. Age, physical disabilities and inter-person variability also need to be accounted for. While current research in HiTL state-inference can reach high levels of accuracy, as discussed in Section II-A2, these results are mostly limited in terms of number of human activities, psychological states and audience. On the other hand, future HiTLCPSs will most likely address a highly heterogeneous target audience. This personalization of existing state inference models should follow a ubiquitous approach and not depend on manually providing training examples or on the collaborative labeling by the system user. To promote usability, it should be a transparent process that happens naturally, as the user lives his daily life.

The identification of new human states that were not predicted at the time of deployment may also be important. However, this brings yet another realm of unresolved challenges. It is necessary to scale the learning of new states, avoid redundant labeling, perform training in a lightweight fashion, ensure security and privacy and take advantage of collaboration between users while avoiding overlapping efforts.

All of these are important challenges for HiTLCPSs that have yet to be properly addressed by the research in the field.

2) Ethical Limitations: As discussed in Section II-A, much of the necessary technology for supporting HiTLCPSs is already in place. But then again, why are current IoT and CPSs still unable to integrate the human element into the control-loop? As previously discussed, we believe that reliability is one of the major factors that influences the current lack of real-world deployments. Reliable and consistent inference of a human's state is essential to the adoption of HiTLCPS in real industrial, medical or social scenarios. The inability to do so can have severe consequences on the effectiveness of the entire system. The reliable networking of sensed data is also crucial for HiTLCPS, since these systems are often large and distributed.

There is, however, another important factor that needs to be taken into consideration: the introduction of radically new technologies is usually accompanied by a considerable dose of skepticism. Thus, reliability is only relevant if the market accepts the underlying technology. This is crucial, since this new paradigm of human-centric technologies has already been previously met with considerable skepticism. As evidenced by Section II-C, current attempts at creating social-networking HiTLCPSs show that users place a high importance on their privacy and in the security of their personal information. In fact, these privacy concerns have been present since the beginning of social networking. Facebook, for example, has been the target of criticism since its early beginnings due to its reliance on the users' willingness to share information as the key point of its business. In fact, according to an AP-CNBC pool [115] with a sample of 1004 people, 59% of Facebook users have little to no trust in Facebook to keep their information private. This apparent lack of trust reflects just how closely people follow intrusive practices, further exemplifying how privacy concerns are one of the biggest obstacles to the growth of social networking and, by extension, to HiTLCPSs. Still, it would have been, perhaps, unthinkable in a pre-social networking era, that people would enjoy publishing their personal information in a public database for their peers to see and comment on. Yet, step-by-step, we have reached a level where huge social networks and photo-sharing are norm. Despite all the past and ongoing privacy concerns and surrounding criticism, both the number of users and their engagement in Social Networks continues to increase [69].

Putting skepticism aside, it is difficult to deny that the idea of someone else monitoring our every step and activity is very disturbing. However, it is also true that this problem does not reside entirely on the existence of HiTLCPS frameworks. For example, Sauvik *et al.* [33] have discussed the possibility of current smartphones posing a security threat to the user, claiming that accelerometers and other sensors within the device can be used without the users consent. They have also shown how activity recognition algorithms can be used to obtain sensitive information about the user without their knowledge by having them identify pre-defined general activities or even make the user's phone learn to identify new ones. Hence, the existence of smartphone-based HiTLCPSs does not impede this type of privacy-invasion, although it might make it easier to accomplish. Thus, security and privacy are two other critical requirements, in addition to reliability, for HiTLCPSs. Industrial processes, medical data or sensitive personal information need to be protected from unauthorized exploitation. As discussed, protecting confidential information is often not only a business requirement but, in many cases, also an ethical and legal requirement.

Another important ethical consideration relates to the use of robotics in HiTLCPSs. As introduced in Section II-A3, robotics is growing at a progressively faster pace and there are some who believe its role in future HiTLCPSs may not be completely optimistic. For example, while robotics enables automation, this may in turn result in human unemployment. In fact, futuristic journalist Kevin Kelly predicts that a wave of automation centered on artificial cognition, cheap sensors, machine learning and distributed smarts will result in 70 percent of today's occupations being likely replaced by automation before the end of this century. Starting with assembly line and warehouse work, agriculture picking, cleaning, "it doesn't matter if you are a doctor, lawyer, architect, reporter, or even programmer: The robot takeover will be epic" [103].

Brynjolfsson and McAffee provide an interesting insight on this matter, arguing that despite the improvement of technology in areas that used to be typically human-oriented, such as pattern recognition, people will still have vital roles to play [17]. As an example, they refer to Garry Kasparov's experience in "freestyle" chess tournaments, where teams combining average-skilled humans and machines dominated both strong computers and human grandmasters [116]. As pointed out in Diego Rasskin-Gutman's book, "Chess Metaphors," what computers are good at is where humans are weak, and vice versa [117]. This is evidence of the importance of human-machine collaboration in the years to come, the cornerstone of HiTLCPSs. Brynjolfsson and McAffee continue their discussion on these "uniquely human" abilities that will remain essential, even in the face of the continued automation of routine tasks by the technological advancement. Despite their impressive calculation capabilities, there has yet to exist a machine that is capable of human creativity and intuition. The ability to create and innovate through new and meaningful ideas is the forefront of artificial intelligence research, and the one task that humans still excel in comparison to machines. Additionally, evolution has shaped humans into highly responsive beings that can quickly adapt to new situations, while current machines simply cannot react outside of the frame of their programming. As evidenced by Brynjolfsson and McAffee, "[The supercomputer] Watson is an amazing Jeopardy! player, but would be defeated by a child at Wheel of Fortune, The Price is Right, or any other TV game show unless it was substantially reprogrammed by its human creators" [17]. Thus, human-machine collaboration will most likely become increasingly critical in the next few decades, at least until machines evolve to a point where they reach (or surpass) "human-like" intelligence. As memorization skills become increasingly redundant due to the assistance of modern search engines, it is this human ability to quickly combine information from different sources and to react to new situations that will remain essential in future HiTLCPSs.

Precursors of this human-robot interaction are already among us. Baxter, a workbot from Rethink Robotics is an early example of a new class of industrial robots created to work alongside humans [118]. Baxter has several characteristics that make it more "human-aware" than most of its ancestors. It is capable of showing where it is looking by shifting drawn eyes on its "head." It is also capable of perceiving humans and avoid injuring them, using force-feedback mechanisms that tell it is colliding with a person or another bot. This "human-like" body-language is an innovation that allows humans to understand and predict the robot's intentions, which may in turn reduce the previous mistrust placed in robotic companions [104], [105]. Equally important is Baxter's capability of learning through imitation: to train it, one simply grabs its arms and guides them through the correct motions and sequence. This mode of operation is remarkably different than traditional industrial robotics, which requires highly educated personnel to program even the simplest tasks. Considering all of these tendencies, it is very likely that, in the future, people will be payed "based on how well they work with robots" [103].

Nevertheless, expecting artificial intelligence to evolve until it becomes "humanlike" is "the same flawed logic as demanding that artificial flying be birdlike, with flapping wings" [17]. In fact, it has already been proven that tremendously complex programs, despite being based on simple instructions, are already able to outperform human thinking. Intelligent HiTLCPSs will most certainly think very differently from us and the long-term consequences of such systems remain to be seen.

VI. Conclusion

In the future, humans will combine elements from robotics, wireless sensor networks, mobile computing and the Internet of Things to achieve highly monitored, easily controlled and adaptable environments. In this survey paper, we have explored the field of HiTL, in particular its applicability in future CPSs and the IoT. These HiTLCPSs still have many multidisciplinary unresolved research questions. In order to contribute to their development, we need a general understanding of their underlying requirements, principles and theory. Thus, we discussed the current state-of-the-art of HiTLCPSs, together with a critical overview of the current taxonomies. On top of this research, we extended the field's knowledge with a novel taxonomic exercise focused not on HiTL applications but on the general roles of the human element in HiTLCPSs, together with a requirement analysis for these types of systems. As far as we know, this is the first effort towards a general, in-depth overview of the existing solutions, projects and taxonomic analysis, as well as the first taxonomic exercise that considered this problem from the point of view of the human roles in HiTLCPSs.

We now begin to understand why current IoT-based CPSs have yet to integrate the Human component in order to achieve an Internet of All: humans, things and robots. There are several technical and ethical limitations that have yet to be completely resolved by current research efforts. Reliability in data-acquisition, state-inference and actuation are issues of great importance towards the adoption of true IoA systems. It is also important to note how cognitive dissonance may affect the market when these HiTL concepts are introduced to people's daily-lives. This is particularly important when considering HiTL social networking applications, which may rely on the use of sensitive personal data. On this matter, security and privacy are important concerns that may directly affect the acceptance of HiTLCPSs.

During our exposition, we have come to expect that HiTL concepts will become increasingly more common in the next few years. Despite being on their infancy, we have found promising research in the area of state-inference, data acquisition and actuation that indicate how we may be reaching a tipping point in our technological evolution. More than having intelligent IoT and CPS systems that autonomously control our environment, these systems will, more importantly, adapt to the human will. In a very real sense, we may be on the verge of achieving a sort of supra-human grip on our environment, one that our ancestors could only conceive in their wildest dreams.

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