Envisioning engineering education and practice in the coming intelligence convergence era - a complex adaptive systems approach

Vision Article

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Abstract: Some of the recent attempts for improving and transforming engineering education are reviewed. The attempts aim at providing the entry level engineers with the skills needed to address the challenges of future large-scale complex systems and projects. Some of the frontier sectors and future challenges for engineers are outlined. The major characteristics of the coming intelligence convergence era (the post-information age) are identified. These include the prevalence of smart devices and environments, the widespread applications of anticipatory computing and predictive / prescriptive analytics, as well as a symbiotic relationship between humans and machines. Devices and machines will be able to learn from, and with, humans in a natural collaborative way. The recent game changers in *learnsapes* (learning paradigms, technologies, platforms, spaces, and environments) that can significantly impact engineering education in the coming era are identified. Among these are open educational resources, knowledge-rich classrooms, immersive interactive 3D learning, augmented reality, reverse instruction / flipped classroom, *gamification*, robots in the classroom, and adaptive personalized learning. Significant transformative changes in, and mass customization of, learning are envisioned to emerge from the synergistic combination of the game changers and other technologies. The realization of the aforementioned vision requires the development of a new multidisciplinary framework of *emergent engineering* for relating innovation, complexity and cybernetics, within the future learning environments. The framework can be used to treat engineering education as a complex adaptive system, with dynamically interacting and communicating components (instructors, individual, small, and large groups of learners). The emergent behavior resulting from the interactions can produce progressively better, and continuously improving, learning environment. As a first step towards the realization of the vision, intelligent adaptive cyber-physical ecosystems need to be developed to facilitate collaboration between the various stakeholders of engineering education, and to accelerate the development of a skilled engineering workforce. The major components of the ecosystems include integrated knowledge discovery and exploitation facilities, blended learning and research spaces, novel ultra- intelligent software agents, multimodal and autonomous interfaces, and networked cognitive and tele-presence robots.

Keywords: Anticipatory computing • Augmented reality • Complex adaptive system, Convergence • Flipped classroom • Game changers • Immersive 3D learning • Intelligence era • Learnsapes • Tele-presence robots

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1. Introduction

The engineering profession is facing a number of major challenges, including the increasing complexity and interdisciplinary nature of engineering systems; the accelerated pace of change of lifecycle tools and processes; the geographically distributed diverse workforce; and workforce skill shortage. High-tech industries are having increasing difficulty in recruiting positions of strategic importance to maintain their competitive position in the global market. Traditional engineering disciplines, and formal engineering programs, proved to be inadequate for meeting the challenges. Some studies and reports have advocated transformative changes in engineering education (see, for example, [1–8]). Others have proposed complementing formal learning with practical applications and lifelong learning to address current and emerging needs. Also, a number of pilot programs have been developed by academic institutions, industry, and research organizations to address some of the needs and challenges of the engineering profession, and to promote pedagogical reforms. These include:

- New interdisciplinary degrees and minor programs as supplements to the formal traditional engineering programs. A number of emerging interdisciplinary fields were identified in [9].
- Capstone, co-op, extracurricular, and service learning programs— combining formal instruction with inquiry-based activities, and related services in the community.
- Bachelor of innovation and entrepreneurship programs, a family of degree programs at a number of academic institutions, including the University of Colorado at Colorado Springs [10], the Universities of Adelaide and Canberra in Australia. These Programs have a common core in innovation and entrepreneurship for providing long-term multidisciplinary team experiences.

A report published by the US National Academy of Engineering in 2012 [11] describes attempts by 29 engineering programs at colleges and universities across the nation to infuse real world experiences into engineering education. It highlights best practices for schools seeking to create new programs. The present paper outlines some of the frontier sectors and future challenges of engineering; provides an updated version of the major characteristics of the coming intelligence convergence era (post-information age); and describes the major game changers in *learnsapes* (learning paradigms, technologies, platforms, spaces and environments) that can significantly

Figure 1. Some of the components of a smart power grid

impact engineering education in the coming era. A vision for engineering education and practice is presented. The need is described for developing intelligent adaptive cyber-physical ecosystems to facilitate collaboration between the various stakeholders of engineering education and to accelerate the development of a skilled engineering workforce for the new era.

2. Frontiers of engineering and future challenges

A broad array of frontier sectors and future challenges for engineers were the focus of several meetings and reports by the US National Academy of Engineering, and other national and international organizations. The frontier sectors include smart grids; urban mobility; smart cities, cognitive manufacturing, 3D/4D printing, programmable matter, big data and predictive / prescriptive analytics. These are briefly described subsequently.

2.1. Smart Grids

Smart grids are digital networks that use information and communication technologies, in automated ways, to improve the efficiency, reliability, and sustainability of the production and distribution of electricity. Ideally, smart grids are also intended to work with multiple power sources, including wind and solar sources, and perhaps eventually small individual sources and ones that provide automotive power. New energy sources can be integrated into a smart grid at different times as well (see, for example [12, 13] and Figure 1).

Because of the complexity of the grid, and the need to ensure stability over a wide range of operating conditions, some recent work has been devoted to future intelligent power grids, wherein neurobiology is combined with engineering to develop brain-like approaches for adaptive op-

timal control of very large grids. A multidisciplinary team from Clemson University, Georgia Tech, and Missouri S and T is working on the project, which is called Brain2Grid (<http://brain2grid.com/>), and is sponsored by the Office of the Emerging Frontiers in Research and Innovation (EFRI) of the US National Science Foundation. The integrated sensing, communications and control of the power grid can transform the modernized end-to-end electric power system into a "smart grid" - an integrated, self-healing and electronically controlled secure and resilient power system. By knowing how failures occur, assessing vulnerabilities and working out self-healing strategies, a holistic risk management, monitoring and control system can be designed and deployed. Application of smart grid concepts to water distribution and management is described in [14]. Interdependent networks of fuel/water supply, end-to-end electric power systems, telecommunications and financial networked systems have a normal, undisturbed state and an alert model that senses precursors to an emergency state. When they are in an aggravated state they attempt to restore to a normal one. The key is to build systems that are simple and smart, that focus on reliability, robustness, efficiency and security.

2.2. Urban mobility and intelligent connected transportation

Significant work has been devoted to the development of a fully connected multi-modal intelligent transportation systems, including networked autonomous vehicles, that can lead to a smart urban mobility. Such systems use telematics (integrated use of telecommunication and informatics), along with other technologies, to integrate workplaces, residential buildings, travel service providers, airlines onto a single platform. The platform can provide a seamless transportation experience that increases sustainability and productivity for communities (see, for example, [15]). The vehicles in the transportation systems have new kinds of attractive functions and features that connect several aspects of human activity. The realization of the smart urban mobility goals require innovative solutions to tackle the two opposing objectives:

1. To improve the safety, comfort and time associated with transportation, getting individuals and goods where they need to be, and when they need to be there; and
2. To reverse the alarming, unsustainable energy and environmental trends associated with transportation, and devise transportation systems that materially enhance sustainability and societal well-being.

Smart Mobility, along with smart energy, smart technologies, smart healthcare, smart buildings, smart infrastructure, smart governance and smart citizens are identified in [16] as the new mega trends.

3. Smart Cities

Several ongoing programs in the US, Brazil, Denmark, South Korea, and other countries are focused on transformation of cities to smarter cities to overcome their socioeconomic problems, associated with urban growth and the significant stress on their infrastructures [17]. The IBM smart cities concept is based on using information, communication and other technologies to reduce cost, improve efficiencies, and deliver quality of life to citizens. The IBM concept is based on treating the city as an interconnected system of systems, integrating a set of interdependent public and private systems that the city can optimize to achieve new levels of efficiency and effectiveness. The component systems include Infrastructural systems (such as energy, water and transportation), human-centered systems (such as education, healthcare and social programs), and administrative planning and management systems. The central component of the IBM concept is an intelligent operations center to coordinate and share data in a single view, creating the big picture for the decision makers and responders who support the smart city.

3.1. Cognitive manufacturing and Smart/Cognitive Factories

Manufacturing systems have evolved over the years in response to many external drivers, including the introduction of new manufacturing technologies and materials, the evolution of new products, the increased emphasis on quality as well as the need for responsiveness, agility and adaptability. Cognitive manufacturing is a new paradigm in which machining and measurements are merged in order to form more flexible and controlled environment [18]. When unforeseen changes or significant alterations happen, machining process planning systems receive on-line measurement results, make decisions, and adjust machining operations accordingly in real time. Further development of the Cognitive manufacturing concept can lead to the concept of *Smart / Cognitive Factories* that enable a more flexible, adaptable, and reliable production (Figure 2). According to this concept, the machines and processes in a factory are equipped with cognitive capabilities that involve reasoning about goals, perception, actions, collaborative task execution, etc., to allow them to assess and increase their scope of operation au-

Figure 2. Smart / Cognitive Factory Concept

tonomously. Causality-based formal representation and automated reasoning methods, from artificial intelligence, can be used for such a cognitive factory with multiple teams of robots and humans, where each team tries to complete a complex assembly task, and where teams communicate with each other for efficiently sharing common resources.

3.2. 3D / 4D printers

3D printing refers to the process of making a three-dimensional solid object of virtually any shape from a digital model. Additive manufacturing – the industrial version of 3D printing is considered distinct from traditional manufacturing techniques, such as casting and machining, which mostly rely on the removal of material by methods such as cutting or drilling (*subtractive processes*). 3D printing is achieved by using an *additive process*, where successive layers of material are laid down in different shapes [19]. The technology of 3D printing is used for both prototyping and distributed manufacturing in many fields, including aerospace, industrial design, architecture, automotive, medical industries, education, geographic information systems, and civil engineering. It is transforming manufacturing from mass production to mass customization. The exploration of the 3D printing process from design to production can open up new possibilities for learning activities (see, for example, description of the projects at the Center for Bits and Atoms at MIT <http://cba.mit.edu/>). Printed 3D models can be used to illustrate complex concepts, or illuminate novel ideas and designs. A recent development, beyond 3D printing, is the 4D Printing process, developed by researchers at the MIT self – assembly Lab and Stratasys Inc. (see http://www.sjet.us/MIT_4D%20PRINTING.html). The process entails the added capability of self-assembly (embedded transformation from one shape to another), directly off the print-bed. This new technique offers a streamlined

path from idea to reality with full functionality built directly into the materials. It can provide robotics-like behavior without the reliance on complex electro-mechanical devices. A new software system, called Cyborg, is being developed by Autodesk to serve as a design platform spanning applications from the nano-scale to the human-scale, to take advantage of the 4D printing technology, from idea conception to reality. The software allows for simulated self-assembly and programmable materials, as well as optimization for design constraints and joint folding. The objective is to tightly couple the Cyborg new cross-disciplinary, and multi-scale, design tool with the real-world material transformation of 4D printing. The tightly coupled software and hardware tools will eliminate the traditional paradigms of simulating then building, or building then adjusting the simulation. Several exciting potential applications of 4D printing can be cited. For example, a self-driving car can be printed, rather than assembled. The car can be packed for shipment by a robot, and then send to the consumer in a flat, streamlined form, ideal for packing and shipping. With the addition of water (the medium currently used for self-assembly), the car is able to reconfigure itself in a matter of moments. Another application is that of developing simple space systems that can be shipped compactly to orbit and then expand and become fully functional on demand while in orbit. The systems can be fully reconfigurable to various other highly functional systems.

3.3. Programmable matter

Programmable matter concept is a digital material composed of small intelligent modules having computation, sensing, actuation, and display as continuous properties, which are active over its whole extent. It is the result of convergence of nanotechnology with autonomous computers. Programmable matter systems are composed of millimeter-scale autonomous microsystem particles, without internal moving parts, bound by electromagnetic forces or an adhesive binder. They are able to form a variety of macroscale objects with specific material properties in response to commands or stimuli. They have the potential of many exciting applications, like shape-changing robots and tools, rapid prototyping, paintable displays, and sculpture-based haptic interfaces. Researchers at Carnegie Mellon University are developing self-assembly modular robots by using very large number of "claytronic atoms", or catoms – basic computers (less than a millimeter in diameter) housed in tiny spheres that can connect to each other, and rearrange themselves (see <http://www.cs.cmu.edu/~claytronics/>). The realization of this concept could enable development of fully

Figure 3. The 5 Vs of Big Data

programmable objects, able to construct, and/or deconstruct themselves. For example, car's surface that change color, tires that adapt to different terrains, or self-heal.

3.4. Big data and predictive/prescriptive analytics

Big data refers to a collection of large, diverse, complex, heterogeneous, longitudinal, and/or distributed datasets that are difficult to process using traditional database management tools. Big datasets generated by large-scale simulations and visualizations in engineering and science led to the emergence of the fourth research paradigm of "Data Intensive Scientific Discovery" (after Experimental, Theoretical, and Computational Sciences). Today big datasets are also generated from instruments, sensors, internet transactions, social networks, and other available digital sources. The five characteristics of big data that can help in augmenting traditional value processes are volume, variety, velocity, veracity (verification or viability) and value. These characteristics are referred to as the 5Vs of Big Data (Figure 3). Big data represents a new era in data exploration and utilization [20]. Some of the recent activities result from three major shifts of interlinked mindset, namely:

- Ability to analyze vast amounts of data about a topic, rather than settle for smaller sets
- Willingness to collect and use larger pools of data, and to embrace real-world messy data
- Attempt to find correlations in the data, rather than elusive causality

Big data analytics refer to the process of examining large amounts of data of a variety of types to uncover hidden

Figure 4. Four levels (phases) of the Data Analytics Hierarchy

patterns, unknown correlations and extract other useful information. Gartner identified four levels (phases) in the data analytics hierarchy, namely, *descriptive*, *diagnostic*, *predictive*, and *prescriptive* (Figure 4). The first two phases answer the questions what happened and why did it happen. The next one, *predictive analytics* [21] answers the questions what might happen and why did it happen. It uses systematic scientific means, including machine learning, data mining, and visualization, to extract useful information from massive data (turning big data into smart data and big ideas), to develop, and continually improve predictions. The final phase is *prescriptive analytics*, which goes beyond predicting future outcomes by suggesting actions to benefit from the predictions, and showing the implications of each decision options. It uses combination of AI and operations research techniques to identify the best course of action to take advantage of opportunities.

A number of new technologies have been developed for analyzing and mining massive amounts of structured and unstructured data for new insights (see, for example, the open source software framework Apache Hadoop <http://hadoop.apache.org/index.html>). The information provided by data analytics can enable breakthrough discoveries in engineering, science, and education. It can allow for data-intensive decision-making, provide competitive advantages over rival organizations, and result in business benefits, such as more effective marketing and increased revenue. Big data analytics can also be used for evidence-gathering concerning new learning technologies (learning data mining, and learning analytics) to help in designing adaptive learning environments that respond to the learner's progress in real time, fostering more engagement in the learning process. Learning analytics can help in setting policy, practice and funding decisions.

4. Characteristics of the coming intelligent convergence era

A brief overview of the coming intelligence convergence era (the post-information age) as envisioned in 2011 was given in [9], along with examples of convergence of technologies, devices and disciplines. Herein, an update of that vision is briefly described. The new era is characterized by the prevalence of adaptive, functional and smart environments. The environments will be filled with sensor webs (sensors smaller than the eye could see, joined together into networks larger than the mind could comprehend), mobile and tablet computing, cognitive and tele-presence robots, and computers that respond to brain waves (i.e., computers that can be controlled by thought). Incorporation of novel smart multifunctional wearable devices in the environment, enable their use in place of accessories the users already wear, such as glasses and wrist watches, and allowing the users to comfortably accomplish variety of tasks. The environments will also include cognitive and intelligent C3 systems (follow-ups on the IBM Watson project), integrating cognitive sensing, computing, communication and networking. The new interdisciplinary field of *Deep Learning*, which is the result of convergence of neuroscience, bioinformatics, and artificial intelligence, has one of its major goals as building machines that can process data in much the same way as the human brain does [22]. These intelligent machines will provide real-time commonsense situational awareness, including scene perception and understanding, perceptual data analytics and high-level control of autonomous systems. Several applications of deep learning that can help humans more effectively recognize patterns and make inferences, are being explored by Google, Microsoft, IBM, and others. The result will be a fundamental shift in the way humans interact with the environment, and a symbiotic relationship between humans and machines. Devices and cognitive machines will be able to learn from, and with, humans in a natural collaborative way [23]. Humans in the environment can have *cybernetic assistants* (cognitive assistant systems, consisting of ultra-intelligent electronic agents) that watch the users' different modalities of interaction with the environment, use predictive / prescriptive analytics to provide them with what they need before they ask for it. The purpose of the environment will be to protect and serve, and not only to make humans more productive, but also to support them in the enjoyment of their lives.

Figure 5. Learnscapes

5. Game Changers in engineering education, and learning, in general

Major advances have taken place in a broad front of learning paradigms, technologies, environments, platforms, and spaces for personal, collaborative, formal and informal learning. These are collectively referred to herein as *Learnscapes*. Recent development in communication and networking of physical objects (e.g., the internet of things) enables the creation of cyber-physical adaptive learning ecosystems combining several aspects of the learnscapes (see Figure 5). Educause, a nonprofit organization whose mission is to advance higher education by promoting the intelligent use of information technology, publishes annual reports identifying the trends and challenges of higher education, and highlighting the six promising technologies for that year (see, the 2013 horizon report [24]). Also, an interesting *infographic* presentation (informative graphic poster), which attempts to organize a series of emerging technologies that are likely to influence education up to the year 2040, is given in [25, 26]. Some of the major game changers for engineering education, and learning in general, are briefly described subsequently. These include Open educational resources; technology-rich classrooms; immersive interactive learning and augmented reality; Gamification of learning and instructions; reverse instruction / flipped classroom; robots in the classrooms; and adaptive personalized learning. These are briefly described subsequently.

5.1. Open educational resources

Since the beginning of the twenty first century, a growing trend of "opening of information" has emerged [27]. The trend is likely to result in disruptive changes in learn-

ing, teaching, assessment and research through having freely accessible tools and facilities, residing in the public domain. The MIT OpenCourseWare Project launched in 2002, and aimed at posting all MIT undergraduate and graduate courses online, is credited with sparking a global open educational movement. This was followed in 2005 by the formation of the OpenCourseWare Consortium, with other leading academic institutions joining MIT in order to extend the reach and impact of open course materials, foster new open course materials, and develop sustainable models for open course material publication. The Concept of *Massive Open Online Courses* (MOOCs), aiming at large-scale interactive participation and open access via the web, originated about 2008 within the open educational resources movement. New institutions have formed around this idea, such as Coursera, edX, Khan Academy, UDACITY, Big Data University, and others are likely to follow. MOOCs are being widely explored as alternatives and supplements to traditional courses. In addition to traditional learners, professionals can use MOOCs to take enhancement classes and maintain an edge in their disciplines (Life-long learning). Examples of massively open online courses in use in higher education settings are given in [24]. As online instruments, simulation tools, data mining, and presentation methods evolve, virtual laboratories can be developed in which some experiments are conducted in simulated space. Also, new forms of archiving massive collections of data that can help in several aspects of research and learning can be developed (e.g., computer-tracking of student activities to identify weaknesses in the teaching; using remotely accumulated measurement and analysis tools to conduct research on data gathered by others, or reanalyzing earlier research data to confirm or refine theories).

5.2. Technology-rich classrooms

Rapid advances in technology have revolutionized the way in which people learn, communicate, socialize and play. A variety of technological gadgets and facilities are now fixtures of our culture. These include smart portable and mobile devices, information appliances (see the animation, Figure 6), wireless networks, robots, educational games, social network sites, and other electronic resources. A shift is taking place from print-centric to high quality interactive, and adaptive digital facilities. For example, tablet computers equipped with wireless connectivity, high resolution screens, and a wealth of applications, are proving to be powerful learning tools inside and outside the classroom.

The aforementioned innovations have created a new culture of learning, which is significantly different from tra-

See ESM1

Figure 6. An Animation showing a smart information appliance with wireless communication

ditional classroom culture [28]. The evolution of technology has added a new dimension into learning, resulting in more learner-centered, active learning experiences. Learners can master vital skills and critical thinking in a collaborative manner. Social media and digital libraries connect learners to a wide range of informational resources. Learners use tablet computers, along with adaptive learning systems and real-life projects, to learn at their own pace, and instructors take on the role of coaches. The new learning technologies offer powerful capabilities for creating high quality learning resources, such as capabilities for visualization, simulation, games, interactivity, intelligent tutoring, collaboration, assessment and feedback. Also, these technologies enable iterative improvement. Several attempts have been made to employ powerful technology integration strategies in classrooms, including the creation of technology-based lessons and instructional activities, some of which can be published on the Web and used by students for both in-class and out-of-class learning activities. These efforts include "virtual / physical studios" in which traditional classrooms are replaced by studios and virtual instruction, resulting in bridging the online-offline gap. Learning then becomes a continuous, interconnected effort, allowing learners to cope with a perpetually changing world.

5.3. Immersive interactive learning and augmented reality

3D is rapidly entering our life. 3D simulation based e-learning takes learners on an interactive journey and involves them in the course. It not only helps learners watch the course, but also to participate in it. Also, 3D immersive simulation training allows the instructor to identify the experience curves of each learner and analyze the learner's interaction and socializing while actively helping them work towards their defined goal. An opportunity to repeat modules of the course, as with all e-learning, helps learners overcome the fear of failure and reach their goals faster. This adds a layer of interactive immersion that engages learners and makes learning more effective [29]. Therefore, it is usually referred to as in-depth learning, and is associated with other learning paradigms such as visual learning, simulation-based learning, and engaged learning. A research study conducted in the Virtual Human Interaction Lab at Stanford University showed that virtual reality had a dramatic effect on the real-life be-

havior of learners. The more engaged people were in an immersive 3D environment, the more they engaged and learnt about the subject matter. A 3D virtual world minimizes the distance between the learner and the subject matter and enables rapid knowledge sharing and instant access to information. Learners from different places can access information at the same time and exchange documents or files like they would in real life. It establishes a knowledge base for interconnected communities and converts traditional online teaching methods into a social experience. It allows learners to demonstrate complex concepts, make simulations and invite others for discussion on various scientific or artistic creations. Participating in a 3D world seems equivalent to participating in a real-world social event. This social aspect can increase learning ability and help with the acquisition and retention of knowledge. Augmented (enhanced or blended) reality refers to the layering of digital information over 3D space to generate a new interactive experience for the user. A key characteristic of augmented reality is its ability to respond to user input. This interactivity provides significant potential for situational learning and assessment [30]. Learners can gain new understanding based on interacting with virtual objects, and understanding how to see contexts. Dynamic processes, large datasets, very large and very small objects can be brought into the learner's personal space at a scale, and in a form, easy to understand and work with. Smart mobile and wearable devices (e.g., Google glass <https://plus.google.com/+projectglass#projectglass/posts>) are bringing new expectations for augmented reality applications (see, Figures 7 and 8).

5.4. Gamification of learning and instruction

Gamification of learning refers to the use of game thinking and game mechanics in order to engage the learners, and to make learning tasks appear like games [31]. A number of classes, and curricula have been developed based on serious games, or game-based learning. Several advantages have been identified for gamification, including technological literacy, critical thinking, creative problem-solving, multitasking, teamwork, long-range planning, and individualized instruction. However, some concerns have been voiced about gamification. These include, the high cost associated with developing serious games, distraction of the learners from other valuable skills, social isolation, and shortened attention span. Current work on gamification is focused on designing adaptive games and effective game frameworks that transform the learning experience. This is done by exploring the manner in which learners engage with games – their behaviors, mindsets, and moti-

Figure 7. Google augmented reality enabled glass with voice command capability

Figure 8. Augmented reality glasses

ventions.

5.5. Reverse Instruction / flipped classroom

Reverse instruction (or flipped classroom) is a form of blended learning which encompasses use of technology to leverage the learning in a classroom, freeing the instructor to interact with the students, instead of lecturing. Lectures (knowledge transfer) are delivered outside the class via some type of streaming video, and learners are expected to watch them on their own time. Turning lectures into homework and projects enables the learners to perform the most cognitively difficult work in class, when

they have the instructors and peers to help them. This can result in boosting student engagement and increasing technology-fueled creativity [32].

5.6. Robots in the classrooms

Significant work has been devoted to the design of artificial tutors, having some of the human capabilities, with the aim of helping to increase the efficiency achieved with a human instructor. The introduction of robots in the classroom, both at school and college and even as extracurricular activity, promotes a host of values such as creativity, participation, support, and teamwork. Instructors can remotely operate robots in distant classrooms. Robots offer a wide variety of learning modalities. Intelligent robots can use built-in domain knowledge to help students learn math and science through experience. Learners can make predictions with math and then verify them with robots. South Korea is using robots with stereo vision, and the ability to move around and interact with students. They use facial expressions to communicate with students. They can articulate gestures, coordinated with the facial expressions, to wink, yawn, and cheer. In the future, robots will not only respond to what the learners say, but to how they say it – factoring in social cues like intonation, gestures and facial expressions. The robots can then respond with appropriate body language. Also, small inexpensive printable robots might be widely used in the classroom.

5.7. Adaptive, personalized and Mass customized learning

In recent years electronic books have generated a strong interest in the consumer sector, and are now increasingly available on campuses. A suite of adaptive learning products for higher education, called LearnSmart Advantage, was developed by McGraw-Hill Education. It takes adaptive learning beyond the realm of course study tools—providing students with more dynamic, personalized learning experiences across the learning experience. Included in the suite are SmartBook, LearnSmart Prep, and LearnSmart Labs. SmartBook is an adaptive e-book, which enable the learners to focus their attention on the content that is most critical to their learning. LearnSmart Prep, provides "before-the-course" adaptive resource designed to prepare students entering complex courses that are critical to the completion of their major or degree. LearnSmart Labs, provides a photo-realistic virtual lab experience that enables meaningful scientific exploration and learning, while eliminating many of the practical challenges of a physical lab setting. In 2012, a digital textbook provider, CourseSmart,

in collaboration with some other partners, launched their analytics package, CourseSmart Analytics (<http://www.coursesmart.com/go/institutions/analytics>). The analytics package closely tracks the learners' activity as they interact with online learning material, and interprets that data for the instructors, providing them with an Engagement Score for each text. The instructors can use this data to select effective engaging digital resources. The facility also provides better insights to help drive learner retention, and better learning outcomes.

6. Intelligent Adaptive Cyber-Physical Ecosystems for Engineering Education

A holistic approach and a comprehensive strategy are needed to meet current and future needs in engineering education, and to put engineering activities on an ambitious trajectory that pushes the frontiers of innovation, discovery and economic development [33]. This can be provided by viewing engineering education and practice, and even innovations, as complex adaptive systems [34, 35]. Complex adaptive systems have a number of major characteristics, including having a number of heterogeneous components; with the components dynamically interacting with each other. The systems have emergent behaviors which result from the interactions, such that the whole becomes greater than the sum of the parts. The application of the complex adaptive systems approach to engineering education enables using the concepts of complexity science to continually enhance the effectiveness of learning. The independent components of the system (instructors, individual, small and large groups of learners) dynamically interact and communicate with each other, and with other components (e.g., instructional materials, learning technologies, assessment tools, and policies). Design of the system should focus on equipping the components with the needed capabilities (e.g., novel technologies and advanced tools), and enabling the interactions to meet the dynamic goal of continually improving learning. A step towards the implementation of the strategy is the development of Intelligent Adaptive Cyber-Physical Engineering Ecosystems to connect the various stakeholders of engineering education, and to provide an infrastructure for collaborative innovation. The ecosystems, which can be thought of as multifaceted entities spanning technology and sociology, should exploit and integrate several of the game changers in engineering education, as well as the innovative capabilities and technologies that emerged in the last few years. The capabilities include the CIF21 – cyberinfrastructure frame-

work for the 21st Century Science and Engineering of the US National Science Foundation, and its applications, including the nanoHUB, and DIA2 - Cyberinfrastructure for Engineering Education. The overall goal of the CIF21 (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504730) is to provide a comprehensive, integrated, sustainable, and secure cyberinfrastructure to accelerate research and education and new functional capabilities in computational and data-intensive science and engineering. The nanoHUB (<http://nanohub.org/>), which is a multiuniversity network led by Purdue university, provides extensive online educational, simulation and collaboration facilities for various aspects of nanoscience and nanotechnology, including manufacturing of complex nanomachines. The DIA2 (<http://www.ci4ene.org/>) is a multi-institutional collaboration project funded by NSF. It is built on the previous NSF-funded project called the Interactive Knowledge Networks for Engineering Education Research (iKNEER), [36] (<http://ci4ene07.ecn.purdue.edu/ikneer/>), which is data-intensive knowledge platform being developed by researchers from Purdue, Virginia Tech, Stanford and Arizona State University. The iKNEER project is used to collect, index, and enable sense making of a large sets of documents on engineering education, as well as to identify possible collaborative partners in this field. The proposed ecosystems are envisioned as broad ecologies of dynamic networked smart devices, cyber collaboration and collective intelligence facilities; blended physical and multisensory virtual environments; novel interaction technologies; telepresence and cognitive robots (with high-level reasoning, planning, and decision making capabilities); and new types of predictive / anticipatory search facilities. The ecosystems will link research and academic institutions with industry, professional societies, technology providers, and other stakeholders. It will combine the novel technologies, facilities and devices being developed to exploit and augment human capabilities. Humans will have multisensory, immersive 3D experiences in blended spaces. Specifically, the ecosystems would provide:

- Knowledge-rich, multisensory immersive environments for integrating engineering practice with learning, training, and workforce development needed for future complex systems and projects.
- Platforms for facilitating and accelerating innovations in future virtual product creation (see Figure 9), and for developing new interdisciplinary fields [9], as well as for expanding the scope of the current ones.
- Environments for adaptive, personalized and mass-customized multisensory learning, providing 24/7

Figure 9. Components of future virtual product creation

access to information, and enabling learning anywhere, anytime with any device.

- Facilities for assessing the effectiveness of new learning paradigms, based on the 4 C's, namely:
 - Critical thinking and Problem solving,
 - Communication, social networking and pervasive computing
 - Collaborative intelligence and crowdsourcing, and
 - Creativity and Innovation.

New patterns of organized culture and new paradigms and technologies for learning and engineering practice will emerge. For example, disintermediation, or undoing the traditional learner-instructor model, and replacing it by adaptive personalized learning (described in a succeeding subsection) The components of the ecosystems are continually updated and expanded. The ecosystems cannot be fully defined *a priori*, but rather emerge from the interactions among the components, as well as the interactions of the users with the environment. Therefore, the design of the ecosystems cannot be based on the traditional top-down systems engineering approach. Rather, a bottom-up emergent engineering approach is used, in which the components are designed and the interactions are engineered to enable the system to change and expand as needed. Through evolutionary adaptation processes, progressively better (and continuously improving) learning environments are generated.

6.1. Major components

Some of the major / key components of the ecosystems, which are not currently available in the NSF-supported

cyberinfrastructure are Knowledge discovery, customization and exploitation facilities; blended learning facilities; visual simulation tools with immersive 3D stereo capability, autonomous interfaces with anticipatory / predictive search engines; novel intelligent software agents and advanced multimodal interaction. These are briefly described subsequently.

- Integrated knowledge discovery, customization and exploitation facilities** – These enable access to massive online data and open educational resources, and provide the right knowledge for the right purpose at the right time. They will include comprehensive information retrieval and customization tools, decision support tools, concept maps, mind maps, interactive visualization, automatic summarization and recommender systems for providing personalized information and expert advice. They should leverage Big data predictive / prescriptive analytics tools and computational knowledge technologies developed by the research teams at the IBM Watson project, Wolfram Alpha, Grok (<https://www.groksolutions.com/>), and other lead organizations. New types of predictive search facilities should be incorporated for dynamic applications, where information is flowing continuously to and from users and devices. An example of the predictive search facility is the Mind-Meld facility developed by Expect Labs. It operates like a combination of Siri and Google Now.
- Blended Learning and research facilities** – Incorporating the latest 3D immersive virtual worlds, virtual holography, augmented / enhanced reality, and novel classroom technologies, to facilitate distributed collaboration and to provide a 360 degree multisensory experience for the user (see Figures 10 to 12). The multisensory representation of large complex engineering data and models through the combined use of visualization, haptic feedback, and other modalities of interaction can significantly increase the bandwidth of human-computer interface.
- Novel Intelligent software agents (Cybernetic Assistants)** – These have cognitive learning and understanding abilities, and serve as virtual assistants and / or effective learning companions. They have the capability to recognize the user's reactions communicated, for example, through facial expressions and the vocal intonation, and provide appropriate response. The interaction with the user will be more like face-to-face interaction. Advances in cognitive neuroscience and neuro-informatics might

Figure 10. Virtual world Lab showing Einstein avatar giving lecture on particle physics

Figure 11. zSpace tablet providing Interaction with 3D Virtual Holographic displays

provide the cybernetic assistant with more insight and understanding of the human thought development. This can result in engaging the users and optimizing (personalizing) the learning for each user.

- Multimodal and Autonomous Interfaces** – including novel mobile / portable / wearable devices and wireless communication, touchless interfaces (see the animations in Figures 13 and 14), brain-based and neural interfaces, multitouch, gestures, adaptable and adaptive interfaces, and media-rich communication tools. Visual interfaces, included in the system, will help in perceiving abstract data and gaining insight from it. With these facilities the user interaction with computing devices, physical systems, and information in general will be simple, natural, and seamless.

Autonomous interfaces, with predictive / anticipatory computing engines, can allow more detailed understanding of

Figure 12. Immersive Interactive Classroom Concept (learners can interact with the 3D model on the large screen, with 3D virtual holographic displays on tablets, and with other information on smart mobile devices)

See ESM2

Figure 13. Animation showing Eon Reality Touchless Interface

the learners' attention and comprehension, thereby enabling individualized and connected learning. This can be accomplished, for example, by tracking the eye movement and facial expressions of the learners, and using big data learning analytics tools, to make carefully calculated adjustments and suggestions to keep learners motivated as they master concepts or encounter stumbling blocks.

- **Cognitive robots, telepresence robots, bots and robotars (visible and virtual)** – operating autonomously in some tasks, monitoring and controlling informational processes, and capable of detecting when the user needs assistance.

7. Concluding remarks

The role and scope of the engineering profession are transforming rapidly. Both what engineers do, and how they do it, are changing. A number of emerging trends are likely to shape the future of engineering education, and of learning, in general. These include the widespread availability of information; the accelerating rate of technology development; the new interdisciplinary fields; future grand challenges, and the expanding role of engineering in the society. To meet future challenges of the rapidly changing engineering fields, a strategy is needed for increasing the pipeline of skilled workforce. Moreover, in the post-information age and the coming of the intelligence convergence era, new cyber, visual, novel media skills will be required from the entrants into the engineering workforce. A holistic perspective and a comprehensive strategy are needed to put engineering activities on an ambitious

See ESM3

Figure 14. Animation showing Touchless Interface using holographic device

trajectory that pushes the frontiers of innovation, discovery, and economic development. A step toward the implementation of that strategy is the development of intelligent adaptive cyber-physical ecosystems. The ecosystems would amplify human cognitive and perceptual capabilities, revolutionize learning, and enable the engineering workforce to perform increasingly complex and imaginative tasks of synthesis and creativity. Engineers can be working with experts in artificial intelligence and other technology teams on transforming many current products, industries, and practices into complex adaptive systems. Future engineering systems (e.g., vehicles, bridges and oil platforms) may be able to alert their human minders that they need repair before failure occurs. Also, biologically-inspired, self-healing engineering systems, will be developed. An example is provided by the bio-inspired Shape shifting, Self-healing Aircraft concept proposed by NASA Langley (see the animation in Figure 15).

See ESM4

Figure 15. Animation depicting bio-inspired Shape shifting, Self-healing Aircraft concept proposed by NASA Langley

The ecosystems will also facilitate the development of the 21st century information, digital, and visual skills among the learners. They will provide 3D immersive environment for promoting active collaborative learning, critical thinking, interpretative analysis, problem solving and knowledge creation, as well as adaptation to rapid change. The innovations that can be realized in the proposed ecosystems extend well beyond anything we can currently imagine. New patterns of organized culture, new paradigms of engineering practice, and new models of engineering education and organizations will emerge within these ecosystems, and support future engineering practice.

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