Position Paper: Low-cost Prototyping and Solution Development for Pandemics and Emergencies using Industry 4.0

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Abstract: Pandemics, such as the coronavirus pandemic and other large-scale public emergencies, including floods, volcanic explosions, and earthquakes, require strategic responses for smooth function and restart of industry. Creative, robust, low-cost, scalable solutions must be deployed for underserved and socially disadvantaged communities. This effort requires compressing product and process development from requirements engineering to final testing and deployment, service, and repair, in terms of timeframes, budgets, and related resource constraints. Exceptional circumstances, such as the coronavirus pandemic, add additional pressures such as social-distancing requirements. Several development techniques and tools are available for teams to respond rapidly and effectively to evolving needs in a cost and resource-efficient manner. Industry 4.0 principles can be extended to support frugal development, manufacturing, and operations in diverse communities. Efforts such as the Maker Movement and the availability of licensing techniques for open hardware and software development further add to the abilities of teams to enable virtual collaboration, solution development, customization, and deployment. The paper describes two positions, one that Industry 4.0 can aid in frugal solution development for underserved communities, and two that Industry 4.0 can be implemented frugally to aid production and quality among underserved and vulnerable communities.

1 INTRODUCTION

The novel coronavirus, SARS-CoV-2, causes the disease labelled COVID-19 ("Naming the coronavirus," n.d.). On Mar 11, 2020, reviewing a record of over 118,000 cases in over 110 countries at that point in time, the World Health Organization (WHO) declared COVID-19 a pandemic (Ducharme, 2020), (Spinelli and Pellino, 2020). Since then, the pandemic has continued into the second half of 2020, with uneven recovery and control, globally. The unavailability of effective treatments or vaccines as of Jun 30, 2020, has led to varying predictions of continued infection rates and multiple waves of the disease globally (Coronavirus Treatment Acceleration, 2020). Vaccines and therapies developed to combat the coronavirus will require manufacturing scaling for quick, wide distribution. Workplaces, schools, retail establishments, and several other places where large groups of humans tend to interact will require special measures including social distancing, screening for symptoms, and other preventive as well as control measures (Kaplan, Hoffman, and Parsons, 2020), (COVID-19 Control and Prevention, 2020).

Besides the COVID-19 pandemic, other emergencies require interventions such as food and medication provision through drones or similar transportation, radiation level measurements, water, and air quality testing in a rapid, efficient manner. Such emergencies include floods, volcanic explosions, earthquakes, and landslides, to name a few. Sometimes, as with the Fukushima Daiichi nuclear reactor accident (Fukushima Daiichi Accident, 2020), the effect of natural disasters and the emergencies they cause can be exacerbated by large-

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scale incidents such as nuclear reactor meltdowns. Industrial disasters, such as the Bhopal Gas Disaster in India, can also cause large-scale medical and resource constraints (Bhopal disaster, n.d.).

Socially disadvantaged, vulnerable groups and medically underserved communities lack access to expensive solutions (UN working to ensure, 2020). This issue of access extends to businesses and organizations offering services to and among such communities. Such access issues can render operations difficult and allow for continued spread of infection within and across communities (Johns and Elsland, 2020).

Even when solutions become available at lower costs, financial constraints can prevent the deployment of such solutions (Mills, 2014). While this is a critical topic of interest, financial considerations are not detailed in the current work.

Industry 4.0 represents the next wave of technologies that can be used to combat social disadvantages across communities. Investment in STEM Education can provide trained workforce who can engage in Industry 4.0 (Njogu, J), (Idin, 2018). Educationally underserved communities face financial and other resource pressures in being able to provide STEM education (Ejiwale, 2013). Low-cost prototypes can be used as tools in educational pedagogy, both for formal instruction (Yamanoor and Yamanoor, GHTC, 2017), as well as in the form of workshops for knowledge sharing and to foment further private and public research as well as citizen science, (Yamanoor and Yamanoor, 2017) and the development of products and solutions to solve various industrial and societal problems (Yamanoor and Yamanoor, Workshop, 2018) (Yamanoor and Yamanoor, 2020, January), (Yamanoor and Yamanoor, 2020, July).

The position paper describes how Industry 4.0 principles and tools can be employed to rapidly develop prototypes and solutions while optimizing for performance and cost by diverse global teams operating under various constraints and requirements.

The goal is to demonstrate through examples of ongoing and completed research of the authors that involve rapidly developed, solutions that are built on the general principles of Industry 4.0, frugally. These solutions are then shared for customization, adoption, and deployment to serve vulnerable, disadvantaged, and underserved communities everywhere.

2 BACKGROUND

2.1 Indusry 4.0

Industry 4.0 consists of the following principles:

1. Systems in the Industry 4.0 context are cyber-physical systems, where operations are digitized and computer-controlled (Cyber-physical system, n.d.).

2. The Internet of Things (IoT), in the context of Industry 4.0, is sometimes referred to as the Industrial Internet of Things (IIoT) is a significant component of Industry 4.0. Internet connectivity promotes digital manufacturing and operations.

   Frequently, IIoT and Industry 4.0 are used as interchangeable terms (Weallans, 2018). Alternately, they are distinguished. IoT is used in the consumer context, and IIoT is used in the industrial context of internet-connected devices. Internet connectivity allows for data transfer and control over the internet, enabling live and real-time actions (IIoT vs., n.d.). The team distinguishes between IIoT and Industry 4.0. IIoT is considered an enabling factor of Industry 4.0.

3. Robotics is another critical component in Industry 4.0. Robots will enable manufacturing and supply chain operations to be efficient and optimized. Robots may be used collaboratively, sometimes termed cobots (Cobot, n.d.). They can also be used as alternatives to human labour.

4. Additive Manufacturing creates opportunities within Industry 4.0 for intricate designs, newer materials and material combinations, production speed, and optimization of costs. It can serve as a complement to, and where possible, replace subtractive manufacturing. Hybrid processes exist, where the finishing operations are performed by subtractive techniques (Weiner, 2019). Maintenance, repair, and component replacement are facilitated by directly employing Computer Aided Design (CAD) information to produce components through additive manufacturing.
   Additive Manufacturing is frequently used interchangeably with the term 3D Printing. However, with the emergence of 4D Printing and other paradigms, this interchangeability will

be rendered inaccurate (4d printing, n.d.). Additive Manufacturing presents advantages such as reduced inventory requirements and fewer breakdowns and disruptions in the supply chain (Thomas & Gilbert, 2014). Batch production can reduce overall costs (Rickenbacher et al., 2013).

5. Immersive technologies, classified as fully or semi-immersive technologies, such as Virtual Reality, Augmented Reality, Extended Reality, and Mixed Reality can immerse users and replace or enhance environments with information to aid in training (Roldan, 2019), (Longo, Nicoletti & Padovano, 2017), operations (Wagner, Herrmann, & Thiede, 2017), maintenance (Yew, Ong & Nee, 2017), troubleshooting (Wolfe, 2019) as well as other applications.

6. Simulations and Digital Twins, with the availability of high-performance computing, will constitute the backbone of Industry 4.0, allowing for the iterative design of workflows, training, operations management including predictive maintenance and servicing, as well as other applications (Rodič, 2017), (Schluse, Atorf & Roßmann, 2017). Simulations can be used for cost reduction, consideration of alternative designs for part and process flows, efficiency improvements, and determination and updates to processes, maintenance, and service plans.

7. Big Data, a term that has come to encompass large volumes and variety of data, that can be processed at very high speeds for possible non-obvious insights will be a key feature of Industry 4.0 (Witkowski, 2017). Increased deployment of various forms of sensors, the ability to collect data continuously during operations as well as in the background, and the ability to communicate and analyze the data will create opportunities for using insights to correct and improve product and process quality, while rendering improvements in operational efficiency, sustainability and other areas (Yan, Meng, Lu and Li, 2017), (Khan, Wu, Xu & Dou, 2017).

8. Cloud Computing and alternately, Edge Computing provides the means to analyse the Big Data that are a consequence of Industry 4.0 (Kim, 2017), (Yen, Liu, Lin, Kao, Wang & Hsu, 2014). Cloud Computing involves the upload of data to remote servers, where multiple analyses can be completed, and the results reported through dashboarding systems. Latency and cost are primary drawbacks of using cloud computing in environments where real-time results are desirable. Edge computing, where the machine learning aspects are directly integrated to the location where the data is collected, offers analytical results in real-time, allowing for corrections and efficient operations (Trinks & Felden, 2018), (Ahuett-Garza & Kurfess, 2018).

9. Machine Learning and Deep Learning, both Probabilistic Artificial Intelligence techniques are used to recognize patterns and insights from data (Ghahramani, 2015). Data sources can include real-time sensory data, synthetic simulated data, and a mix of different data types, secured from the various functional elements of Industry 4.0. When edge computing is implemented, the results of learning can be applied in the form of real-time recommendations for machinery to alter operations to make error and course corrections and improve quality and efficiency.

10. Network Connectivity is the backbone of Industry 4.0 implementations. Various scalable solutions are available to manage the requisite communication and data transfer requirements (IoT Connectivity for, n.d.), (Li, Wan et al., 2017).

Technologies such as Bluetooth Low Energy can be used to deploy low-cost solutions within the Industry 4.0 paradigm (Svensson, 2018). The team takes advantage of such opportunities to reduce infrastructure costs.

2.2 Industry 4.0 and Team Goals

Industry 4.0 can be used to accrue efficiencies and cost-savings, which align well with the team's objectives of developing low-cost prototypes and solutions for underserved communities.

In the rapidly evolving COVID-19 pandemic, this has resulted in a prior accepted publication of a Proof-of-Concept (PoC) solution developed by the team for a low-cost non-contact infrared thermometer, with ongoing research work (Yamanoor, Yamanoor and Srivastava, in press) followed by a similar solution for contact thermometry (Yamanoor and Yamanoor, in press). These works and similar development is accomplished through multiple elements of Industry 4.0.

1. Projects are aimed at vulnerable, disadvantaged, and underserved communities, whether they are personal, industrial, or population-based projects. Every essential element of the project, including hardware and software, Bills of Materials (BOMs), is made available through open licensing schemes. This is in keeping with the principles of the Maker Movement (Capps, 2020), (Applin 2020).

2. The objective for all designs and solutions is to be safe, effective, and as optimal performance at the lowest total cost. Frugal Engineering principles must be embraced at all stages of the project. The products must be manufactured with sustainable materials and processes wherever feasible. Digital Prototyping, Direct CAD to Prototypes, Additive Manufacturing, and other manufacturing paradigms that are components of Industry 4.0 allow the team to minimize iterative development costs. Efficiencies gleaned through Digital Manufacturing promote sustainability.

3. Customizability, usability, manufacturability, scalability, implementation ease, reliability, and serviceability are vital considerations during design and development. Simulation and digital twins are applied to accomplish these goals, where possible.

4. To scale solutions and reduce variance, standard, off-the-shelf components and assemblies are selected when possible. Though high levels of customization are feasible with Industry 4.0 (Tom & Veneker, 2019), minimizing customization can lead to fewer errors, cost savings, and variations.

3 PROCESSES AND TOOLS

A brief discussion of the processes and tools used by the team is presented in support of the position that Industry 4.0 lends both low-cost development and how low-cost products can be used to implement Industry 4.0 paradigms to serve underserved communities.

3.1 Hardware

3.1.1 Compting

The team selects a microcontroller or a single board computer (SBC) depending on project needs. The Arduino microcontroller architecture (Arduino – Home, n.d.) is openly published and inexpensive clones are available. The Arduino Microcontroller can be used to prototype as well as implement affordable Industry 4.0 solutions (Subekti et al., 2020).

Recently, the team has gained experience using the Seeeduino XIAO Arduino microcontroller. The XIAO microcontroller has the smallest footprint in the family offered by Seeed. List prices range from $4.90 to $4.30 USD, depending on order quantities (Seeeduino XIAO, n.d.).

The team's experience has shown that the smaller physical and power footprint and computing capabilities allow it to be useful in Internet of Things (IoT) and Industrial Internet of Things (IIoT) projects.

The Raspberry Pi Single Board Computer (Teach, Learn, n.d.) is a powerful, relatively inexpensive computer with diverse applications in education, academic research, and private industry and the hobby makers movement.

The potential for the deployment of Raspberry Pi in Industry 4.0 applications has been demonstrated (Kim & Son, 2018), (Johnston & Cox, 2017). The team has extensive experience developing projects with this product line (Yamanoor and Yamanoor, 2015), (Yamanoor and Yamanoor, 2017). At a list price of $35 USD, it is a very affordable computer with enough processing power to allow for the design and implementation of multiple solutions.

The Raspberry Pi Foundation introduced the Raspberry Pi Zero Single Board Computer, designed to have a smaller physical footprint, and extremely affordability around $5 - $10 USD, while still maintaining robust performance (Buy a Raspberry, n.d.). The team has used the Raspberry Pi for Proof of Concept and has successfully replaced it with the Raspberry Pi Zero during prototyping and later development stages. Compared to the XIAO and other microcontrollers, the Pi Zero is best suited for DC Power consumption, while providing superior computing and communication capabilities.

The team continues to review and experiment with other options to review fit against project objectives and IoT or IIoT applications (Yamanoor & Yamanoor, IEEE Spectrum, 2017).

3.1.2 Sensors

Sensors are typically presented on breakout boards that allow for drop-in testing and development (What is a breakout, 2015). Breakout boards have several advantages, including an efficient footprint, reusability, labelling, documentation, and other advantages. The availability of affordable sensor breakout boards has effectively allowed affordable solutions to be designed for underserved communities (Patel, 2016).

Recently, the team applied the AMG8833 sensor breakout board to develop a Proof-of-Concept low cost non-contact thermometry device for temperature screening of employees and foot-traffic by industries in underserved communities. The sensor breakout board is priced at $39.99 USD (Yamanoor, Yamanoor, and Srivastava, in press).

3.1.3 Printed Circuit Board Assemblies

Custom Printed Circuit Board Assemblies (PCBAs) allow for various advantages. Form, fit, and function can be controlled, and in addition, the circuit can be optimized for component placement, efficiency, and costs. Shortcomings include difficulties in iterative design, lead times, and difficulties in repair and replacement (Klopotic, 2019).

The team has gained experience working with low-cost PCBA vendors and has reduced initial and iterative costs. Aided by remote near-instant quoting using CAD files and modern batch manufacturing techniques, vendors such as OSH Park (OSH Park, (n.d.)) have provided quick turnarounds for traces on short order-runs at very low costs. The PCBA traces for the non-contact thermometer, cost $7.55 USD each, for a short-order run of three items. Industry 4.0 will further drive improvements in PCBA manufacturing quality, turnaround times and costs.

3.1.4 Enclosures and Related Hardware

The team has used both additive and subtractive manufacturing for hardware needs, including enclosures and other structural elements of product designs. Additive manufacturing, a core element of Industry 4.0 (Dilberoglu et. al., 2017) has become a reliable method for most ongoing manufacturing needs for the team (Yamanoor & Yamanoor, December 2017). The advantages include the ability to collaborate remotely, use CAD files eschewing detailed drawings, and the ability to explore multiple materials and design alternatives as well as obtain repeatable, consistent results. The final design configurations are shared with the public at large for adoption, meeting one of the team's core objectives of open, low-cost design.

3.2 Software

3.2.1 Application Software

Among several languages available for development, Python has been identified by the team and others as a suitable language for programming IoT and IIoT applications (Dasgupta, 2020). The availability of tutorials, books, code samples, and other features makes it amenable to develop solutions in Python. The team has successfully engaged Python in several projects (Yamanoor & Yamanoor, 2015), (Yamanoor & Yamanoor, 2017), (Yamanoor & Yamanoor, 2018), (Yamanoor & Yamanoor, 2020) (Yamanoor, Yamanoor & Srivastava, 2020).

3.2.2 Software for Edge Computing and AI

TensorFlow is an open-source machine learning platform used for AI applications (TensorFlow, n.d.). TensorFlow Lite, a lightweight variant, is designed for microcontrollers. The team has used both tools in implementations.

The team has worked with other open software programs such as TinyML for various application development purposes. Open-source software solutions have the potential to reduce the cost of development and implementation of Industry 4.0 solutions. Machine Learning, Deep Learning, and related techniques have the potential to impact Industry 4.0, unlike any of its other components.

4 CONCLUSIONS

There are two key positions taken by the team concerning the Industry 4.0 paradigm encompassing elements such as additive and digital manufacturing, smart sensors, cloud computing, machine learning, and others, elucidated with examples in this work.

1. The elements of Industry 4.0 can be applied to reduce the cost of developing and implementing solutions that solve community issues for underserved and vulnerable communities.
2. The elements of Industry 4.0 can be established to function inexpensively through the careful selection of tools and applications. This may further battles against pandemics, epidemics, natural and manmade disasters in the future.

5 RECOMMENDATIONS

Industry 4.0 principles can be utilized to combat pandemics and emergencies. Industry 4.0 elements can also be applied to alleviate the quality of goods and services in underserved and vulnerable communities.

Design and Manufacturing can be distributed and crowdsourced, with the same quality, globally, allowing solutions to be implemented among several communities. Remotely collaborative teams can form and change, performing speedy, iterative designs, and implementing solutions.

Combined with sustainable materials and practices, frugal engineering paradigms, open design principles, and user-centric customization, a true revolution can be brought about without prohibitively expensive infrastructure investments through the meticulous selection of appropriate tools and processes. As the technologies mature, there can be a cascading effect of quality improvements and cost savings.

Standards should be developed and updated as needed, for low-cost Industry 4.0 principles. These standards can guide the creation of baseline pipelines, allowing for shared infrastructural elements and designs, further reducing expenses for industries globally. In future works, the team will be presenting the outlines for such frugal Industry 4.0 standards.

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