Integrating biophotovoltaic and cyber-physical technologies into a 3D printed wall

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The research presented in this paper investigates the development of ``3D printed ceramic green wall'', a technological Nature Based Solution (NBS) aimed at regenerating urban areas by improving spatial quality and sustainability through clean and autonomous energy production. Building upon previous research, the challenge of this system is to adapt additive manufacturing processes of ceramic 3D printing with biophotovoltaic systems while simultaneously developing digital and cyber-physical frameworks to generate site and user responsive design and autonomous solutions that optimize system performance and energy generation. The paper explores the complex design negotiations between these drivers, focusing particularly on their performance optimization, and finally highlights the system potential as exemplified through a successful implementation of a 1:1 site responsive wall prototype.

Keywords: *Nature based solutions, biophotovoltaic systems, additive manufacturing, responsive design, cyber-physical networks, augmented reality*

TECHNOLOGICAL NATURE BASED SOLUTIONS

Nature Based Solutions (NBS) are systems that work with nature to address socio-environmental challenges, providing cities with solutions to address urban issues using a holistic approach. They are defined by the European Commission as "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits" (Bauduceau et al. 2015). These innovative systems should take advantage of advanced digital manufacturing methods and technological developments to provide novel design protocols and possibilities for enhancing urban design, both in the quantity and quality of public space intervention. The 3D printed ceramic green wall falls under the framework of these Technological Nature Based Solutions and utilizes a multidisciplinary design approach, traversing technology with biology, to innovate the solution design, implementation process and responsiveness, and optimize system performance.

The 3D printed ceramic green wall relies on the conclusions of two precedent IAAC investigations which are of particular interest: FoodVoltaic and Digital Adobe. FoodVoltaics is a green wall system which explores how herbs might be used as a source of renewable energy through biophotovoltaic technology, which allows for the production of small amounts of energy through the naturally occuring electrons generated due to photosynthesis. On the other hand, Digital Adobe demonstrates the potential of building full-size robotically 3D printed wall prototypes using clay materials, which can improve the sustainability of buildings by optimizing the qualities of the clays and can extend the possibility of developing complex geometries to house the organic matter and technical equipment and sensors. The challenge associated with the 3D printed ceramic green wall consists of adapting the manufacturing process of Digital Adobe to the needs of the FoodVoltaic system, while also integrating I2oT sensors and communication electronics connected to a cloud computing platform for data acquisition and analysis with the objective of optimising the processes of energy generation. As a green wall system, the 3D printed ceramic green wall can be applied strategically to help regenerate urban neglected areas by improving their spatial quality and sustainability through clean and autonomous energy production while simultaneously boosting the quality of the physical environment.

In contrast to traditional green walls, the 3D printed ceramic wall is a sophisticated system designed according to the elaborate relationship between physical processes and the cyber systems they govern, and vice versa (Figure 1). The realization of this cyber-physical system relies on several drivers: on biophotovoltaic technologies for energy generation and collection, on robotic additive manufacturing for novel materials and mass customization, on a responsive design platform to allow for design adaptations to site-specific conditions, and finally on a platform of sensors, cloud computing and machine learning softwares, and immersive visualizations systems to study system behaviour and provide predictive and corrective measures for optimizing system performance. The complex negotiations between these design drivers will be further explored.

Figure 1
3D printed ceramic green wall outcome as a sophisticated system-driven solution

BIOPHOTOVOLTAIC SYSTEMS: PLANTS AND ELECTRICITY

In order to generate electrical energy, the 3D printed ceramic green wall relies on a biophotovoltaic system (PBV) that exploits the natural process of photosynthesis. The plants use energy from light to consume carbon dioxide and water from the environment and convert it into organic compounds, which are then released back into the soil containing symbiotic bacteria. This bacteria feeds and breaks down the compounds, releasing byproducts that include electrons. By providing an electrode within the system for the microorganisms, the resulting electrons can be collected as electricity.

The energy collection system developed was based on the previous research carried out at Cambridge (Wey et al 2015) and consists of an anode (carbon fibre mesh) and a cathode (carbon paper). The carbon fiber mesh was embedded into the soil substrate for root growth contact and the carbon paper was positioned strategically onto an opening in the bottom of the container to provide oxygen to the root system through this semi-permeable barrier (Figure 2).

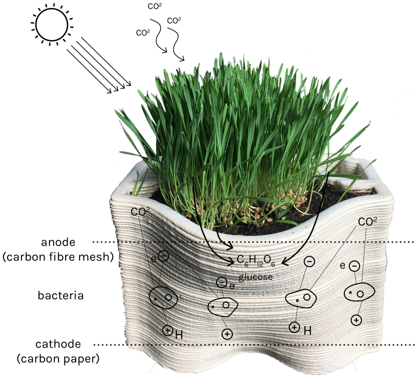


Figure 2
Diagram of biophotovoltaic system components and processes

This system was implemented and tested over a 6-month period using standard plastic containers along with sensors to monitor plant growth over time to understand the logics behind a healthy system. The sensors fitted analyze both the internal conditions of each pot (temperature, soil moisture, pH, electrical conductivity) and the external conditions of the surrounding environment (air temperature, humidity, lighting, NO2, CO). The following conclusions were generated for the system to thrive and generate maximum electricity:

- Higher water saturation yields higher electrons due to the additional water in the medium promoting electrolysis within the soil.
- A positive correlation exists between the quantity of electrons generated and time passed.
- The larger the root growth, the more productive the system is, and therefore containers with larger soil volumes generated the most electrons.
- The bacteria in the soil is aerobic, requiring openings in the base that allows exposure to oxygen in addition to excess water drainage.
- The anode and cathode need to be distanced, otherwise the system short-circuits upon contact and energy collection fails.
- The process of energy generation is interrupted by the evaporation or freezing of water from the soil.
- Each system relies on the healthy growth of the plant and every plant species requires different conditions of light, water and root growth capacity to meet those requirements.

This final deduction highlighted the importance of plant selection and led to further investigation into specific plant typologies and the subsequent correlation between growth requirements and variabilities within the planter morphology. Because the prototype was to be erected within Barcelona, two categories of plant species were considered: Native edible plants suited for Mediterrainean climates that can be applied to outdoor settings, and tropical low-maintenance plants for indoor applications. Plants of each category were selected and their performance analyzed as a function of light, water, and root growth mass comparatively over different planter morphologies. General observations recorded suggested a relationship between the ratio of the amount of plant tissues above ground to the amount of those below ground and the supporting soil volume. Plants with smaller above ground biomass fared better in shallow planters with smaller soil volumes thanks to their size proportional root structure systems. Similarly, plants with larger above ground biomass fared better in larger planters that could support a higher soil volume. Additionally, the surface area calculation of the planter's topsoil had a positive correlation to the moisture content within the planter; an increase in top surface area resulted in an increase in water evaporation from the soil.

ADDITIVE MANUFACTURING: CERAMICS AND DESIGN

Robotic additive manufacturing technologies offer a new flexible methodology for manufacturing green wall systems in part due to novel material possibilities and the ability to mass customize complex geometrical forms The first phase of the investigation focused on identifying a locally sourced clay body suitable for printability and potential application within the 3D Printed Ceramic Wall. Studies focused specifically on stoneware, known for its robust working properties and extremely low water absorbency levels when compared to other ceramics, which is crucial for preventing damage from extreme outdoor weather conditions and the internal high water content required for the biophotovoltaic system. Stoneware can be glazed to achieve similar strengths to porcelain, is significantly cheaper in costs, and has a lower shrinkage rate, a property fundamental to controlling material behaviour at every step of the formation process, from fabrication to firing.

Ceramics undergo two stages of uncontrolled shrinkage, once during the drying process and again during the firing process. As water evaporates from the clay body, the resultant particle packing shrinks the entire matrix, highlighting the importance of the water content and clay particle size on shrinkage. Water content also plays a critical factor within the additive manufacturing process in achieving the required material consistency and malleability for optimal extrusion. Material studies were conducted to understand the critical relationship between the water percentage of a clay body on both clay behaviour and its resulting influence on performance post-firing. Five varieties of stoneware were selected and tested at various water content levels, and compared for printability, viscosity, total shrinkage, material strength, and water absorption. The resultant data indicated that the PRAM clay, manufactured by SIO-2®, with 22% added water outperformed in reducing the percent of change in material behaviours and was therefore selected for its optimal performance in both wet and fired state (Figure 3).

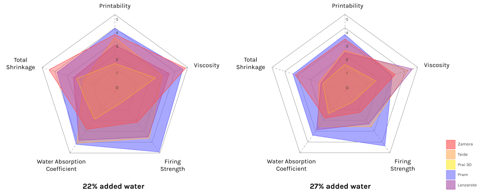


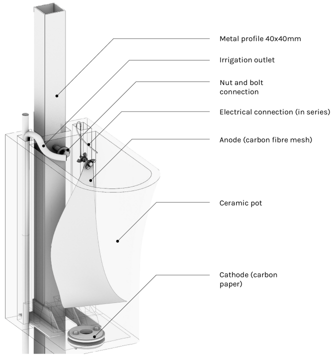
Figure 3
Comparison of documented changes in material performance as a result of varying water content in clay bodies

The second phase focused on investigating the material and structural limitations of 3D printing based on previous work developed at IAAC along with testing to extract a set of patterns and rules to define the geometry. Initial printing experiments helped deduct the following guidelines for successful structures:

- Any geometry needs to be sliced into layers of continuous printing paths for production optimization.
- Walls with double curvature achieve greater stiffness and resistance to stress deformation than vertically extruded straight lines, measured by its resistance to buckling.
- A volumetric structure can reach a maximum stable height of up to 60cm by increasing the number of vertices within the printing path.
- While infill can greatly improve structural stability, it also significantly increases the material required and therefore the weight of the final object.
- For stability, it is important that the center of gravity of the body remains within the boundaries of the footprint of the geometry.
- Any geometry can exhibit a maximum overhang angle of 30°, but with appropriate and adequate infill, this angle can be increased up to 40°.
- Rotation and torsion coupled with a shift in the center of gravity of the top layer with respect to the bottom layer may result in structural instability.
- Any structure should be designed considering a total material shrinkage of 11%, resulting in a dimensional tolerance within +/- 0.5-1.5mm assuming the drying temperature and humidity levels are controlled.

Prototype investigations were conducted to further extend the design possibilities and geometrical complexities achievable with additive manufacturing towards pot functionality. Several prototype designs of horizontal and vertical extensile iterations were analyzed for their potential for parametric variability as required of the pot morphology to support the growth requirements of various plant species. In designing the pot module, it became critical to understand the part-to-whole relation to drive further system development. Initial starting design investigations were oriented towards creating a seamless wall, whereby the edge boundaries between pots joined to minimize the separation between them. Ultimately, a component-based wall system proved to be the ideal condition as a result of the warping that occurs from the uncontrollable shrinkage of clay during the drying and firing process, compromising any attempt at creating seamless joineries. In order to improve the surface quality of the pots, explorations of textural applications were explored and imposed to force a controlled patterning system. The multipurpose surface texture of the pot not only serves a visual purpose, but it also increases surface area to provide more humidity control and further stabilizes the structure of the pot due to the increase in the number of vertices that help counter the buildup of material loads. Exterior glaze finishings were applied to program necessary flora conditions related to light amplification through increased reflections.

Figure 4
Unit axonometric of components and structural detailing



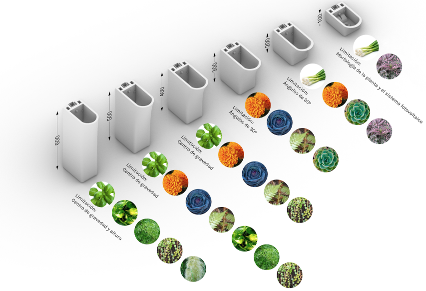
In addition to housing organic matter and biophotovoltaic components, the pot design integrates a standardized structural system, adaptable to any height, that allows for easy installation onto the secondary support structure and ease of maintenance or replacement. This bottom detailing allows the pot to safely slot onto two L-brackets and is secured from the top by a nut-and bolt system to prevent rotational moment. A secondary nut-and bolt system secures the carbon fibre mesh in place, preventing a system short circuit, and providing an outlet for the modules to be connected in series and in parallel for energy collection (Figure 4).

INTEGRATION IN DIGITAL INTERFACES: RESPONSIVE DESIGN

Computational design softwares, specifically Rhino and Grasshopper plug-ins, were implemented for design modeling and optimization of solutions as well as facilitating the development of a common design platform that allows for adjustments based on defined parametric inputs. This algorithmic script influences the system design on both the individual pot level and the overall global system design according to site-specific and regional-specific inputs, resulting in an innately responsive design.

The script allows for the topological variability of each pot through two parameters vital to the success of any plant species growth and energy generation: height and opening angle. An increase in the height of the pot allows for greater soil capacity and can support plants with larger roots, while a decrease in height yields less soil capacity and best support plants with smaller root systems. Similarly, the opening angle of the planter can be modified to control the soil moisture levels by increasing or decreasing the surface area exposed to water evaporation from the soil and are defined by a plant's ideal water and humidity conditions.

Figure 5
Catalogue of pot height and angle limitations with respective flora possibilities



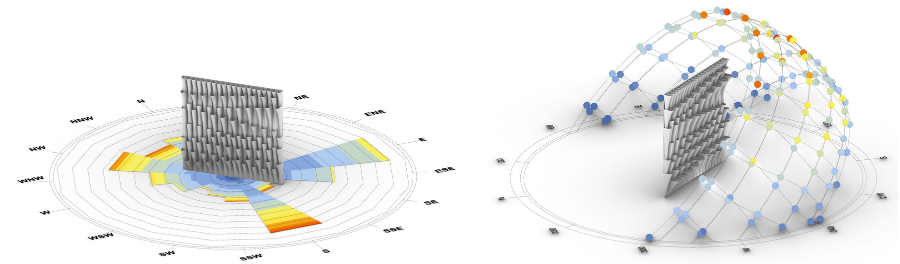


Figure 6
Generated wall design for Barcelona driven by local environmental inputs including solar path and wind

Table 1
The responsive inputs considered by the algorithm script

Local (Site-specific inputs)	**Global (Regional-specific inputs)**
Local flora requirements	Temperature
Solar Path	Humidity
Wind	Rain
User preferences	

Globally, the system parameters consider specific local site conditions, as well as specific regional and global environmental conditions, and distributes the most suited plant variety and subsequent pot morphology accordingly (Table 1).

While plants need light for photosynthesis, a process critical for biophotovoltaics, not all plants require the same light nor is all light the same. Understanding the sun and light intake requirements is vital to determining the optimal opening angle and distribution of the modules. The solar path, altitude and azimuth angle help determine shadow regions and appropriate pot opening angles. Wind equally is important for plants as it helps them grow sturdy yet strong or cold winds can damage or kill plants by drying out the soil moisture levels. Plants that are densely branched to the ground, such as basil, marigolds, and ferns, can act as windbreaks by strategically placing them to protect vulnerable plants highlighting the importance of plant selection for extreme environments. Similarly extreme heat, humidity and rain all have significant effects on the soil moisture content levels, a factor that can be very detrimental to both the biophotovoltaic system and plant health, yet can be mitigated through appropriate plant selection and controlled irrigation (Figure 5).

The algorithm also supports design influences from external actors within the design process. The flexibility of this system can facilitate the negotiations of these open-ended parameters between citizens and their city governments, empowering communities. Due to their subjective nature, these participatory design parameters rely heavily on preferences, accommodating varying degrees of user or client customization.

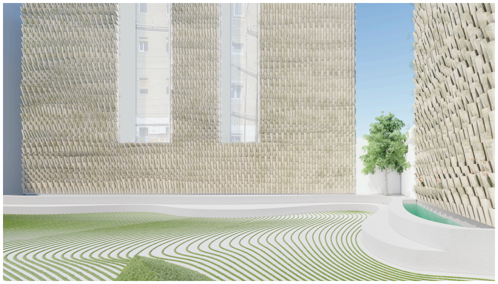


Figure 7
Potential system application in an urban public space context.

INTEGRATION IN PHYSICAL INTERFACES: CYBER-PHYSICAL SYSTEMS

The cyber-physical platform associated with 3D printed ceramic green wall provides real-time information on the energy generation process through its expert analysis of data and use of immersive visualization tools, ensuring the sustainability and productivity of the wall. The architecture of this platform comprises the following technological elements: Green Leafs; Green Stems; Green Platforms; and Green Client.

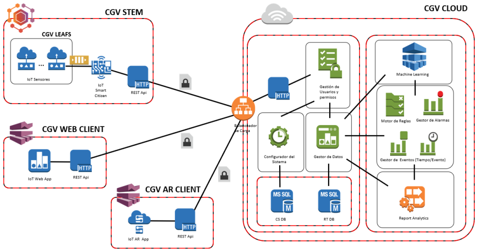


Figure 8
Cyber-physical system architecture

Each independent module found in the wall system intended to house plants and fully functional biophotovoltaic systems is referred to as a Green Leaf. As previously stated, this biophotovoltaic system consists of an anode made of carbon mesh fibers to help attract electrons and a cathode made of carbon paper, which attract protons from the anodic biological material. Each Green Leaf is fitted with a water irrigation outlet and a number of I2oT sensors for monitorization of the energy processes based on plant photosynthesis. The sensors embedded within the Green Leafs analyze environmental and plant conditions. The different sensors (Green Leafs) are connected to a Smart Citizen Kit v2.0 SCK, which is an Arduino-based open software platform acting as a central controller (Green Stem) and is responsible for collecting real-time data from the sensors, pre-processing it and sending it to the cloud computing software system (Figure 6).

Figure 9
Voltage energy readings for one of the Green Leafs and the substructure of the supporting structural, irrigation and electrical systems

The Green Platform, or the cloud computing infrastructure, integrates both the hardware elements required for the cloud infrastructure (Green Cloud) and the software elements (Green ML Brain) required for analysis, archiving, optimization, and decision making. In addition to storage and management of energy and real-time data, the cloud infrastructure also allows for the analysis of data obtained through automated machine learning algorithms to optimize production processes and facilitate predictive maintenance of the different distributed Green Leafs.

The final element of this cyber-physical architecture is the visualization elements that operate through either platform-independent applications with valid internet connectivity (Green UI Client) or applications based on augmented reality techniques for devices with built-in cameras (Green AR Client). These immersive visualization systems offer a more informative understanding of the data obtained and ultimately a more effective overall user experience.

PROTOTYPE PRODUCTION AND ANALYSIS

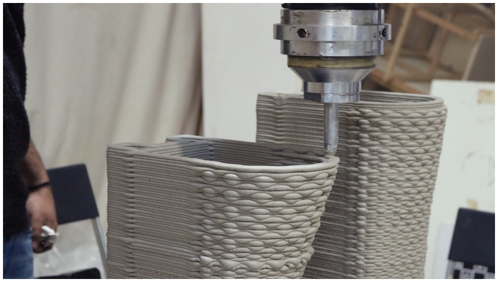


Figure 10
Production of the 3D printing ceramic pots

To test the viability of the overall wall system, a prototype was designed, and developed within a real-world environment with the objective of carrying out the complete integration and validation of the digital and physical platforms to monitor effectiveness and optimize the energy production system. The selected study site was the city of Barcelona and the prototype was evaluated in two locations, one within the IAAC laboratories, and the other was exhibited and demonstrated to the public during an international construction fair. The relevant global and local climatic conditions were input into the algorithmic software, and a 1.2x1.2m sectional of the resulting parametric wall generated was extracted and selected for mass fabrication. In total, 21 modules were 3D printed, dried, fired, and glazed (Figure 8). The morphology of these pots ranged from 200 to 500mm in height with a maximum cantilever angle of 35.0°. The resulting outcome of this analysis best supported sturdy and low maintenance plant varieties, including fern, pothos, asparagus, echeveria, hypoestes, and rosario.

The pots were assembled onto a self-standing metal structural system developed using 40x40mm metal profiles to support the weight of the system and to integrate a cavity between the pots to store the automated irrigation system components: a 36L water tank, a water filter, and a pump. Once all the modules were installed and connected, the electrical wires were connected to the Smart Citizen kit to monitor the health of two plants through specific sensors. The hardware was also connected to an ipad screen that informed the public about the general status of the system, as well as an AR marker that allowed the user to install a free application to download and visualize the system health and productivity data themselves. This automated irrigation system is initialized when soil moisture sensors detect low levels, activating the pump to distribute water through a series of plastic tubes fed up through the metal profiles with outlets distributing water for each pot. The fair lasted 4 days, after which it was dismantled and transported back to its origin (Figure 9).

The hardware and software systems integrated in this prototype were successfully installed and worked well (Figure 10 & 11). The system was equipped with the sensors of a complete SmartCitizen kit together with other cheaper sensors using the KNX protocol. These sensors were integrated in two pots to correlate the data between the two and provide a good impression of the system status. The AR application was also successfully tested and provided users with the ability to scan the AR marker and go to the application to download and understand the data collected by the sensors. The automatic irrigation system was also installed and operated successfully.

Figure 11
Final set-up and assembly of the 3D print ceramic green wall, including the cyber-physical platforms

First feedback from the construction fair was highly promising, as visitors expressed their interest and appreciation for the greenery and aesthetics of the system. The positive reception received suggested a similar marked improvement on urban ecosystems thanks to the introduction of plants. One of the main issues with any green wall is its maintenance, however, the monitoring platform of the 3D printed ceramic green wall gives the system the ability to provide its own expert care for the plants with minimal and targeted external intervention if necessary. This cyber-physical platform, along with strategic design solutions integrated within the modules to avoid evaporation, help minimize the water consumption required by the system and maximizes the energy production.

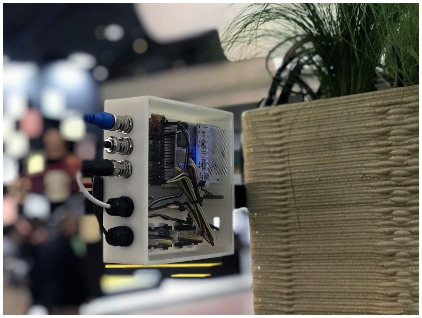


Figure 12
The SmartCitizen kit providing real-time information on the health of the plants and energy productivity

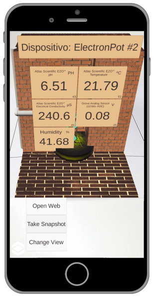


Figure 13
An augmented reality (AR) phone application allows users to visualize overall system health and to interact with each plant using real-time sensor data

CONCLUSIONS

The 3D printed ceramic green wall system featured in this paper has proven itself successful as demonstrated by the 1:1 prototype, paving the way toward its implementation in real world applications with a number of possibilities for further development. Significant improvements could help further simplify the assembly and installation process of the pots through either plug-in-play methodologies that simplify the connections between anode and cathode, or by exploring and integrating conductive materials into the additive manufacturing process to embed conductive performance within the material behaviour of the stoneware. Further research needs to be conducted to expand the repository of plant varieties available for applications within environments that fall outside of Barcelona's climatic conditions, while also considering the possibility of adapting the system for urban agriculture in which the local products may be cultivated. Another design opportunity lies in embedding an augmented reality code marker into the textures of the modules, so that each texture may transform into uniquely identifiable markers that provide specific data to that module's energy readings and plant health.

Lastly, the digital fabrication of 3D printed ceramic green wall has only been tested at a maximum scale of the 1:1 prototype, and its immersion and relevance within urban spaces depends on the implementation of on-site full scale prototypes, in the formulation of a wider and deeper integration between additive manufacturing, responsive design, energy generation and collection, and embedded sensors. With each iteration, the productivity and application of this novel cyber-physical system improves and further solidifies the framework for a larger set of alternative plants, designs, materials, and processes yet to be explored.

FUTURE PERSPECTIVES

The 3D printed ceramic green wall is part of the Urbinat Project Nature Based Solutions Catalogue. The solutions in this catalogue are to be co-selected by Nantes, Porto and Sofia citizens for implementation in deprived areas of their cities. The Catalogue Solutions will be co-selected in October 2020 and co-implemented in 2021. Urbinat Project focuses on the development of co-creation processes to stimulate neglected areas Urban Regeneration.

Figure 15

URBiNAT

The URBINAT project has received funding from the European Union's Horizon 2020 research and innovation programme under the grant agreement No 776783

ACKNOWLEDGEMENTS

Our thanks to Paolo Bombelli from the Department of Biochemistry at Cambridge University for his pertinent and insightful input. Also, our deep gratitude to Toni Cumella of Cumella Ceramics, for his contribution to material research and his assistance in the firing and glazing processes. The cyber-physical platforms were developed with the efforts and support of our partner Amaisys and the overall project management was carried out by Solartys.

Figure 14
Data sensor readings of the prototype validation exhibiting marked improvements after March 12, a day when a system redesign was initiated.

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