Smart City Digital Twin Convergence Workshop
FINAL REPORT

NSF Environmental Sustainability (EnvS)
Award #1929928

Georgia Institute of Technology
Atlanta, GA
September 16-17, 2019

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This report can be accessed at: www.smartcitydigitaltwins.gatech.edu/NSF-SCDTConvergence
NSF 2019 Sustainable Urban Systems Conference & Workshop Awards

Acknowledgements

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Georgia Tech Smart Cities & Inclusive Innovation

Members of the Georgia Tech Network Dynamics Lab

Georgia Tech CODA Building (This convergence workshop took place in a new convergence innovation facility—the Coda Building—in Midtown, Atlanta, adjacent to the Georgia Tech campus. The Coda Building is designed to act as a convergence innovation collaboration hub. It is organized according to interdisciplinary research areas and puts academic researchers together in close proximity with industry practitioners from large established companies and small entrepreneurial ventures.)

This material is based upon work supported by the National Science Foundation under Grant No. 1929928. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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1. Introduction

Cities around the world are increasingly integrating socio-technical advancements to transform their urban infrastructure systems toward smart cities. As the world continues to urbanize, convergent engineering of urban systems is needed to ensure such transformative developments champion sustainability principles that benefit citizens and societies at large. The successful transformation of a city into a smart and sustainable city requires both: (1) convergence of a variety of academic disciplines and practitioner expertise from city stakeholders; and (2) convergence of cyber-enabled technology systems at the human-infrastructure interface, creating a new virtual system that we refer to as a *Smart City Digital Twin*.

Digital twins are cyber-physical computational systems that pair the virtual and physical worlds using iterative feedback loops between measurable data acquired from the physical world and simulated processes and behaviors acquired from the virtual world. The Smart City Digital Twin Convergence Workshop organizers are working to advance these systems, which integrate cyberinfrastructure-enabled technologies—such as Virtual Reality (VR), Augmented Reality (AR), and Internet of Things (IoT)—into multiscale urban systems to enable a digital replica of a city. When we introduced the concept of Smart City Digital Twins [1], we described them as progressively informed by real city data through real-time spatiotemporal sensing, enabling engineers and others to eliminate the levels of abstractions traditionally assumed in modeling various city infrastructure systems. Smart City Digital Twin infrastructure, cognizant of a city's infrastructure performance, human dynamics, and interactions and interdependencies in time and space, thus becomes a more accurate virtual representation of a city's actual systems, over time developing an ability to anticipate changes of state in such systems.

Smart City Digital Twins transform our ability to accurately model, predict, and adapt to emergent behaviors in the physical world. A short animated video describing smart city digital twins and their application is available at: www.smartcitydigitaltwins.gatech.edu. With a vision to advance understanding, development, and application of Smart City Digital Twins, this Smart City Digital Twin Convergence Workshop (see Appendix A for workshop agenda) brought together experts from academia, industry, municipalities, and nonprofit organizations from several of the largest metropolitan statistical areas (MSAs) in the United States [2] (see Appendix B for list of workshop participants) to begin to develop a convergent technological framework for delivering smarter services through Smart City Digital Twins. The workshop enabled us to explore opportunities in basic research occurring at the intersection of infrastructure systems, human systems, and technology systems and to carry out the groundwork to establish a community of thought leaders in this emerging area of inquiry.

Smart City Digital Twins represent a new form of critical infrastructure, transforming city operations and management. Existing knowledge on the requirements for single infrastructure Smart City Digital Twins was shared, including emerging testbeds in the areas of energy, water, and mobility. This sharing of knowledge provided fundamental insights on multi-infrastructure interdependencies, as well as how human-infrastructure interactions can be sensed, analyzed, controlled, and visualized using Internet of Things (IoT) technology. We engaged invited interdisciplinary experts, industry practitioners, and government officials in facilitated discussions to (1) begin to develop a framework for understanding Smart City Digital Twin efforts and (2) to envision future Smart City Digital Twin efforts that advance urban sustainability, resilience, and social well-being.

Improving our understanding of, developing, and applying Smart City Digital Twins addresses the National Academy of Engineering (NAE) Grand Challenges of Enhancing Virtual Reality and Restoring/Improving Urban Infrastructure [3], while simultaneously incorporating the NSF Big Ideas of Harnessing the Data Revolution and the Future of Work at the Human-Technology Frontier [4]. Taken together, these convergence workshop activities provided a critical coalescing force as a new discipline surrounding Smart City Digital Twins emerges. Smart City Digital Twinning efforts have the potential to transform the livability, sustainability, and resilience of cities, creating new business opportunities for companies of all sizes, new forms of citizen engagement by communities, creative forms of pedagogical practices in academia, and new approaches to city operations and management by governments. As an indicator of this potential, a recent analyst report predicts that 500 cities will have smart city digital twins by 2025 [5].

1.1. Opening Remarks

The workshop was initiated with opening remarks from Georgia Tech and City of Atlanta leaders:

- Raheem Beyah, Vice President for Interdisciplinary Research, Georgia Tech
- Tye Hayes, Chief Technology Officer, City of Atlanta
- Don Webster, Karen & John Huff Chair, Civil & Environmental Engineering, Georgia Tech

Prof. Beyah, Vice President for Interdisciplinary Research, Georgia Tech.

Opening remarks by Tye Hayes (left), Chief Technology Officer, City of Atlanta; and Prof. Webster (right), Karen & John Huff Chair, Civil & Environmental Engineering, Georgia Tech.

1.2. Workshop Purpose & Goals

Following the opening remarks, PI John E. Taylor (Frederick Law Olmsted Professor, Civil & Environmental Engineering, Georgia Tech) and Co-PI Debra Lam (Managing Director, Smart

Cities & Inclusive Innovation, Georgia Tech) gave an overview of the workshop purpose and goals (see Appendix C for slides presented):

Overview of the workshop purpose and goals by Prof. Taylor (left); and composition of workshop participants (right).

The workshop opened with discussion that the emerging field of Smart City Digital Twin research is moving forward rapidly, but with high levels of abstraction and narrow foci on single infrastructure system digital twinning. Moreover, the field moves forward without a shared understanding or definition of the stages of Smart City Digital Twin evolution, making it difficult to share, compare or build upon results. Such a shared understanding, framework, and road map will be needed to inform, stimulate, and educate the scientific community working in this area and the stakeholders impacted by it. In this coalescing workshop, we rationalized discussions of smart cities to advance a smart city agenda for all cities through the following focal activities:

1. Share state-of-the-art knowledge on on-going single infrastructure Smart City Digital Twinning across a community of scholars, practitioners, and government officials,
2. Discuss a convergent framework for describing and understanding Smart City Digital Twin evolution.
3. Discuss and develop a forward-looking plan to guide future Smart City Digital Twin efforts.

In order to address these goals, the workshop was organized into the three parts. Presentations followed by questions and answers and discussion in Part 1, and by breakout groups with facilitated brainstorming and gathering together in a full group for discussion in Parts 2 and 3. We adopted and followed the Georgia Tech anti-harassment policy (see Appendix D) for all aspects of the workshop. The Anti-Harassment Policy at Georgia Tech includes details on why and how harassment in any form is prohibited at Georgia Tech, a description of the types of situations that represent harassment, and how to report instances of harassment. This policy was distributed to workshop participants prior to attendance at the workshop and made available during the workshop. The three constituent parts of the workshop described above are summarized below.

Part 1 :: Smart City Digital Twin State-of-the-Art (September 16, 8:30am – 12:30pm) – Following a general introduction to the workshop and participant introductions, conference style presentations of current single infrastructure system Smart City Digital Twin efforts across academic, industry, and government perspectives took place. This was followed by technology demonstrations of single infrastructure digital twinning efforts. The State-of-the-Art presentations and demonstrations were followed by a discussion of the barriers, challenges, and opportunities associated with Smart City Digital Twinning to capture perspectives across disciplines and across academia-industry-government boundaries.

Part 2 :: Designing a Smart City Digital Twin Framework (September 16, 12:30pm – 5:00pm) – A plenary presentation provided direction on how the group was to be broken up into smaller groups to brainstorm. Then, workshop style breakout sessions established the components of a Smart City Digital Twin framework that would enable understanding and comparison of Smart City Digital Twinning efforts across cities, which may also be useful in the future to enable plotting a city's digital twin evolution. These elements were discussed in reports to the full group, which were also followed by a discussion of those elements that are most critical to understanding and comparing Smart City Digital Twin development efforts.

Part 3 :: Smart City Digital Twin Road Mapping (September 17, 8:30am – 12:30pm) – This session opened with a review of the results from Parts 1 & 2, and the results of a workshop on "From Science Fiction to Smart Cities" organized by PI Taylor and Co-PI Derrible in 2017. This was followed by workshop style breakout sessions to plot the key barriers and forward development trends of Smart City Digital Twins. This was followed by reports to the whole group and further discussion to begin the process of developing a road map of the key trends for future Smart City Digital Twinning efforts.

2. Smart City Digital Twin State-of-the-Art

A total of 15 conference style presentations of current single infrastructure system (i.e., mobility, water, and energy) Smart City Digital Twin efforts took place followed by seven smart city digital twin technology demonstrations. The State-of-the-Art presentations and demonstrations were followed by panel discussions on the barriers, challenges, and opportunities associated with Smart City Digital Twining to capture perspectives across disciplines and across academia-industry-government boundaries.

2.1. Mobility Infrastructure System Digital Twins Presentations

- Sybil Derrible, Associate Professor, University of Illinois, Chicago :: *Digital Twinning Mobility*
- David Emory, Director, Technology Strategy and Innovation, MARTA
- Lillie Madali, Smart City Program Director, City of Atlanta
- Jane Mcfarlane, Director of Smart Cities Research Center, University of California, Berkeley :: *Big Data Solutions for Mobility Planning*

Dr. Mcfarlane presenting *Big Data Solutions for Mobility Planning*.

2.2. Water Infrastructure System Digital Twins Presentations

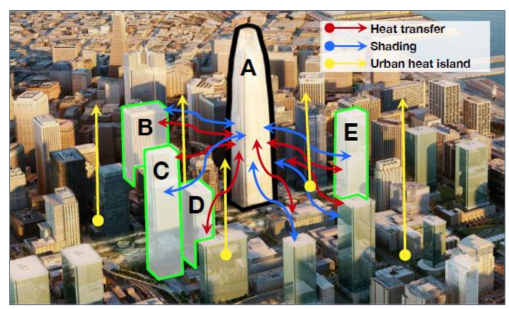
Grace Simrall presenting *The Road to a Smart City.*

- Stephen Bourne, Director and Research and Development Chair, Atkins :: *Using Holistic City Simulation to Test Resilience Adaptation Strategies*
- Patricia Culligan, Robert A. W. and Christine S. Carleton Professor of Civil Engineering; Chair, Department of Civil Engineering and Engineering Mechanics, Columbia University :: *Water Infrastructure Systems: Urban Stormwater Management*
- Michael Diaz, AVP/Area Manager, Arcadis :: *Digital Twin Technology - WATER*
- Jonathan Levy, Open Data Program Manager, City of Chicago
- Grace Simrall, Chief of Civic Innovation, Louisville Metro Government :: *The Road to a Smart City*

Michael Diaz presenting *Digital Twin Technology – WATER.*

2.3. Energy Infrastructure System Digital Twins Presentations

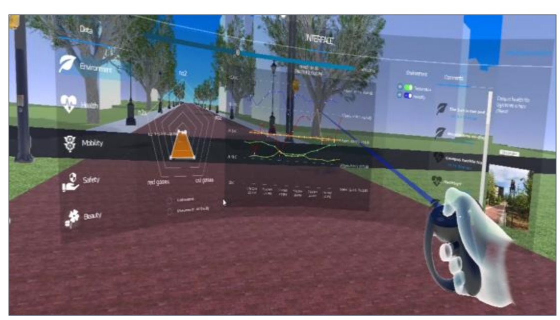
- Sam Edelstein, Chief Data Officer, City of Syracuse :: *Digital Twins in Syracuse, NY*
- Rishee Jain, Assistant Professor, Civil & Environmental Engineering, Stanford University :: *Urban Informatics: Harnessing Data & Digital Twins to Understand People, Buildings and Energy Systems in Cities*
- Laura Meixell, Enterprise Data Architect, Allegheny County Department of Human Services :: *Towards a Digital Twin*
- Jack Montgomery, Digital Innovation & Thought Leadership, Siemens Management Consulting
- Josh Sperling, Urban Futures & the Energy-X Nexus Fellow, National Renewable Energy Laboratory (NREL) :: *Urban Futures and the Energy- X Nexus*



Data-driven Urban Energy – Simulation (DUE-S), Stanford Urban Informatics Lab

2.4. Smart City Digital Twin Technology/System Showcase

- Burcin Becerik-Gerber, Professor of Civil and Environmental Engineering, University of Southern California
- Michael Hunter, Professor, Civil & Environmental Engineering, Georgia Tech
- Madhav Marathe, Division Director and Professor, Biocomplexity Institute, University of Virginia :: *Synthetic Living Social Habitats*



Georgia Tech Smart Corridor Digital Twin, Network Dynamics Lab

- Neda Mohammadi, City Infrastructure Analytics Director, Network Dynamics Lab, Georgia Tech :: *Smart City Digital Twins: Spatiotemporal Knowledge Discovery & Interventions*
- Kouros Mohammadian, Professor and Department Head, Civil & Materials Engineering, University of Illinois, Chicago :: *Agent-based Dynamic Activity Planning and Travel Scheduling (ADAPTS)*
- Mina Sartipi, UC Foundation Professor, Computer Science and Engineering, University of Tennessee-Chattanooga
- Keith Swearingen, Office of Chief Information Officer, National Aeronautics and Space Administration (NASA)

3. Smart City Digital Twin Framework

Three concurrent breakout sessions were organized to establish the components of a Smart City Digital Twin framework that would enable digital twinning efforts across cities followed by a report-back to and discussion by the entire group to identify those elements that are most critical. Each breakout group focused on discussions around one of the Infrastructure System Digital Twins (i.e., Water, Mobility, or Energy) from the perspective of: (A) Distribution Efficiencies, and (B) Interoperability using the Question Prompt Lists below:

(A) <u>Distribution of Efficiencies:</u>

- Based on the state-of-the-art knowledge discussed, and your own expertise, how could the infrastructure system digital twin focus in your breakout discussion benefit from or be extended by what you learned today or based on your expertise?
- What new enabling technologies/features/functionalities or opportunities can you identify?
- What are barriers to or risks associated with each?

Panel discussions on the barriers, challenges, and opportunities associated with Smart City Digital Twining for the Mobility Infrastructure System.

(B) <u>Interoperability:</u>

- How do Smart City Digital Twin technologies and systems need to be adapted to integrate and/or function across multiple interdependent infrastructure systems?
- What barriers, risks, or other considerations are associated with each adaptation?

3.1. Water Infrastructure Systems

Digital twins offer new possibilities for the water sector in cities. Current urban water infrastructure systems often lack borders. There is a difference between water supply and water management and flooding that can be resolved. Different usage levels are often reported at a certain timescale (e.g., daily usage reports) and the water industry is constantly being reactive. There is a need to be more proactive and examine whether or not it is necessary for cities to worry about real-time data modeling for water. Knowing that water's final destination are homes and businesses, digital twins can help determine what information is essential (i.e., water could be tracked hourly, every half-hourly) or the system could have real-time smart meter reports from citizens. Digital Twins could facilitate the simulation of rain-falls as well as implementation of water/storm water re-routing technology.

Digital Twins can support additional checkpoints for the water systems by evaluating the performance of smart meters on measuring the water flow, their effectiveness for small measurements, and their effectiveness for point of connection (what enters the home/business) versus point of use (what comes out of the tap). In this way, the Digital Twin can be used for asset management (e.g., replacing pipes, etc.). However, there are some negative aspects including the cost for homeowners/ businesses; and the threat of it being used as a proxy for localizing people.

Digital Twins can be a baseline for developing a framework for optimized data collection from the water infrastructure systems. Currently, despite some commonalities between cities, cities have different compositions. This will further enable water prioritization for different agents in the city. Some common characteristics that would be included in such framework include: Agents, Geography, System, and Interdependencies.

Digital Twins can also address a number of future concerns about the urban water infrastructure systems such as collecting upstream water data and determining ways to use less water. It can further inform the growing need to invest in storm water infrastructure. Digital Twins can optimize and move our cities forward positively from a societal impact standpoint, but there are also malicious ways to use these Digital Twins. Therefore, among the challenges, security is an important issue. A side effect is that a lot of the data from the infrastructure may not be readily available. We also need to be careful how the data is being managed and who is using the data. Many citizens are not open to data sharing and do not wish others to know about their usage data.

3.2. Mobility Infrastructure Systems

Digital Twins for mobility infrastructure systems can help proactively resolve transportation issues (e.g., see pattern and fix it before something happens) as the transportation system collapses twice a day, despite the use of models since the 1950s. There are currently no major mode shifts away from automobiles. How do we enable radical changes? Does data availability improve our ability to achieve radical changes? Modeling mobility using activity patterns is different than using shared-economy and, in general, access to individuals' location data is challenging. The new generation may be willing to give out their location, and may also expect to be rescued if something happens to them. Mobility is contextual and we need to make the modal shifts more competitive, incentives and nudging do not always work. For example, the complexity of routing system in the mobility mobile apps often requires abstraction and elimination of context (e.g., start/closing time and location of grade schools). As a city we need to decide how complex/contextualized are we defining our mobility network. Determining the fidelity of the Digital Twins is important (i.e., time scale, spatial characteristics, data format issues, etc.)

Digital twins can enable more data-driven modeling (observe real-time vs. simulation for traffic). This can extend the landscape of what can be done (e.g., correlate potholes, schools, etc.) and bring the humans in the loop, address equity issues, and reach global optimum for the individuals (e.g., impact of adding one bus user on travel time) they can identify the impact of mobility on individual safety and wellbeing (e.g., Google map makes you use local roads, which may result in increasing safety risks and decreasing air quality). However, poorer communities do not have apps; many use burner phones, so there are equity considerations.

Digital twins need to leverage municipal IT departments that tend to cut across all departments. The opportunity lies between mobility and telecommunications. This is already being used, but could be even better. The Interstate-85 bridge collapse in Atlanta in 2016 resulted in significant congestion, but not nearly as much as it would have been if people did not have phones to adapt/adjust their travel.

Digital twins can enable testing of “what if?” scenarios and innovative strategies. For example: what if we make the transit free on certain days of the week? Or, what if we use transport funds to help public schools, which will encourage people to live downtown, which will reduce congestion. In addition, such understandings can be transferred to other (integrated) infrastructure systems and inform mutual decision making among departments (e.g., using mobility digital twin to help water digital twin and vice versa).

There exists a number of challenges in mobility infrastructure digital twinning including:

- Loss of data and data standardization;
- Lack of official definitions/ontologies as most city data is currently not sorted. We have bottom-up data, not top-down sorting of city data, therefore, models need to be more data-driven and less synthesized. "Data drives model; model should not drive data". Often times, not only does the data differ, but also the model goals differ. We need to integrate both data and goals and implement additional cost/benefit analyses;
- Data privacy and ownership (departments need to be able to exchange data more easily);
- Cybersecurity, which is not yet implemented because of possible breaches (not feasibility issues). We need to determine what is the level of accuracy of the digital twin in different dimensions involving personal concerns;
- Need to execute major shift from publicly-owned to privately owned data; data management challenges such as data storage/usage and merging of various data sources since coupling models is non-trivial;

- Lack of heterogeneous data standardization and data fusion challenges due to variety of sensors/vendors (temporary barrier);
- Interoperability problems between departments, utilities, and private sector partnerships.
- What is "smart city ready"? When can we employ sensors, what data, what infrastructure is available that can provide a feed?
- Lack of integration of behavioral data statistics. Digital twin models need to be wary of how bad information/deception can exacerbate existing problems.

Interoperability is one of the most important aspects in mobility infrastructure system digital twinning. Some of the major challenges include structural departmentalization of cities (budgets, separate staff), ownership of data in both public and private sector (need better specs for projects so city owns the data), and generational gap in data operability (i.e., different tactics for different populations/generations for mobility/location data is needed). Government entities would prefer not to be silo'ed, but need a framework and incentives to get involved. For example, Atlanta’s MARTA perspective is that it is not that departments don't talk to each other; systems are not compatible between departments. Scheduler and bus location systems have different vendors & different IDs. As a result, any new systems must be compatible with at least one existing system. Mobility digital twins should also ultimately be operable between neighboring states. Interoperability between city systems and private systems is also necessary, otherwise voluntarily shared geographic in information can be dangerous; we need to determine how to use the network more effectively?

3.3. Energy Infrastructure Systems

At the top level, having the city practitioners in the room helped to bring us back down to reality and make sure we focus on how we effectively partner between the public, the private, and the research spaces. What is the cadence of interactions? What is the feedback loop? And what are the expectations of each other? Elements of real-time varies based on seasons. How do we use these variations in digital twins to predict over different time horizons or seasonal conditions or even population groups (e.g., low income)? Citizen behavior patterns differ. How do we include that in a digital system that may not enable national standards to always work? Concerns were raised regarding benchmarking, identifying anomalies, issues of security, vulnerability, future uncertainty, and identifying the knowledge-based understanding. How do we use the digital twin as a management tool with the utilities across different scales of campuses, district-level, and cities? How can a digital twin play a role in achieving net zero by 2030 (achieving sustainability goals)? What the role is of centralized versus decentralized? What are the symbiotic opportunities and what is the interoperability between these systems?

Barriers and risks involved in digital twinning of the energy infrastructure systems include the level of details. We need to have humans with domain expertise to bridge gaps and not just rely on the models. We need to understand the difference between areas (suburban vs. urban) to achieve generalizability. Developing digital twins for the energy infrastructure systems can enable preparation and access to safe and efficient heat/energy services during extreme weather changes (seasonal variation) and facilitate modeling and management for municipalities/campus/community scales of buildings including finding anomalies and unexpected or easy to fix issues during the monitoring process. For example, through the process of trying to model city buildings, the city of Pittsburg identified a commercial refrigeration facility using city energy for free.

Digital twins can provide more context-specific solutions that are more location specific and contextualize issues and opportunities as (1) national standards don't always work, and (2) one model does not fit all. This allows for better understanding of building benchmarking that is local/regional; and identifying anomalies for locating vulnerabilities and increasing security. Digital twins can help understand more broadly what is going on in cities beyond the individual building as we replace buildings across a community, slowly making the city smart.

Digital twins allow the city managers to monitor trends and forecast climatic issues followed by testing "what if?" scenarios to enable (1) adaptation to the current physical environment, and (2) operational energy management by incorporating more recent data that represent more realistic patterns. They can enable predictive modeling for when to start chiller plants and shut down chiller plants. Digital twins also have the potential to become a development platform that engages actors who are incentivized to take part in platform (i.e., buildings decide to give data to the platform) by understanding the needs of surrounding buildings. Maybe they can develop their own exchange between buildings (i.e., extra cooling capacity to share with nearby building) to better understand this symbiotic relationship and extend this to an exchange of physical resources (integrating infrastructure around energy, water, nutrients for food).

Interoperability in energy infrastructure system digital twinning entails various challenges some of which relate to current unanswered questions/inherent tensions such as:

- How to develop models that are locally relevant and at the same time extensible to other places? (i.e., can insights from Savannah be extended to San Francisco? Can we establish generalizable factors that shape the energy outcomes? What can we learn from across sectors? When can we pick up patterns of generalizability? Can digital twin modeling approaches give us the necessary cross-scale information (i.e., from street- to district- to region- to state- levels) to address the increased complexity and emergent behaviors that are unpredictable.
- Being hyper-focused on model accuracy with the assumption that more detailed data will simply solve more problems. Not having enough data is not the major issue with model accuracy. Given that most simulated results are not accurate, there can be substantial differences that require revised and refined energy modeling. If standard energy models remain the same, relative comparisons between the results of the alternative futures are still useful. Another data-related issue in the energy infrastructure system digital twinning is the occupancy data in the sense that due to many different preferences and personalities it requires grouping people by similar types of preferences. Moreover, interactions between different building sub-systems needs to be incorporated into the models, which raises

accuracy issues. How exact do we need to be (2 decimal points? 6 decimal points?)? Should we build a model that is problem specific? Is the relative understating generated by a more generalized model is sufficient? Lack of consistency between buildings data exacerbates this problem. Every city has different sources, formats, and data ontology extending from one state or city to the next is almost impossible, thus we need to segregate the data based on inherent different characteristics. Datasets are built in a way that they can be linked (everyone is making them up as they go along due to local conditions such as legal/privacy concerns (dealing with tax and personal information) and the necessity for acquiring numerous consents from people who probably will not give consent. These issues often lead to excessive focus on data without enough focus on the problem at hand.

- Digital twins can be beneficial in understanding qualitative characteristics of energy consumption such as recreating human experiences in buildings and building better models. The question will be raised, "Are Smart City Digital Twins able to meaningfully deal with city scale complexities?" Let's say we are able to do simulations better than we have ever done in the past… what does that change? Where does that leave us? To simulate things to solve a set of problems that we are not that clear about is not helpful to society. It's more important to focus on the problems that we are trying to address. There are fundamentally different problems and the ways would we approach them and the tools we would use will be different. Analysts need to be mindful of treating "smart" as better simulation capabilities. Even by improving simulations, by making the next best simulation it may work in the short term but does nothing to predict systematic level changes in the longer term.

Some of the potential unintentional consequences of Smart City Digital Twins include:
- Digital twins can solve problems, but they also create complexity and lots of new problems; having/collecting/aggregating more data creates new and complex problems such as Cyber-security, privacy, surveillance; more energy use from computers processing computations; and disagreement over consideration of the inherent risks of deploying/developing technologies and where responsibility lies. This is a very multidisciplinary issue and requires collaboration initiatives and practices.
- Smart City Digital Twins enable us to explore futures and can help us understand how to make better decisions; Smart City Digital Twins create means by which we can inform people about XYZ (i.e., carbon footprint). Making data more open inherently has risks and we need to invest energy and attention to be more aware of such risks. One specific example is dealing with a localized cloud instead of putting data in a hackable cloud (need to have adaptable systems). However, more broadly, the bigger question is whether or not we should move forward with this technology, and the answer to this is very scope and context specific. From the industry perspective Smart City Digital Twins are viewed as very valuable enabling streamlining, and aggregation of data to pull useful information and make it as tailored or as broad as desired. Digital twins can help model and figure out if blackouts are going to be an issue in the foreseeable future.

- Can we come up with the right questions that need to be addressed by the research community? It is often challanging to convince engineers why democracy should matter to them (i.e., quick to dismiss why we should be having conversations about community surveillance or why the municipality is not working faster to get a permit). There seems to be a lack of understanding between academia and municipalities. From the municipality perspective, they look back to academia to sort through what the private sector is giving them (a new technology vs. repackaged technology); from the academic perspective, researchers can be more effective by collaborating with city practitioners. The academic community needs to further participate in existing democratic processes to understand different perspectives. From the government perspective, digital twins helps us think about how we create conditions that operations are running more efficiently, but governments sometimes do not operate as fast or as efficiently as possible by design.
- A number of other big questions are; does anyone understand what we mean by Smart City Digital Twins? How does someone opt out from a model that is trying to track everything across a city for decision making? Realistically, cities are not just going to have robust cyber security systems. Something bad is going to happen—an important part in creating Smart City Digital Twins to support decision making is ensuring that we have contingency plans for operations so we can continue to operate without the digital tools (that are helping us) so that we are not completely reliant. We want data to be more interoperable and have multiple different points of access, but does this at the same time make us more susceptible? Academia is interested in deploying sensors, but the technical capacity might not be there for some smaller towns. Lessons learned in these types of partnerships we often not having discrete questions well defined from the outset leading to a bunch of sensors being deployed with no maintenance. Collaboration and interaction between industry/government and academia is extremely difficult. We need to encourage analytic deliberation. For example, infusing analysis into democratic processes of decision making and having some humility in our approaches (i.e., starting with "this is what we understand" and being able to iterate together as a feedback loop). Data is never going to be perfect and there is a need to have both sides engaged to assess if we feel comfortable with this level of uncertainty. The government sector generally would like the partnership to be very outcome focused. With the SCDTs there is an opportunity to move from a donor driven approach in research to a market-based funding strategy and promote entrepreneurial opportunities for students.

4. Envisioning the Future of Smart City Digital Twinning

After reviewing the results from the breakout sessions and plenary discussions, a second set of workshop style breakout sessions were formed to discuss the key forward development trends of Smart City Digital Twins. This was followed by reports back to the entire group and (See Appendix E for details of the Needs, Prioritization and Features of Smart City Digital Twins discussed). This discussion led to the following insights and ideas for future investigation:

- *"Smart City Digital Twin" is not a well-defined concept*. Fundamental research questions need to be defined. Among the many discussions occurring in academia, industry, communities and government, it can be a challenge to determine what is a Smart City Digital Twin? Many smart city efforts are being called digital twinning. Are maps, phones, and/or better websites digital twins? There are too many people defining Smart City Digital Twins differently. Future efforts need to clarify and bound what is meant by Smart City Digital Twin, and efforts need to be made to broadly disseminate such a definition.

- *The implementation of Smart City Digital Twins should be grounded in objectives that are rooted in real world problems*. The objectives must be clear and valuable, leading to improved livability, sustainability, and resilience while addressing social and economic concerns. City governments recognize there are challenges that need to be figured out technologically speaking, but running experiments in the real world can scare citizens. More time needs to be spent in problem identification working with various stakeholders. Efforts should be made to do some of these experiments virtually using Smart City Digital Twins, but questions remain as to how such research can inform and influence decision making. Risk and security issues should be at the forefront when evaluating Smart City Digital Twin objectives. Convergent approaches are needed that involve actors from academia, industry, community groups, national labs, government entities, and any other relevant stakeholders.

- *The stages of Smart City Digital Twin evolution should be determined based on the problem(s) being addressed and outcomes anticipated*. The stages should be influenced by the degree of complication, by the degree of accuracy needed, by the availability of the necessary technology and supporting infrastructure, by the geographic scale, by the degree of fatigue/age/maintenance required, by the degree of integration/coupling/interactivity of infrastructure systems involved, by how far into the future the system can or needs to predict, and by the type of data needed (virtual/simulated vs. from citizens). Additionally, livability, sustainability, and resilience are broad and ambitious goals, we need to define steps along the way to be certain that the Smart City Digital Twin stages of evolution are carrying society toward these broad objectives. Finally, validation of the Smart City Digital Twin needs to happen continuously within and as we achieve each stage of evolution.

- *Attributes of the Smart City Digital Twin need to be considered as the concept evolves.* The degree to which the real system is dependent on the virtual system (and vice-versa) needs to be established. The degree to which the system can adapt/self-correct/compensate needs to be understood and implemented carefully. The attributes may need to vary as the boundary of what constitutes the "city" are fuzzy and may evolve (urban vs. quasi-urban vs. rural). The connectivity (e.g., 5G) need to be carefully considered, as well as the digital literacy of the citizens. The Smart City Digital Twin should be able to quantify uncertainty and bias. The flow of data into the Smart City Digital Twin will need to be managed/maintained. Approaches for knowledge representation need to be developed.

5. Closing Discussion & Next Steps

Cities are transforming as they deploy technologies, develop systems, and collect and analyze data to mirror actions in their urban systems. This effort has been described as creating a Smart City Digital Twin and it is predicted that 500 cities will deploy Smart City Digital Twins by 2025 [5]. However, we need to ensure such transformative developments champion sustainability principles that benefit the citizens and societies at large. With a vision to advance understanding, development, and application of Smart City Digital Twins, this Smart City Digital Twin Convergence Workshop brought together experts from academia, industry, municipalities, and nonprofit organizations to begin to develop a convergent technological framework for delivering smarter services through Smart City Digital Twins. We explored basic research occurring at the intersection of infrastructure systems, human systems, and technology systems, establishing a nascent community of thought leaders in the process.

At the workshop, existing knowledge on the requirements for single infrastructure Smart City Digital Twins was shared, including emerging testbeds in the areas of energy, water, and mobility, as well as other technology development efforts. This sharing of knowledge provided fundamental insights on multi-infrastructure interdependencies. We engaged invited interdisciplinary experts, industry practitioners, and government officials in workshop-style facilitated discussions to (1) begin to develop a framework for understanding Smart City Digital Twin efforts, and (2) to envision future Smart City Digital Twin efforts that advance urban sustainability, resilience, and social well-being.

Smart City Digital Twinning efforts have the potential to transform the livability, sustainability, and resilience of cities, creating new business opportunities for companies of all sizes, new forms of citizen engagement by communities, creative forms of pedagogical practices in academia, and new approaches to city operations and management by governments. However, this workshop makes it clear that there are still many fundamental questions surrounding the scope and application of Smart City Digital Twins that need to be resolved.

Notwithstanding the rapid proliferation of Smart City Digital Twins anticipated in cities around the world, there is an urgent need to: (1) define and disseminate a definition for Smart City Digital Twins that can be used to understand and compare efforts across cities, (2) to set specific objectives for Smart City Digital Twin implementation projects that equitably and responsibly address problems agreed to across stakeholder groups, (3) to plan out the stages of Smart City Digital Twin evolution with continuous validation efforts, and (4) to include attributes that allow for, for example, uncertainty quantification, to ensure that the Smart City Digital Twin can achieve the intended benefits in a manner that is equitable to all citizens. Such efforts need to include community groups to gather the citizen perspective on proposed Smart City Digital Twin advancements.

The Smart City Digital Twin Convergence Workshop organizers and participants anticipate that this workshop will be the first of many discussions and future convergent endeavors to define, understand and prepare the groundwork for Smart City Digital Twins that positively and equitably impact the livability, sustainability, and resilience of our cities.

6. References

[1] Mohammadi N, Taylor JE. Smart city digital twins. 2017 IEEE Symp. Ser. Comput. Intell., IEEE; 2017, p. 1–5.

[2] US Census Bureau. Metropolitan and Micropolitan. [Online] www.census.gov (accessed May 2, 2019).

[3] Ramaswami A, Bettencourt L, Clarens A, Das S, Fitzgerald G, Irwin E, et al. Sustainable urban systems: articulating a long-term convergence research agenda. A report by the Advisory Committee for Environmental Research & Education 2019.

[4] Mervis J. NSF director unveils big ideas. Science 2016;352:755 LP – 756. doi:10.1126/science.352.6287.755.

[5] ABI Research. 2019. “Digital Twins, Smart Cities, and Urban Modeling” Report AN-5239, September 2019.

Appendix A

Smart City Digital Twin Convergence Workshop
CODA Building, Floor 2, Room 230
Atlanta, GA 30308

DAY 1 — Monday, September 16

7:30am **Registration, Networking + Breakfast**

8:00am **Welcome + Opening Remarks**

Raheem Beyah, Vice President for Interdisciplinary Research, Georgia Tech
Tye Hayes, Chief Technology Officer, City of Atlanta
Don Webster, Karen and John Huff Chair, Civil & Environmental Engineering, Georgia Tech

8:30am **Introduction to Workshop Purpose and Goals**

Debra Lam, Managing Director, Smart Cities & Inclusive Innovation, Georgia Tech
John Taylor, Frederick Law Olmsted Professor, Civil & Environmental Engineering, Georgia Tech

PART 1: CURRENT SMART CITY DIGITAL TWIN EFFORTS

8:45am **First Panel – Mobility Infrastructure System Digital Twins**

Sybil Derrible, Associate Professor, University of Illinois, Chicago
David Emory, Director, Technology Strategy and Innovation, MARTA
Lillie Madali, Smart City Program Director, City of Atlanta
Jane Mcfarlane, Director of Smart Cities Research Center, University of California, Berkeley

9:45am **Second Panel – Water Infrastructure System Digital Twins**

Stephen Bourne, Director & Research and Development Chair, Atkins
Patricia Culligan, Robert A. W. and Christine S. Carleton Professor of Civil Engineering; Chair, Department of Civil Engineering and Engineering Mechanics, Columbia University
Mike Diaz, AVP/Area Manager, Arcadis
Jonathan Levy, Open Data Program Manager, City of Chicago
Grace Simrall, Chief of Civic Innovation, Louisville Metro Government

10:45am **Networking Break**

11:00am **Third Panel – Energy Infrastructure System Digital Twins**

Sam Edelstein, Chief Data Officer, City of Syracuse
Rishee Jain, Assistant Professor, Civil & Environmental Engineering, Stanford University
Laura Meixell, Enterprise Data Architect, Allegheny County Department of Human Services
Jack Montgomery, Digital Innovation & Thought Leadership, Siemens Management Consulting
Josh Sperling, Urban Futures & the Energy-X Nexus Fellow, National Renewable Energy Laboratory (NREL)

12:00pm	**Working Lunch – Smart City Digital Twin Technology/System Showcase**
	Burcin Becerik-Gerber, Professor of Civil and Environmental Engineering, University of Southern California *Michael Hunter*, Professor, Civil & Environmental Engineering, Georgia Tech *Madhav Marathe*, Division Director and Professor, Biocomplexity Institute, University of Virginia *Neda Mohammadi*, City Infrastructure Analytics Director, Network Dynamics Lab, Georgia Tech *Kouros Mohammadian*, Professor & Dept. Head, Civil & Materials Engineering, University of Illinois, Chicago *Mina Sartipi*, UC Foundation Professor, Computer Science and Engineering, University of Tennessee-Chattanooga *Keith Swearingen*, Office of Chief Information Officer, NASA

PART 2: TOWARD A SMART CITY DIGITAL TWIN FRAMEWORK

2:00pm	**Kick Off Smart City Digital Twin Framework Discussion Breakouts**
2:30pm	**Breakout Groups Discuss Elements of Framework**
4:00pm	**Breakout Groups Report**
4:30pm	**End of Day Summary, Discussion + Next Steps**
5:00pm	**Reception & Group Photo** (14th Floor Atrium)
	Merry Hunter Caudle, Program Manager – Economic Development, Georgia Tech

DAY 2 — Tuesday, September 17

7:30am	**Registration, Networking + Breakfast**
8:00am	**Discuss Smart City Digital Twin Framework Developed in Day 1 + Plan for Day 2**

PART 3: FUTURE OF SMART CITY DIGITAL TWINNING

8:30am	**Kick Off Smart City Digital Twin Forward Looking Breakout Exercise**
9:00am	**Breakout Groups Use Framework to Envision Future of Smart City Digital Twins**
11:00am	**Breakout Groups Report**
11:30am	**Closing Discussion + Next Steps**
12:30pm	**Adjourn/Lunch**

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Appendix B

NSF Smart City Digital Twin Convergence Workshop - List of Participants

	Last Name	*First Name*	*Title*	*Organization*
1	Andris	Clio	Assistant Professor	Georgia Tech, City + Regional Planning & Interactive Computing
2	Balchanos	Michael	Research Engineer II	Georgia Tech, Aerospace Engineering
3	Becerik-Gerber	Burçin	Professor of Civil and Environmental Engineering	University of Southern California (USC)
4	Beyah	Raheem	Motorola Foundation Professor & VP for Interdisciplinary Research	Georgia Tech
5	Blair	Scott	Managing Editor	Engineering News-Record (ENR)
6	Bourne	Stephen	Director & Research and Development Chair	Atkins
7	Chang	Michael	Deputy Director	Georgia Tech, Brook Byers Institute for Sustainable Systems
8	Chester	Mikhail	Associate Professor	Arizona State University
9	Cho	Nam	R&D Manager - Innovation, Lighting Division	Eaton Corporation
10	Culligan	Patricia	Robert A. W. & Christine S. Carleton Professor & Chair	Columbia University, Civil Engineering & Engineering Mechanics
11	Derrible	Sybil	Associate Professor	University of Illinois, Chicago, Civil and Materials Engineering
12	Diaz	Michael	AVP / Area Manager	ARCADIS
13	Duncan	Scott	Research Engineer II	Georgia Tech, Aerospace Systems Design Laboratory
14	Edelstein	Sam	Chief Data Officer	City of Syracuse
15	Emory	David	Director, Technology Strategy and Innovation	MARTA (Metropolitan Atlanta Rapid Transit Authority)
16	Evans	Jeff	Principal Research Engineer	Georgia Tech Research Institute (GTRI)
17	Evans	Scott	GIS Coordinator	Columbus Consolidated Government
18	Glus	Peter	Vice President	ARCADIS
19	Guhathakurta	Subhro	Professor and Chair	Georgia Tech, School of City & Regional Planning
20	Hayes	Tye	Chief Technology Officer	City of Atlanta
21	Heydarian	Arsalan	Assistant Professor	University of Virginia, Engineering Systems and Environment
22	Hibbard	John L.	Operations Division Director	Georgia Department of Transportation (GDOT)
23	Hu	Ming	Assistant Professor	University of Maryland, Architecture, Planning and Preservation
24	Hunter	Michael	Professor	Georgia Tech, Civil & Environmental Engineering
25	Jain	Rishee	Assistant Professor	Stanford University, Civil & Environmental Engineering
26	Jazizadeh	Farrokh	Assistant Professor	Virginia Tech, Civil & Environmental Engineering
27	Lam	Debra	Managing Director	Georgia Tech, Smart Cities and Inclusive Innovation
28	Levy	Jonathan	Open Data Program Manager	City of Chicago, Department of Innovation and Technology
29	Leynes	Gene W	Data Scientist	City of Chicago, Department of Innovation and Technology
30	Macfarlane	Jane	Executive Director Smart Cities	UC Berkeley & Lawrence Berkeley National Laboratory
31	Madali	Lillie	Smart City Program Director	City of Atlanta
32	Marathe	Madhav	Division Director	University of Virginia, NSSAC, BII
33	Meixell	Laura	Enterprise Data Architect	Allegheny County, Department of Human Services
34	Miles	Jeremy	Technical Operations Manager	Columbus Consolidated Government
35	Mohammadi	Neda	City Infrastructure Analytics Director	Georgia Tech, Network Dynamics Lab
36	Mohammadian	Kouros	Professor & Department Head	University of Illinois, Chicago, Civil and Materials Engineering
37	Montgomery	Jack	Digital Innovation & Thought Leadership	Siemens Management Consulting
38	Mujumdar	Vilas	Consulting Engineer, Former NSF ProgDir	Self Employed

39	Panknin	Josh	Director of Real Estate Technology Initiatives	Columbia University, Engineering
40	Rakha	Tarek	Assistant Professor	Georgia Tech, School of Architecture
41	Ravulaparthy	Srinath	Research Scientist	Oak Ridge National Laboratory
42	Renambot	Luc	Associate Research Professor	University of Illinois, Chicago
43	Rowan	Josh	General Manager, Renew Atlanta & TSPLOST	City of Atlanta
44	Sartipi	Mina	Professor	UT Chattanooga, Computer Science & Engineering
45	Simrall	Grace	Chief, Office of Civic Innovation and Technology	Louisville Metro Government
46	Sperling	Joshua	New Concepts Incubator, Urban Futures and the Energy-X Nexus	National Renewable Energy Laboratory
47	Stewart	Emma	Associate Program Leader, Defense Infrastructure	Lawrence Livermore National Laboratory
48	Swearingen	Keith	IT Specialist/Digital Transformation Center Rep	Office of Chief Information Officer (OCIO)
49	Taylor	John E.	Frederick Law Olmsted Professor & Associate Chair	Georgia Tech, Civil & Environmental Engineering
50	Tien	Iris	Assistant Professor	Georgia Tech, Civil & Environmental Engineering
51	Toelle	James Forrest	Information Technology Director	Columbus Consolidated Government
52	Varghese	Alan	Consultant	Berg Insight
53	Wang	Qi "Ryan"	Assistant Professor	Northeastern University, Civil & Environmental Engineering
54	Webster	Don	Karen and John Huff School Chair & Professor	Georgia Tech, Civil & Environmental Engineering
55	White	David	Research Professor of Electrical & Computer Engineering	Clemson University, Electrical & Computer Engineering

Georgia Tech School of Civil and Environmental Engineering
College of Engineering

Smart Cities and Inclusive Innovation

NSF

Smart City Digital Twin

Convergence Workshop

Georgia Tech
Columbia University
Stanford University
UIC

September 16-17, 2019

John E. Taylor, PhD; *Frederick L. Olmsted Professor* (CEE) & *Director* (Network Dynamics Lab)
Debra Lam; *Managing Director* (Smart Cities & Inclusive Innovation)

8:00am — **WELCOME + OPENING REMARKS**

- ***Tye Hayes***
  Chief Technology Officer, City of Atlanta
- ***Raheem Beyah***
  Vice President for Interdisciplinary Research, & Motorola Foundation Professor of Electrical & Computer Engineering, Georgia Tech
- ***Don Webster***
  Karen & John Huff Chair, Civil & Environmental Engineering, Georgia Tech

8:30am **INTRODUCTION TO WORKSHOP**

- ***Debra Lam***
  Managing Director, Smart Cities & Inclusive Innovation, Georgia Tech
- ***John E. Taylor***
  Frederick Law Olmsted Professor, Civil & Environmental Engineering, Georgia Tech

Smart City Digital Twin

Convergence Workshop

September 16-17, 2019

Georgia Tech | Columbia University | Stanford University | UIC

Smart City Digital Twins

Neda Mohammadi & John E. Taylor
School of Civil & Environmental Engineering
Georgia Institute of Technology
Atlanta, GA, USA
{nedam, jet}@gatech.edu

***Abstract*—Driven by the challenges of rapid urbanization, cities are determined to implement advanced socio-technological changes and transform into *smarter cities*. The success of such transformation, however, greatly relies on a thorough understanding of the city's states of spatiotemporal flux. The ability to understand such fluctuations in context and in terms of interdependencies that exist among various entities across time and space is crucial, if cities are to maintain their smart growth. Here, we introduce a *Smart City Digital Twin* paradigm that can enable increased visibility into cities' human-infrastructure-technology interactions, in which spatiotemporal fluctuations of the city are integrated into an analytics platform at the real-time intersection of reality-virtuality. Through learning and exchange of spatiotemporal information with the city, enabled through virtualization and the connectivity offered by Internet of Things (IoT), this *Digital Twin* of the city becomes smarter over time, able to provide predictive insights into the city's smarter performance and growth.**

***Keywords*—Digital Twins, Interdependence, IoT, Smart Cities, Spatiotemporal Flux.**

I. INTRODUCTION

Cities, responsible for much of the world's total resource

expected increase in urban population to nearly 6.3 billion by 2050 [4], combined with the resulting complexities stemming from human activities, are managed to effect positive outcomes in allocating resources, providing security, maximizing services, facilitating human activities, and preventing disruption, while continuously adapting to the changing behaviors of the citizens. Leveraging effective instrumentation, interconnection, and collective intelligence of the city [5], smart cities are expected to improve operational efficiency and quality of life. However, cities, as complex adaptive systems, experience several changes of states in their operations with respect to individuals' activities that are increasing due to the dynamic pressure of population growth. Therefore, successful transformation of cities to smart cities demands advancing city performance through integration of human, infrastructure and technology (Fig. 1). Both spatial and temporal performance equilibria are subject to vulnerabilities that make human-infrastructure-technology systems susceptible to changes of state, or collapses. A better understanding of the underlying drivers of this process will facilitate the identification of the systems' reactive, recovery, and adaptive capacities across time and space.

December 2017

'Transformative' urban digital twin and city modelling deployments to exceed 500 by 2025, says ABI

ABIresearch
for visionaries

0

Posted by ANASIA D'MELLO
SEPTEMBER 11, 2019

September 2019

Smart City Digital Twin

Convergence Workshop

September 16-17, 2019

Georgia Tech
Columbia University
Stanford University
UIC

DAY 1 — Monday, September 16

7:30am **Registration, Networking + Breakfast**

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John Taylor, Frederick Law Olmsted Professor, Civil & Environmental Engineering, Georgia Tech

PART 1: CURRENT SMART CITY DIGITAL TWIN EFFORTS

8:45am **First Panel – Mobility Infrastructure System Digital Twins**
Sybil Derrible, Associate Professor, University of Illinois, Chicago
David Emory, Director, Technology Strategy and Innovation, MARTA
Lillie Madali, Smart City Program Director, City of Atlanta
Jane Mcfarlane, Director of Smart Cities Research Center, University of California, Berkeley

9:45am **Second Panel – Water Infrastructure System Digital Twins**
Stephen Bourne, Director & Research and Development Chair, Atkins
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10:45am **Networking Break**

11:00am **Third Panel – Energy Infrastructure System Digital Twins**
Sam Edelstein, Chief Data Officer, City of Syracuse
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Laura Meixell, Enterprise Data Architect, Allegheny County Department of Human Services
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Josh Sperling, Urban Futures & the Energy-X Nexus Fellow, National Renewable Energy Laboratory (NREL)

12:00pm **Working Lunch – Smart City Digital Twin Technology/System Showcase**
Burcin Becerik-Gerber, Professor of Civil and Environmental Engineering, University of Southern California
Michael Hunter, Professor, Civil & Environmental Engineering, Georgia Tech
Madhav Marathe, Division Director and Professor, Biocomplexity Institute, University of Virginia
Neda Mohammadi, City Infrastructure Analytics Director, Network Dynamics Lab, Georgia Tech
Kouros Mohammadian, Professor & Dept. Head, Civil & Materials Engineering, University of Illinois, Chicago
Mina Sartipi, UC Foundation Professor, Computer Science and Engineering, University of Tennessee-Chattanooga
Keith Swearingen, Office of Chief Information Officer, NASA

PART 2: TOWARD A SMART CITY DIGITAL TWIN FRAMEWORK

2:00pm **Kick Off Smart City Digital Twin Framework Discussion Breakouts**

2:30pm **Breakout Groups Discuss Elements of Framework**

4:00pm **Breakout Groups Report**

4:30pm **End of Day Summary, Discussion + Next Steps**

5:00pm **Reception & Group Photo** (14th Floor Atrium)
Merry Hunter Caudle, Program Manager – Economic Development, Georgia Tech

DAY 2 — Tuesday, September 17

7:30am **Registration, Networking + Breakfast**

8:00am **Discuss Smart City Digital Twin Framework Developed in Day 1 + Plan for Day 2**

PART 3: FUTURE OF SMART CITY DIGITAL TWINNING

8:30am **Kick Off Smart City Digital Twin Forward Looking Breakout Exercise**

9:00am **Breakout Groups Use Framework to Envision Future of Smart City Digital Twins**

11:00am **Breakout Groups Report**

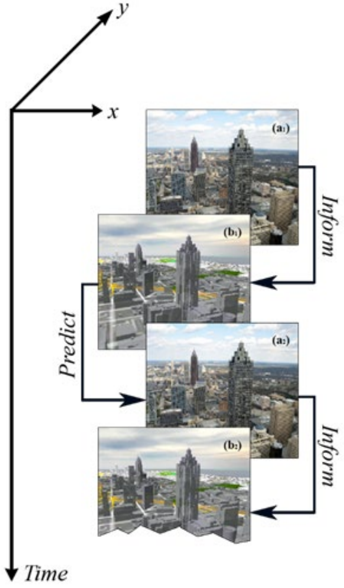
11:30am **Closing Discussion + Next Steps**

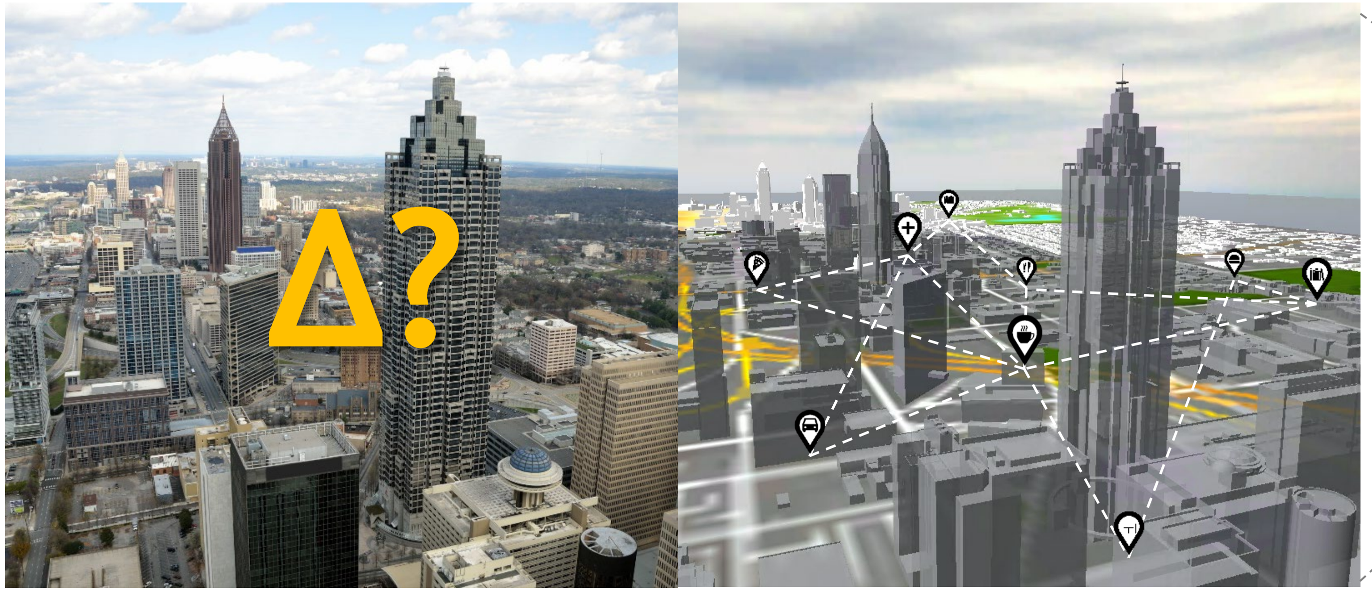
12:30pm **Adjourn/Lunch**

What is a Smart City Digital Twin?

"A *Digital Twin* is a…pairing of virtual and physical worlds [that] allows analysis of data and monitoring of systems to head off problems before they occur, prevent downtime, develop new opportunities, and even plan for the future using simulations." [Forbes, 2017]

What is a Smart City Digital Twin?





A *Smart City Digital Twin* is a smart, IoT-enabled, data-rich virtual platform of a city that can be used to replicate and simulate changes happening in the real city to improve resilience, sustainability, and livability. *[Mohammadi & Taylor, 2017]*

National Science Foundation
WHERE DISCOVERIES BEGIN

’Identify areas of research where investment in **convergent** approaches…**united to solve problems** – have the potential to translate to high-benefit results and advance ideas from concept to deliverables’

‘To **enable capabilities far beyond what is currently possible** in either the private or public sectors’

‘Bringing together researchers with many different specialties, and partners from across the spectrum of scientific innovation and application -- will **create environments where innovation can thrive**’

National Science Foundation
WHERE DISCOVERIES BEGIN

8 Government

17 Universities

15+ disciplines

3 National Labs

6 Industry

Smart City Digital Twin

Convergence Workshop

September 16-17, 2019

Smart City Digital Twin Convergence Workshop Purpose/Goals

- *Share state-of-the-art knowledge on on-going single infrastructure system digital twinning across community of scholars, practitioners and government officials.*
- *Discuss/develop framework for understanding and comparing Smart City Digital Twin evolution across cities.*
- *Discuss and develop a road map of an envisioned future for Smart City Digital Twinning efforts.*

Smart City Digital Twin Convergence Workshop Format to Achieve Goals

- *Share state-of-the-art knowledge on on-going single infrastructure system digital twinning across community of scholars, practitioners and government officials. → 3 Panel + 1 Technology/Systems Showcase*
- *Discuss/develop framework for understanding and comparing Smart City Digital Twin evolution across cities. → Breakouts Afternoon Day 1*
- *Discuss and develop a road map of an envisioned future for Smart City Digital Twinning efforts. → Breakouts Morning Day 2*

Smart City Digital Twin Convergence Workshop Communications

- *Social Media*
- *Filming Interviews for Short "Smart City Digital Twin" Video*
- *Note-takers*
- *Media*
- *Summary Article*

Smart City Digital Twin Convergence Workshop Code of Conduct

- *Did everyone receive it electronically? Please review it.*
  - *We are committed to having a safe/productive meeting that fosters open dialogue and exchange of ideas, promotes equal opportunity and treatment for all participants, and is free of harassment or discrimination.*
  - *This workshop is a forum to consider and debate science-relevant viewpoints in an orderly, respectful, and fair manner.*
  - *Any form of harassment, sexual or otherwise, is prohibited at this workshop. Harassment should be reported immediately to the Workshop Chairs:*

Chair: John E. Taylor; jet@gatech.edu; (540) 808-6063
Co-Chair: Debra Lam; debra.lam@gatech.edu; (530) 750-9881

Harassment can also be reported directly to NSF at programcomplaints@nsf.gov.

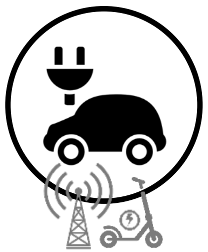
Smart City Digital Twin Convergence Workshop Panels

Sybil Derrible UIC
David Emory MARTA
Lillie Madali Atlanta
Jane Mcfarlane UCB+LBNL

Stephen Bourne Atkins
Patricia Culligan CU
Mike Diaz Arcadis
Jonathan Levy Chicago
Grace Simrall Louisville

Sam Edelstein Syracuse
Rishee Jain Stanford
Laura Meixell Alleghany
Jack Montgomery Siemens
Josh Sperling NREL

Smart City Digital Twin Convergence Workshop Panels + Technology Showcase



Sybil Derrible UIC
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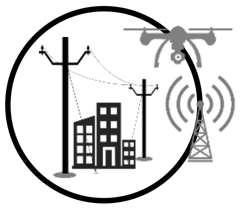

Sam Edelstein Syracuse
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Josh Sperling NREL

Burcin Becerik-Gerber USC
Michael Hunter GT
Madhav Marathe UVA
Neda Mohammadi GT

Kouros Mohammadian UIC
Mina Sartipi UT-C
Keith Swearingen NASA

 |

MOBILITY INFRASTRUCTURE SYSTEMS PANEL

Sybil Derrible UIC
David Emory MARTA
Lillie Madali Atlanta
Jane Mcfarlane UCB+LBNL

WATER INFRASTRUCTURE SYSTEMS PANEL

Stephen Bourne Atkins
Patricia Culligan CU
Mike Diaz Arcadis
Jonathan Levy Chicago
Grace Simrall Louisville

ENERGY INFRASTRUCTURE SYSTEMS PANEL

Sam Edelstein Syracuse
Rishee Jain Stanford
Laura Meixell Alleghany
Jack Montgomery Siemens
Josh Sperling NREL

Smart City Digital Twin

Convergence Workshop

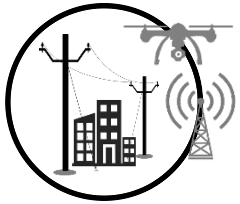
September 16-17, 2019

Smart City Digital Twin Technology Showcase

Burcin Becerik-Gerber USC
Michael Hunter GT
Madhav Marathe UVA
Neda Mohammadi GT

Kouros Mohammadian UIC
Mina Sartipi UT-C
Keith Swearingen NASA

Smart City Digital Twin Convergence Workshop Preparing for Breakouts

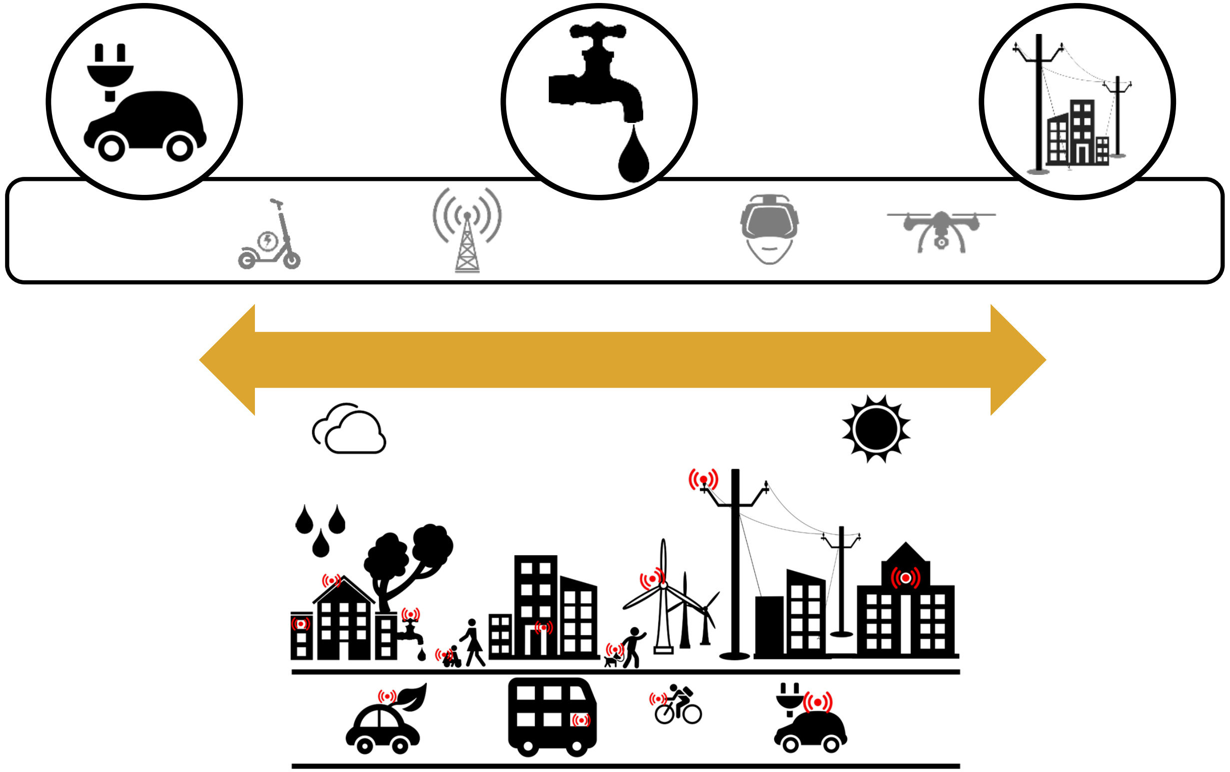


Smart City Digital Twin Convergence Workshop Preparing for Breakouts

Smart City Digital Twin Convergence Workshop Preparing for Breakouts

Distribution of Efficiencies
Interoperability of Technology/Systems

Smart City Digital Twin Convergence Workshop Preparing for Breakouts



Smart City Digital Twin Convergence Workshop Preparing for Breakouts

Join the Mobility, Water, or Energy Panel for a breakout discussion…

- [DISTRIBUTION OF EFFICIENCIES]
  - *-Based on the state-of-the-art knowledge discussed, and your own expertise, how could the infrastructure system digital twin focus in your breakout discussion benefit from or be extended by what you learned today or based on your expertise?*
  - *-What new enabling technologies/features/functionalities or opportunities can you identify?*
  - *-What are the barriers to or risks associated with each?*

- [INTEROPERABILITY OF TECHNOLOGY/SYSTEMS]
  - *-How do Smart City Digital Twin technologies and systems need be adapted to integrate and/or function across multiple interdependent infrastructure systems?*
  - *-What barriers, risks or other considerations are associated with each adaptation?*

Appendix D

Workshop Code of Conduct

Smart City Digital Twin Convergence Workshop

Georgia Institute of Technology

September 16-17, 2019

The following code-of-conduct addresses sexual harassment, other forms of harassment, and sexual assault, and includes clear and accessible means of reporting violations of the policy or code-of-conduct.[1]

Workshop Organizers' Commitment

The organizers of this workshop are committed to providing a safe and productive meeting environment that fosters open dialogue and the exchange of scientific ideas, promotes equal opportunities and treatment for all participants, and is free of harassment and discrimination. All participants are expected to treat others with respect and consideration, follow venue rules, and alert staff or security of any dangerous situations or anyone in distress. Speakers are expected to uphold standards of scientific integrity and professional ethics. This includes notifying organizers in advance of the meeting about any possible conflicts of interest. The organizers recognize that there are areas of science that are controversial. This workshop can serve as an effective forum to consider and debate science-relevant viewpoints in an orderly, respectful, and fair manner. The policies herein apply to all attendees, speakers, exhibitors, staff, contractors, volunteers, and guests at the workshop and related events.

The organizers of this workshop prohibit any form of harassment, sexual or otherwise. Harassment should be reported immediately to any of the Workshop Chairs:

Chair, Dr. John E. Taylor; jet@gatech.edu; (540) 808-6063

Co-Chair, Debra Lam; debra.lam@gatech.edu; (530) 750-9881

As an NSF funded workshop, harassment can also be reported directly to NSF at programcomplaints@nsf.gov.

What is Harassment?

Harassment includes speech or behavior that is not welcome or is personally offensive, whether it is based on ethnicity, gender, religion, age, body size, disability, veteran status, marital status, sexual orientation, gender identity, or any other reason not related to scientific merit. It includes stalking, unnecessary touching, and unwelcome attention.

Behavior that is acceptable to one person may not be acceptable to another, so use discretion to be sure that respect is communicated. Harassment intended in a joking manner still constitutes unacceptable behavior. Retaliation for reporting harassment is also a violation of this policy, as is reporting an incident in bad faith.

[1] This Workshop Code of Conduct was adapted from the *AAAS Annual Meeting Code of Conduct*; adopted by the AAAS Board of Directors October 2016; https://meetings.aaas.org/policies/; accessed March 19, 2019.

Appendix D

Reporting Harassment

The organizers of this workshop are committed to supporting a productive and safe working environment for everyone at the meeting. If an individual experiences or witnesses harassment, they should contact the workshop Chairs as noted above, or use a venue phone and ask for security if they feel unsafe.

While on Georgia Tech's campus, Georgia Tech Police are available by dialing 911 or while on or off campus at **(404) 894-2500**. All complaints will be treated seriously and responded to promptly.

If an individual experiences harassment, it is recommended that, in addition to notifying workshop Chairs, they write down the details, as they may be asked to fill out a report. They are not expected to discuss the incident with the offending party. Their confidentiality will be maintained to the extent that it does not compromise the rights of others.

If an individual wishes to file a formal complaint of harassment:

- Notify Workshop Chairs (Taylor or Lam).
- The Chair(s) will discuss the details with the individual filing the complaint, then with the alleged offender; seek counsel if the appropriate course of action is unclear; and report findings to the Georgia Tech Office of Human Resources or the Georgia Tech Police Department as appropriate, AND to the workshop funding sponsor (National Science Foundation).
- The Chair(s) will consult with the individual filing the complaint prior to taking any action.

Workshop organizers reserve the right to remove an individual from the workshop without warning or refund, prohibit attendance at future workshops, and notify the individual's employer.

For any questions about this policy, please contact Dr. John E. Taylor, Workshop Chair, at jet@gatech.edu; (540) 808-6063, or Debra Lam, Workshop Co-Chair, at debra.lam@gatech.edu; (530) 750-9881.

Appendix E

Smart City Digital Twins Needs, Prioritization & Features

Needs	Features (bolded items = highest prioritization)
· **Mitigate congestion, move people more quickly to spend $ locally** · **Disaster preparedness** · **Prosperity/livelihood** · **Build things better/cheaper/faster** · **Business of running city government** · **Special events in city** · **Maintenance** (failing infrastructure) · **Inequality** (addressing social equity/inclusiveness in provisioning services / environmental justice) + catch up from a generation of neglect · **City Service Catalog** (major items): Police and public safety, Parking / curbside management, Availability of food / drinking water, Air quality, "Call before you dig", Storm water / Sewerage removal, Affordable Shelter/Housing, Trash service, Fire/Emergency response, Power, Tree limbs down and removed, and Snow removal. · Some education of decision-makers to show value of Smart City Digital Twins. · Need buy-in from local authorities / governments to test the efficacy of Smart City Digital Twin. · Need feedback loop to show citizens the benefits of a Smart City Digital Twin (e.g., show a map of potholes and say when it will be fixed with different ways to see and interact with the data). · Need to develop Smart City Digital Twins for education: to show how infrastructure works to engineering students for example or even the larger public. · Need new educational programs to educate domain experts (e.g., civil engineers) with computational skills. · Need some consistency / standards to be more interoperable between departments and even between cities. · Need to get more stakeholders together to determine the needs for Smart City Digital Twins. · Officials frequently have to make long-term decisions (20-30 years). Most cities do not have tools or models to test long-term scenarios. · Need to think about what technology can elucidate for us to make sense out of the "chaos" of layers of infrastructure built upon one another, built at different time scales. · Need to be resilient from both shocks (short term) and stresses (chronic, long term). Elected officials are elected based on shocks, Smart City Digital Twin needs to develop small wins in the medium term to follow election cycles. · Need to take into account what each department can control.Need to be able to simulate stresses that we do not know, generate a palette of solutions automatically and test their performance. · Need to overlay infrastructure systems to get attention from policy makers (e.g., transport, land use, etc.)	· **Mobility/Disasters -** Data fairness, Data quantity (representativeness, precision), mitigate with deep learning, mobilization of resources (human-in-loop), data privacy / data security (data needed that may not be public, could be used against you (e.g., deliberate misinformation), partial closures in city, feedback loops with citizens, real-time/quasi-real-time. · **Equity -** Data collection across assets, populations, and locations, assume we can use phones to collect data not always the case need to plug them in somehow, multi-lingual interactions, social embeddedness (engagement), feedback loop to/with citizens · Geofencing – How are policies made/implemented? · Features that enable interaction between agencies (city, airport, etc.) · Decision-making view is needed (while respecting privacy and including human-in-the-loop). · Usability (needs to be able to be learned quickly) · Pattern recognition (how people move, buildings work) · Conditional learning (when 311 request placed, then something actually happens) · Reward system – to encourage use across convergent range of stakeholders · Sample datasets – Cities should be able to experiment with a Smart City Digital Twin before making a broad deployment decision · Cybersecurity – Needs to be secure and private, but some aspects should be open so that constituents/stakeholders can try scenarios themselves. Design principles to build features for Smart City Digital Twins: 1. Decentralized: Let individual actors build functions that meet their needs 2. Interoperable / integrated: How infrastructures talk / affect one another 3. Modular: Ability to improve individual models separately 4. Localizable: Adaptable to local needs 5. Stiff: Some things change fast and others slow, different scales, etc., this need to be accounted for 6. Openness: Needs to be open access / open source so it can be shared