RESEARCH ROADMAP IN INFRASTRUCTURE AREA

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1. Introduction

Infrastructure is the combination of fundamental systems that support a community, region, or country including the services and facilities necessary for its economy to function. Infrastructure systems comprises physical structures, as well as cyber and fiscal processes that manage and control everything from water and sewer systems, to air, road and rail networks, to national power and natural gas grids, to economic and fiscal systems. Infrastructure systems are diverse and can include: A) Engineering and Construction Infrastructure – fixed, hard infrastructure assets that are in the form of a large network, such as airports, highways, roads, bridges, tunnels, canals, railways, dams, inland waterways, ports, pipeline transport, water supply and quality, storm management, sewers, waste disposal and management, hazardous waste; B) Military Infrastructure – buildings and permanent installations necessary for the support of military forces; C) Energy Infrastructure – hardware and software required to produce, transport/distribute, and manage energy including power generation, energy delivery and storage, and renewable; D) Communications Infrastructure – the physical backbone of the communications network (e.g., geostationary satellites) upon which various broadcasting and telecommunication services are operated; and E) Civil Defense and Economic Development – critical facilities for public/emergency services, such as schools, hospitals, police stations, fire engines, and basic financial services.

This strategic plan and research roadmap aims to develop Missouri S&T's regional, national and international leadership and partnership in infrastructure research and technology transfer by creating, conveying, and applying knowledge that serves our communities, neighboring states, and nation, and helps solve the world's great challenges associated with aging infrastructure. We will focus our efforts to improve the safety, sustainability, and resilience of our nation's critical infrastructures under normal operations and extreme events (both man-made and natural).

2. Infrastructure Core Expertise and Existing Facilities at Missouri S&T

Infrastructure is well-represented at Missouri S&T where research initiatives are mainly coordinated through three university research centers: the Center for Infrastructural Engineering Studies, the Center for Intelligent Infrastructure, and the Center for Research in Energy and Environment. The centers are grounded in interdisciplinary and trans-disciplinary research collaborations, team building activities, proposal development activities as well as experimental and computational facilities to undertake research. These centers include expertise in chemical and biochemical engineering (CBE), chemistry, civil engineering (CArEE), computer science and engineering (CSE), environmental engineering (CArEE), electrical and computer engineering (ECE), engineering management and systems engineering (EMSE), geosciences and geological and Petroleum engineering (GGPE), materials science and engineering(MSE), mathematics and statistics, mechanical engineering (MAE), and mining and nuclear engineering (MNE). These centers will coordinate efforts to connect Missouri S&T with infrastructure research centers/groups across the University of Missouri System (UM, UMKC, and UMSL) and beyond.

Missouri S&T's expertise and capabilities in infrastructure are largely grouped into three clusters: (1) Infrastructure Materials and Engineering, (2) Smart Engineering Infrastructure, and (3) Energy Infrastructure. Each group is briefly described with identified members and strengths in Table 1. Major experimental and computational facilities to support S&T's infrastructure research are summarized in Table 2.

Table 1 Research Interests, Faculty Talents, and Strengths in Infrastructure Area

Area	**Description**	**Existing Strengths**	**Faculty/Department**
Infrastructure Materials and Engineering (Design, Construction, and Repair)	Design and discovery of novel and sustainable materials for construction and rehabilitation of physical infrastructure (building, transportation, and energy sectors). Enhancement of resilient design and materials for stronger and safer communities. Extension of service life, use of recycled materials, and new binders	• Global leaders in advanced materials for sustainable and environment-friendly infrastructure (alternative binders, recycled materials, and high-performance concrete with adapted rheology). • Novel carbon-efficient binders for sustainable infrastructure. • Nano materials, smart materials adaptive to environmental/mechanical loads enabled by phase change materials, humidity-adjusting agents, and self-healing mechanisms, functionally graded materials, and water-to-energy materials. • Pavement materials (asphalt and concrete), high-performance concrete, composite materials, fiber-reinforced polymers, masonry materials, and structural steel. • Structural design and systems (structural behavior of specialty concrete and reinforcement, seismic design, resilient structural design, and retrofitting of infrastructure). • Use of nondestructive testing for material inspection.	Khayat*/CArEE Abdelrahman/ CArEE Awuah-Offei/MNE Chen/CArEE Corns/EMSE Das/CSE El-adaway /CArEE ElGawady/CArEE Farzadnia/CIES Feys/CArEE Imqam/ GGPE Kumar/MSE Liu/CArEE Long/EMSE Ma/CArEE Myers/CArEE Okoronkwo/ CBE Perry/MNE Sedighsa-rvestani/ECE Sherizadeh/ MNE

	with near-zero carbon footprint. New structural form and materials for accelerated construction.	• Structural analysis and behavior under man-made attacks (e.g., explosion) and natural hazards (e.g., earthquake, flood, tornado, etc.). • Unique first principles and artificial intelligence based methods to aid in material design, and predict and optimize properties of cementitious formulations. • Data visualization and geospatial modeling to assure design resilience. • Machine learning and artificial intelligence aided materials design to predict performance of structural materials. • Broad range of funded projects that are of great interests to federal and state DOTs, DOE, NSF, and private companies.	Shuman/Chemistry Yan/CArEE Wu/CArEE
Smart Engineering Infrastructure (Operation, Management, and Mitigation)	Cyber-physical-social infrastructure systems with dependence and interdependence for sustainable and resilient society. Smart materials and sensor integration for data-driven infrastructure asset management with AI decision-making tools. Robotic platforms for inspection and maintenance. Life-cycle assessment, reliability, and post-disaster resiliency and recovery of infrastructure systems under man-made (explosives) and natural hazards (earthquakes, floods, and tornados).	• Global leaders in robot-assisted bridge inspection and maintenance as well as emergency response. • Cooperative ground, climbing, and aerial robotics to advance infrastructure asset operation, management and emergency response. • Unique capabilities in sensor fabrication, calibration, and application. • Complex networking of cyber-physical infrastructure systems with dependence and interdependence. • Smart materials and structures towards optimal solutions for condition monitoring (both online and offline), system assessment, and maintenance strategy development of civil infrastructure. • Broad cross-disciplinary expertise in construction management, asset management, modeling, simulation, artificial intelligence and data analytics. • Structural health monitoring of a variety of infrastructure systems (e.g., bridges, buildings, dams, pipelines, tunnels, wind turbines). • Machine learning and artificial intelligence for real-time abnormality detection and performance prediction of complex structures. • Machine learning and complex adaptive systems modeling to capture emergence and provide real-time mitigation. • Diverse profile of funded projects that are of great interests to ARL, DARPA, DHS, DOE, federal and state DOTs, and NSF.	Chen*/CArEE Awuah-Offei/MNE Bo/ECE Canfield/ EMSE Cen/CS Das/CS Dagli/EMSE El-adaway /CArEE Khayat/CArEEKwasa/EMSE Landers/MAE Liang/CHE Liu/CArEE Long/EMSE Corns/EMSE Ma/CArEE Madria/CS Myers/CarEE Sarangapani /ECE Sedighsar-vestani/ECE Wu/CArEE Yan/CArEE Zhang/CArEE
Energy Infrastructure (Electrical, Mining, Oil/Gas)	Infrastructure for energy production, conversion, transmission, storage, and distribution. Development of technologies enabling an efficient, reliable, resilient, sustainable, clean,	• Diverse experts in the area of energy production, transmission, storage, and distribution, and in the area of material, power electronics, power systems. • Strong expertise in exploration, sustainable mining and processing, and post-mining closure of minerals critical for energy infrastructure. • Strong group working in the modeling (across all scales), controls, power electronics, and systems in energy storage and energy system platforms. • Strong history of research collaboration with industry (Eagle Pitcher, Microgrid Consortium).	Park*/MAE Kimball*/ECE Alagha/MnEE Awuah-Offei/MnEE Bai/GGPE Bo/ECE Canfield/ EMSE Chen/CArEE Dogan/MSE El-adaway/ CArEE

	and secure future energy infrastructure. Raw material needs for energy transition.	• Energy reliability and resiliency of electrified transportation infrastructure. • Real-time digital simulator (RTDS) for microgrid simulation and hardware in the loop testing. • Commercial grade national-scale power system simulation software and datasets. • Detection and assessment of pipeline leakage and corrosion. • Data science modeling for infrastructure investments and economic development. • Experimental Mine to evaluate sustainable mining methodologies. • Expertise and instrumentation to evaluate resiliency of energy infrastructure components to explosions. • Strong funding history from DOE, NSF, and industries.	Imqam/ GGPE Johnson/MnEE Landers/MAE Liang/CHE Locmelis/GGPE Long/EMSE Moats/MSE Perry/MNE Sedighsar-vestani/ECE

Table 2 Major Experimental and Computational Facilities

Area	**Description**	**Key Features/Capabilities**
Infrastructure Materials and Engineering (Design, Construction, and Repair)	• Clayco Advanced Construction and Materials Lab (ACML) • Materials Research Lab (MRC) • Structural Engineering Research Laboratory (SERL) • Wind Hazards Mitigation (WHAM) Laboratory • Energetics Research Facility (ERF)	• World-class research infrastructure - $7M investment housing over $3.5 M of state-of-the-art research equipment to study hydration kinetics, rheology, visco-elastic, mechanical, and transport properties, and durability of cementitious materials. State-of-the art mixing equipment including batching plant. • MRC includes several advanced materials characterization equipment including solid-state NMR, field emission SEM, TEM, XRD, XPS, and FTIR. • A complex of a high bay structural testing laboratory, a materials laboratory, and a machine shop. The high bay structural testing laboratory features a fixed 5.5 m tall L-shaped reaction, a 20-ton overhead crane, a twin tunnel basement under strong floor, large-capacity actuators, and two single-degree-of-freedom shake tables. • Tornado simulator in the USA that can produce translating tornadoes. The maximum rotational wind speed is 20 m/s, which is associated with the wind speed in the highest intensity, EF5 tornado, in full scale. It allows a bigger structural model to be tested, better informing the design tornadic wind loading. • Structural testing of materials or components to intentional or accidental explosions. • Nano-/micromechanical characterization equipment including in-situ SEM pico-indenter and microelectromechanical (MEMS) probing devices.
Smart Engineering Infrastructure (Operation, Management, and Mitigation)	• Bridge Inspection Robot Deployment Systems (BIRDS) • Robot Engineering and Application Laboratory (REAL) • System and Process Assessment Research (SPAR) Lab	• Solar-powered ground vehicle to support field tests at bridge sites, using climbing robots, unmanned aerial vehicles, multimodal vehicles, sensors, nondestructive evaluation devices. • Robotic design, fabrication, testing, and demonstration, including two indoor drone testing environments with motion capture camera systems. • Nano sensor design and fabrication with integration of graphene and other 2D structures. • Multiscale and multiphysics modeling and characterization of functional nanocomposites

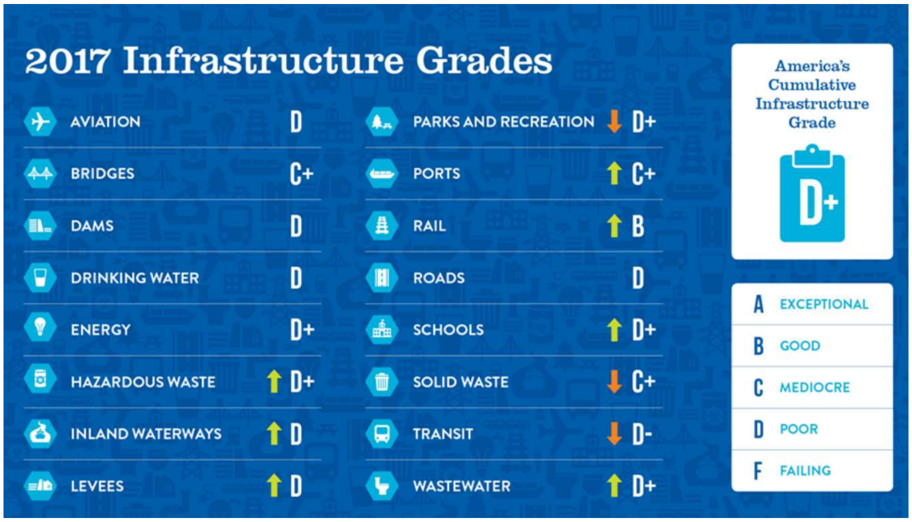
	• Visual Inspection Research & Training Using Augmented Learning (VIRTUAL) Lab • Web and Wireless Computing Lab (WWCL) • Civil Infrastructure System-of-Systems Interdependency Laboratory (CI2SI-L) • Missouri Consortium for Construction Innovation (MO-CCI)	• Design, fabrication, and calibration of both grating and scattering based fiber optic sensing systems, including long period fiber gratings, Brillouin optical time domain reflectometry/analysis (up to 25 km in distance), an ultra-high sensitivity and high frequency response acoustic sensing system (up to 1 km in distance), and • Multi-physics measurement devices (acoustic, electromagnetic, magnetic, optical, and radar) for complete assessment of structural behaviors (e.g., crack, corrosion, debonding, scour, yielding). • Inspector and pilot training using augmented reality and virtual reality towards a certificate program. • An in-house cloud, big data and Hyperledger blockchain infrastructure environment, including a private hybrid cloud using a Eucalyptus open source platform.
Energy Infrastructure (Electric, Mining, and Oil/Gas)	• Center for Research in Energy and Environment (CREE) • Engineering Design Center (EDC) • Experimental Mine • Advanced Energy Materials and Systems Lab (AEMS) • Advanced Ceramic Materials Lab (ACML) • Nano Research Lab (NRL) • Solid State and Materials Chemistry Laboratory (SMCL)	• Nanomaterial synthesis (CVD, Electrospining, Solid-state reaction), Device fabrication (batteries, fuel cells, solar cells) and Test equipment, Thermal chamber, Fuel cell station, 3D printing/deposition systems, Surface modification and treatment system (laser and plasma), Sintering system/Atomic simulation s/w (VASP, Material Studio), Continuum scale simulation tools (Ansys, Flow3D, Comsol, Abaqus), Workstations. • Processing, microstructure and property relationships of energy materials including solid oxide fuel cells, high temperature superconductors, high energy capacitors and lead-batteries. • Electrochemical testing systems to utilize hydrocarbon fuels for SOFC as highly efficient energy conversation devices to generate electricity. • Atom layer deposition reactor for thin film coating, lithium ion battery testing system. • Multi-channels Battery charger, several potentiostats for measuring properties of battery and super-capacitor related energy storage devices. Expertise in crystal structure determination of materials from single-crystal X-ray and high resolution synchrotron X-ray diffraction data. • 400 MHz Solid state NMR (Chemistry department). Single-crystal X-ray diffractometer (Chemistry department). • EDC Human-systems integration and resilient design (EMSE). • Proof of concept for developments in sustainable mining or tunneling advancements • Explosion resiliency evaluation of energy infrastructure components (generation, distribution, storage, etc.) and developed protection techniques/systems. • Bench scale mineral processing (comminution and flotation) and hydrometallurgy equipment. • Life cycle modeling and material flow analysis capabilities.

3. Addressing Local, State, and National Needs

The research enterprise in the field of infrastructure at Missouri S&T is directly related to critical needs at the local, state, and national levels that seek to develop safe, sustainable, and cost-effective solutions to construct, maintain, inspect, and rehabilitate the various categories of the infrastructure that are elaborated in Section 1. The research is focused on fulfilling the needs for maintaining our nation's infrastructure, where the problem is particularly acute in urban areas given the growing population as well as the increasing occurrence of natural disasters that stress society's support systems. The proposed strategic planning will be focused on inter-disciplinary research to deliver new technologies with increased intellectual merit in areas with high broader impact; the outcomes of the proposed strategic planning will position S&T as a national leader in multi-disciplinary research areas. This include the development of technologies to enhance the use of recycled and by-product materials in durable, economical and more sustainable infrastructure. Some of the key national priorities in the field of infrastructure engineering that are addressed by the research at Missouri S&T are described below.

A. *Restore and Improve Urban Infrastructur*e, which is one of the 14 National Academy of Engineering (**NAE**) **Grand Challenges**. The NAE calls for expedient development of novel materials, monitoring methods, and greater reliance on automation to restore and improve urban and rural infrastructure systems and advance transportation and energy, water, and waste systems and create more sustainable urban and rural environments.

B. *Extend the Durability, Service Life, Resilience, and Safety of the Aging Infrastructure*. The 2017 American Society of Civil Engineers (**ASCE**) **Infrastructure Report Card** presented our nation with a poor (at risk) grade across 16 types of aging infrastructure and a mediocre (requiring attention) grade to several infrastructure categories, as shown below. The backlog of rehabilitation on every category of these critical infrastructures requires billions of dollars of investment to maintain in state of good repair.



C. *Reduce Greenhouse Gases*. Global warming associated with emission of greenhouse gases is a grand challenge for humanity. Reducing global warming is critical to reducing the rate of the rise in sea water and frequency of extreme events, such as fires, floods, hurricanes, and tornados that threaten the integrity and safety of our infrastructure. Efforts to maximize the use of sustainable and green materials, renewal and clean energy, and climate-resilient development of infrastructure are in alignment with the 2016 Paris Agreements within the **United Nations Framework Convention on Climate Change**.

D. *Develop Sustainable Cities*. Sustainable cities is one the 17 goals of the **Sustainable Development Goals** (SDGs) adopted by all **United Nations** Member States in 2015 that aim at ending poverty, protecting the planet, and ensuring that all people enjoy peace and prosperity by 2030.

4. Synergistic Infrastructure Roadmap for the Future

Missouri S&T envisions to establish a unique mid-scale infrastructure city to elevate the current (physical) infrastructural materials and engineering and management research frontiers to a city-scale, zero emission and fully-digitalized platform that is overlaid with green and smart materials, and cyber infrastructure that is seamlessly intertwined with social infrastructure. This infrastructure city is a connected system of bridges, buildings, pipelines, roads, solar farms, tunnels, autonomous vehicles, and wind turbines through wireless communications. This integrative infrastructure city will serve as a test bed and a technological showcase for the design and implementation of several innovations in sustainable and resilient infrastructure materials and engineering, smart engineering infrastructure, and green energy infrastructure. This undertaking is hereafter referred to as the CREATE (*Center for Research and Entrepreneurship towards an Autonomous and Transformative Ecosystem*) initiative. The overarching mission of the CREATE initiative is to promote industry-university collaborative research, development, patented technology, commercialization, and workforce training and education in the area of design and use of sustainable materials and engineering, resilient design and construction, smart engineering infrastructure, and green energy infrastructure.

The CREATE initiative will stimulate inter- and trans-disciplinary research opportunities in the greater area of infrastructure and will position Missouri S&T to seek major external funding opportunities. Some of the unique technologies that will be developed and implemented in the CREATE initiative are listed below:

- Novel and smart construction materials capable of meeting stringent sustainability performance specifications will be deployed. This includes the implementation of 100% portland cement-free CO_2-efficient binders developed at the *Center for Novel Carbon-Efficient Binders for Sustainable Infrastructure* of the UM System seeking 50% reduction in CO_2 emissions as well as high-performance concrete with adapted rheology, modular construction, and 3D printing technologies to accelerate construction operations.
- Highly durable infrastructure materials to double service life and secure a five-fold increase in structural toughness. Other novel materials include smart structural materials that are adaptive to environmental and/or mechanical loads, enabled by protective barrier coating technology, phase change materials, humidity-adjusting agents, and self-healing mechanisms as well as self-sensing composite materials and nanomaterials to enhance structural performance.
- State-of-the art, resilient structural design and construction of the infrastructure to resist extreme loads including both natural and manmade events such as earthquakes, fires, explosions, floods, hurricanes, and tornados.
- Advanced sensing and computing, real-time structural health monitoring system with cloud-based database and machine learning capabilities for critical infrastructure performance evaluation and maintenance decisions. This includes material deterioration science, collaborative human-machine domain-specific learning, human-machine interaction, and social science.
- Robot-assisted autonomous inspection and maintenance of infrastructure with embedded, surface, and remote sensing, real-time data-enabled damage/deterioration evaluation, artificial intelligence-supported decision-making, in-situ renewable energy harvesting,

cyber-physical-social (CPS) system interdependence, and value-driven design and value engineering.

- Integrate automated, intelligent, data-driven design-build-management enterprise of cyber-connected bridges, buildings, power microgrids, pipelines, roads, transportation, and wind turbines that will be developed in a semi-controlled environment and powered by geothermal, solar, and wind energy.

5. Transforming Current Capabilities into a New Horizon

The CREATE initiative aims to plan, design, and develop a real-world, mid-scale smart city with minimum environmental footprint aiming for near zero-emission within few years of operation. The city will combine current and future designs to demonstrate how an urban environment can accommodate denser populations more efficiently. Some parts of the physical infrastructure will be constructed using novel materials and designs elaborated in Section 4 and compared with those from the current materials and design. Some of the buildings will seeks LEED (Leadership in Energy and Environmental Design) Gold international green building certification. The city will be densely-instrumented infrastructure testbed that will serve as S&T's 4.0 industrial revolution showcase to the world and as a digital technology theme park for the City of Rolla. The testbed represents a comprehensive CPS system of subsystems connected by a wireless communication network and engaged by both local residents and visitors. Each subsystem consists of one type of infrastructure (e.g., bridges, buildings, pipelines, roads, transportation, or a microgrid of geothermal, solar, or wind power stations) with specific roles and functions that are adaptive to changes in climate and are scalable to other cities/states.

Various infrastructure components will be constructed in phase over the next 5-10 years. They can be supported through four categories of funding sources:

a. Federal, state, and local funding, such as NSF, USDOT, state DOTs
   MoDOT Collaboration
   NIST Research Infrastructure Investment
   NSF Major Research Instrumentation
   NSF Mid-Scale Research Infrastructure
   The City of Rolla Utility Services and Construction Support

b. Small and medium sized business
   Private Donations
   Research Foundations

c. Corporate initiative
   Industrial consortia to facilitate large research efforts and technology transfer
   NSF GOALI Program
   Industrial In-kind Support (e.g., autonomous vehicles, wind turbines, transmission towers)

d. Kummer Institute through alignment with the various research centers of the institute and the Kummer Institute for Entrepreneurship and Economic Development that can be beneficial to facilitate the integration of new research infrastructure, strategic recruitment of faculty to reinforce multi-disciplinary aspects of the CREATE initiative, and create opportunities for spin-off companies associated with the research efforts.

6. Leading the Way to Create Next Generation of Infrastructure

The CREATE initiative will create a facility that is first of its kind in the world. It is a bold step that is required to distinguish S&T from other major institutions in the U.S. Such an initiative will position S&T to lead an NSF Engineering Research Center focused on digital infrastructure systems, sustainable and green construction materials, greater automation in construction, community resilience to disasters, U.S. economic prosperity, and social equity in living environments.

Once developed, the mid-scale infrastructure city will play a critical role in the development of a digital infrastructure platform that has a profound impact on:

- Economic Prosperity – to enable individual government management sectors to develop high-fidelity scenario analyses for better cost-benefit ratios when expanding their business opportunities in infrastructure, and more cohesive interactions among various business sectors at a city level;
- Living Environment – to understand the effect of infrastructure construction on surrounding environments and the role of infrastructure management in minimizing adverse impacts on the environment;
- Social Dynamics – to quantify the disaggregated effects of infrastructure construction and management on various cultures and communities as pertaining to ethics and equity; and
- Societal Resilience – to enable a greater preparedness and credible performance assessment of a digital infrastructure city in the context of emergency response and functional recovery in the wake of a natural disaster, pandemic threat, or terrorist attack.