



Fall 2019

INSPIRE Newsletter Fall 2019

Missouri University of Science and Technology. INSPIRE - University Transportation Center

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INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

VOL. 3 | ISSUE 2 | FALL
INSPIRE-UTC Biannual Publication

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Awarded in December of 2016 by the U.S. Department of Transportation, the five-year **INSPIRE UTC** is a Tier 1 University Transportation Center with a research priority of preserving the existing transportation system as part of the UTC Program (<https://www.transportation.gov/utc/2016-utc-grantees>) that was authorized under the Fixing America's Surface Transportation Act.

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Director's Message

Greetings, colleagues and friends! Since our last newsletter, the INSPIRE UTC has experienced several noteworthy achievements on a national and international platform. We are currently underway with the annual external proposal review for Year 4 projects. New projects will be announced by the end of the year to center members.



INSPIRE UTC continues to grow and expand its efforts to be a vital part of nation's transportation research enterprise. It is now housed and operated under a new university research center established on the Missouri S&T campus, the Center for Intelligent Infrastructure. While addressing broader challenges with nation's aging infrastructure and increasing public demands, the university center will provide sustained support and administration for the INSPIRE UTC in the years to come. A kickoff meeting of the new university center was held on August 8, 2019 with invited federal and state transportation research leaders, faculty and students, including Ms. Diana Furchtgott-Roth, USDOT Deputy Assistant Secretary for Research and Technology, and Dr. Mo Deghani, Missouri S&T Chancellor who has achieved recognition with research center success.

This summer we held the INSPIRE UTC annual meeting in conjunction with the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9) in St. Louis, MO, August 4-7, 2019. National and International representatives were in attendance to exchange ideas and technologies on the advancement of structural health monitoring research and applications. In addition to reviewing the past accomplishments and discussing the planned activities in the next year, the annual meeting served as the kick-off of the five-year pooled-fund study on Traffic Disruption-free Bridge Inspection Initiative with Robotic Systems. Technical points of contact from seven (7) sponsoring state departments of transportation were present to discuss project objectives and schedules, selection of bridges to be inspected, and related technologies to be tested at bridge sites.

This newsletter issue will feature the research robot operating and training system, and bridge inspection robot deployment research conducted by INSPIRE UTC. This issue also highlights the Missouri Local Technical Assistance Program at Missouri S&T, the pooled-fund study, and Kaleidoscope update for its Robotics Program.

We hope you enjoy the featured articles and exciting news of INSPIRE UTC, and invite you to visit our website at inspire-utc.mst.edu for additional information about upcoming events and webinars.

Sincerely,

Genda Chen, Ph.D., P.E., F. ASCE, F. SEI, F. ISHMII
Professor and Robert W. Abnett Distinguished Chair in Civil Engineering
Director, INSPIRE University Transportation Center
Director, Center for Intelligent Infrastructure
Missouri University of Science and Technology



Dr. Anil Agrawal's Team Investigates Collapsing of the Florida Bridge

A simple truss structure of reinforced concrete materials was fabricated, transported, and placed on two end piers to serve as a main span of the pedestrian bridge spanning over the U.S. Highway 41 (Fig. 1). The bridge weighing 950 tons has a span length of 174 feet with a reinforced concrete deck casting around the truss structure with a cold joint. Five days after its relocation, the bridge collapsed on March 15, 2018 (Fig. 2), raising a concern with the safety of bridges under accelerated construction.



Fig. 1. Main span of the bridge before collapse.



Fig. 2. Collapse scene of the pedestrian bridge.

INSPIRE UTC researchers, Drs. Anil Agrawal and Ran Cao, recently conducted a computational forensic analysis on the cause of this incident in collaboration with Dr. Sherif El-Tawil of the University of Michigan. Their comprehensive research showed that the northern end joint area was significantly underdesigned for shear capacity due to the miscalculation in shear demand, initiating the truss-deck sliding as indicated by the observed crack and simulated stress distribution. However, the bridge collapse mainly resulted from a re-tensioning force applied on the diagonal member 11 of the truss with the intent of remediating the crack situation. This study provides important insights into the collapse mechanism of the truss bridge and highlights lessons learned to prevent similar collapses from happening. A full story of this detailed study will be covered in the next issue of INSPIRE UTC newsletter.



FOR MORE INFORMATION CONTACT:

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CHANCELLOR'S MESSAGE



INSPIRE is certainly a fitting name for this center! I certainly was inspired when, during my first week at the university, I attended an opening ceremony for S&T's new Center for Intelligent Infrastructure and consequently learned about Inspecting and Preserving Infrastructure Through Robotic Exploration. Research is all about possibility thinking. At S&T, Dr. Chen's teams have envisioned the possibility of merging robotics with aerial vehicles to inspect and maintain infrastructure to enhance public safety. This is no small undertaking and we are not doing it alone. At that August 2 event, I met and engaged with leaders from the International Society of Structural Health Monitoring of Intelligent Infrastructure, the U.S. Department of Transportation, and the Missouri Department of Transportation. Our university is known worldwide and has collaborative partnerships statewide, nationally and internationally. Missouri S&T has the opportunity to touch lives by conducting research that could lead to safer transportation. That, to me, is extremely inspiring.

Mo Deghani, Ph.D.

Chancellor, Missouri S&T



Dr. Genda Chen receives SHM Person of the Year

Dr. Genda Chen, professor and Robert W. Abnett Distinguished Chair in Civil Engineering at Missouri S&T, recently received one of two 2019 Person of the Year Awards given by the Structural Health Monitoring (SHM) Journal at its 12th International Workshop on Structural Health Monitoring.

These awards are given to individuals that work or have worked in government, industry or academic sectors from any region of the world and have made an outstanding contribution to the field of SHM. Awardees were nominated by experts in the SHM field and selected by an awards committee of editors and associate editors of the SHM journal.

Pictured from left to right are Dr. Genda Chen, Dr. Michael Todd (managing editor of the SHM journal), and Dr. Wieslaw Ostachowicz (member of the Polish Academy of Science).

Chen's nominations included mention of his leading work on lab-on-sensor theory for direct assessment of crack, corrosion and scour susceptibility of structures through innovations in sensor hardware design. In collaboration with his colleagues in electrical engineering, Chen improved the reliability of sensors and the relevance of practical applications and eased engineers' acceptance and adoption. Chen has also led the research community in analytical mode decomposition of vibration signals, together with adaptive wavelet transformation, for enhanced detectability of fatigue vulnerability with adaptive noise filtering capability.

Within the International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII), Chen has delivered invited presentations at several society conferences, was elected to be an ISHMII council member in 2013 and an ISHMII Fellow in 2019. He also chaired the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure in St. Louis, MO USA.

Since 2016, Chen has directed a nationwide University Transportation Center at Missouri S&T that consists of six research partner universities with over \$7 million in funding in five years. The goal of this center is to transform current inspection processes into a data-driven decision-making protocol for bridge inspection and maintenance. The data sets collected from sensors and non-destructive devices will be used to develop a risk-based inspection program and optimize and prioritize preservation strategies.

A member of the Missouri S&T faculty since 1996, Chen is also Director of the newly established Center for Intelligent Infrastructure at S&T. He earned a Ph.D. in 1992 from the State University of New York at Buffalo and was a postdoctoral trainee at the National Center for Earthquake Engineering Research. He is active in the American Society of Civil Engineers, Earthquake Engineering Research Institute, International Society of Optics and Photonics, International Society for Structural Health Monitoring of Intelligent Infrastructure, Structural Engineering Institute and Transportation Research Board.

Posted October 3, 2019-Missouri S&T News and Events



Missouri Local Technical Assistance Program offers Right-of-Way Training

The Missouri Local Technical Assistance Program (LTAP) is located at Missouri University of Science and Technology (Missouri S&T) and operates with funding from the Missouri Department of Transportation (MoDOT) and the Federal Highway Administration (FHWA). Missouri S&T's INSPIRE University Transportation Center (UTC) also supports the efforts of the Missouri LTAP by collaborating on relevant activities that further the impact of research conducted on campus and disseminate new information as well as resources to local public agencies (LPAs) throughout Missouri.

Missouri LTAP recently developed a training agreement with MoDOT that will make new courses available to local agencies throughout the state. The agreement allows MoDOT staff to coordinate and/or instruct courses for Missouri LTAP, thus creating courses for local agencies never before offered as part of the LTAP program. Dr. Heath Pickerill, Missouri LTAP Director, stated, "MoDOT has staff who are experts in many areas that are of interest to Missouri's local agencies. This partnership allows Missouri LTAP to provide new courses taught by individuals who have valuable knowledge and insight to share with LPAs as well as consultants and contractors involved in federally funded projects at the local level."



Dr. Heath Pickerill, LTAP Director

As an example, right-of-way training was recently coordinated through MoDOT based on very strong interest among Missouri LTAP customers and encouragement from the program's advisory committee. The training will be presented by FHWA's Resource Center. The course will assist LPAs in following the Uniform Act and abide by the necessary regulations when acquiring right-of-way for their projects. Pickerill revealed, "LPAs must follow these guidelines for any federal funding secured through the Local Programs, which, as outlined by MoDOT, provides federal funding to cities and counties for their infrastructure improvement projects. Therefore, it is imperative that they be aware of right-of-way regulations." He added, "Missouri LTAP is very pleased to finally offer this much needed training to the local agencies we serve." The training was held on October 16-17, 2019 in Columbia, MO. For more information, please visit www.moltap.org

Another course being developed in partnership with MoDOT staff includes basics of surveying. Because this course is not something that Missouri LTAP has a high-demand for all of the time, Pickerill shared, "Working with MoDOT staff offers a means of providing surveying information to local agencies in the most cost effective way possible when there is a demand." Some other topics being discussed include courses like introduction to materials, material inspection, asset management, and introduction to local traffic practices and safety.

In addition, Missouri LTAP now offers the Americans with Disabilities Act (ADA) course as part of its regular training schedule. This exciting development has been met with enthusiasm from local agencies, consultants, and contractors eager to review ADA guidelines as they apply to public projects. Mr. Ron Effland, instructor, last taught the course in 2016 while still working for MoDOT. Since retiring, Effland has joined Missouri LTAP as a contract instructor, allowing the course to be offered more frequently throughout the state. Several ADA trainings were held in the spring and several more are scheduled throughout the fall.

Finally, the INSPIRE UTC will collaborate with LTAP to deliver high-quality training programs to transportation professionals using new technology being developed in its research. INSPIRE will develop a robotic simulator to train the next generation of transportation workforce. Efforts will be made to reach professionals in state DOT bridge maintenance departments, consulting firms, and railway industries.

For more information on Missouri LTAP or to view a schedule of other upcoming classes, please visit the LTAP website at www.moltap.org.



Traffic Disruption-Free Bridge Inspection Initiative with Robotic Systems: A New POOLED-Fund Project Led by MoDOT

Starting in August 2019, the INSPIRE UTC Director, Dr. Genda Chen, led a five-year, pooled-fund study initiated by the Missouri Department of Transportation (MoDOT) in partnership and collaboration with six other State departments of transportation (DOTs). The goals of this five-year project are to engage closely with State DOTs in the early stage of technology development at the INSPIRE UTC, and leverage the Center's resources to develop case studies, protocols, and guidelines that can be adopted by state DOTs for bridge inspection with minimum adverse impact on traffic.

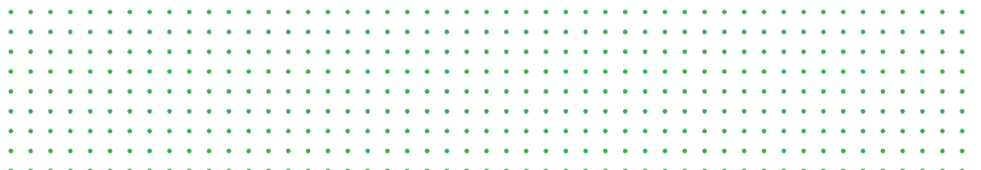
The initiative involves the integration, field demonstration and documentation of a robotic system of structural crawlers, Unmanned Aerial Vehicles (UAVs), Bridge Inspection Robot Deployment Systems (BIRDS), NDE devices, sensors, and data analytics. The proposed objectives of this initiative include, but are not limited to:

- Development of inspection/operation protocols for various types of bridges with the robotic system integrated into current practice.
- Comparison and correlation of bridge deck inspections from the top and bottom sides of decks to understand the reliability of traffic disruption-free bridge inspection from the underside of decks.
- Design and technical guidelines of measurement devices on a robotic platform for the detection of surface and internal damage/deterioration in structural elements, and for the change in lateral support of foundations.
- Data fusion and analytics of measurements taken from various imaging and sensing systems for consistency and reliability.
- Development of best practices on bridge inspection using the robotic system.

The future impacts of this project will benefit State DOTs by reducing costs and safety risks, and improving efficiencies and alleviating traffic disruption in the inspection and maintenance process. Bridge inspection often requires the use of heavy lifting and access equipment, thus increasing operation time and direct costs. If access to the inspected area must be made from bridge decks, the indirect costs associated with road closure multiplies. In such a case, travelers are frustrated with traffic congestion and, both the travelers and inspectors are subjected to a safety concern on high volume highways. Moreover, visual inspection is quite subjective and inconsistent. It is thus of economic, psychological and social importance to develop an alternative platform for bridge inspection that does not impact traffic flow and is faster, safer, cheaper, and more consistent.



The future impacts of this project will benefit State DOTs by reducing costs and safety risks, and improving efficiencies and alleviating traffic disruption in the inspection and maintenance process.



INSPIRE UTC Annual Meeting at SHMII-9 Conference

The INSPIRE UTC held its annual meeting on August 4-7, 2019 in conjunction with the 9th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-9) in St. Louis, MO (see Fig. 1 for conference participants). Technical presentations were made as part of the SHMII-9 Conference Program, allowing the INSPIRE PIs to share their research results and seek feedback from international participants. The business meeting within the INSPIRE UTC was held at the end of the SHMII-9 Conference, including the kick-off of the TPF (5)-345 Pooled Fund Study with representatives from seven (7) state departments of transportation. The SHMII-9 Conference was chaired by Dr. Genda Chen, INSPIRE UTC Director, and co-chaired by Dr. Sreenivas Alampalli, Director of Structure Management Bureau at New York State Department of Transportation.



Fig. 1. Group photo prior to the opening ceremony.

Drs. Genda Chen and Sreenivas Alampalli and Mr. Caesar Singh, University Grant Program Director from the U.S. Department of Transportation, delivered welcome remarks at the SHMII-9 Conference (see Fig. 2). The Conference received about 280 registrations from 21 countries, including 94 (33%) student attendees and 81 (29%) industrial/governmental participants.

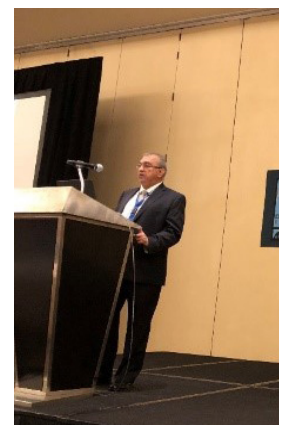


Fig.2. Drs. Genda Chen and Sreenivas Alampalli, and Mr. Caesar Singh deliver welcoming remarks.



The SHMII-9 Conference covered research and development, technology transfer, and technology demonstration in 52 sessions. It provided a forum for the exchange of ideas, knowledge sharing, and technology-need matchmaking in the global structural health monitoring (SHM) community. It also served as a unique venue to showcase the technologies and achievements in transportation infrastructure, demonstrate the practical value of SHM research, and raise public awareness of the need for further SHM research and applications. The Conference was sponsored by the International Association for Structural Health Monitoring for Intelligent Infrastructure (ISHMII) in collaboration with American Society for Civil Engineers (ASCE), American Society for Nondestructive Testing (ASNT), Transportation Research Board (TRB), American Concrete Institute (ACI), International Association for Bridge Maintenance and Safety (IABMAS), International Association for Life-Cycle Civil Engineering (IALCCE), and Missouri Department of Transportation (MODOT).

The three-day program included keynote lectures, invited lectures, panel discussion, and a technical demonstration of the latest sensing, nondestructive evaluation, and robotic technologies. The program also included a student poster competition to encourage student participation, a short course on fiber optic sensing applications, and a SHM Education workshop geared towards fostering incorporation of SHM concepts as part of undergraduate and graduate curriculums. The two-volume conference proceedings include 245 peer-reviewed, full-length papers submitted to SHMII-9.

Among 11 exhibitors at the SHMII-9 conference, the INSPIRE UTC displayed for the first time a hybrid vehicle of combined flying and traversing operation modes. The INSPIRE UTC also coordinated the SHMII-9 student competition among 25 posters (see Fig. 3).



Fig. 3. Hybrid vehicle show and student poster competition.

For more information, visit: shmii-9.mst.edu

Dr. Genda Chen Awarded ISHMII Fellowship



Dr. Genda Chen was presented with an ISHMII Fellow Award from Dr. Aftab Mufti during the Awards Ceremony at the SHMII-9 Conference.

Fellows are initiated by the ISHMII Council for their outstanding contributions to the development of the structural health monitoring (SHM) of civil structures. Nominees must be a Society member and hold or have previously held a senior position in academics, industry or government performing important work in engineering or science and be qualified to direct, conceive, plan or design engineering works, create an SHM undergraduate or graduate curricula in a university or have established an SHM research institute.

Center for Intelligent Infrastructure Established

Effective September 1, 2019, the Center for Intelligent Infrastructure (CII) is established at Missouri S&T in Rolla, MO. Dr. Genda Chen, INSPIRE UTC Director, serves as the inaugural Director for this newly established University Research Center.

The mission of the Center is to become Missouri S&T's research and education conduit for intelligent physical infrastructures, when overlaid by cyber infrastructure, to achieve their sustainability, safety, and resilience under environmental, operational, and extreme loads. The research focus of the Center lies in the integration of automation, informatics, and actuation into the life-cycle assessment, performance prediction, risk analysis, and post-disaster recovery of cyber-physical systems through multi-scale modeling and sensing.

The Center provides long-term, sustained support and services to externally-funded projects and research centers related to intelligent infrastructure, such as the INSPIRE UTC. It was welcomed during the Opening Ceremony on August 8, 2019 by campus leaders (Chancellor Mo Deghani, Vice-Provost and Dean for College of Engineering and Computing Richard Wlezien), representatives from state and federal agencies (Diana Furchtgott-Roth, Deputy Assistant Secretary for Research and Technology at the U.S. Department of Transportation, Caesar Singh, Director University Grants Programs at the U.S. Department of Transportation, and Jennifer Harper, Research Director at Missouri Department of Transportation), and international guests from China, Italy and the United Kingdom.

The Center also held an inaugural Open Forum on October 9, 2019 with members of the campus community. Topics of discussion included an overview of the center and mission, strategic plan, projected team expertise, leveraging opportunities, expanded opportunities, and center benefits and membership.



Missouri S&T Chancellor, Mo Deghani and CEC Dean Richard Wlezien deliver opening remarks.



Diana Furchtgott-Roth, Deputy Assistant Secretary for Research and Technology delivers a speech during the ceremony.



Jennifer Harper, Research Director at Missouri Department of Transportation presents the Missouri Center for Transportation Innovation.

**“I am looking forward to the growth of this new University Research Center as it builds strong collaborative relationships with our other URCs and with faculty across campus,”
Dr. Costas Tsatsoulis, Vice Chancellor of Research and Dean of Graduate Studies**



Visiting Scholars & Students join INSPIRE UTC



Shuling Gao: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Shuling Gao is a visiting scholar at Missouri S&T from Hebei University of Technology in Tianjin, China. Shuling recently joined the INSPIRE research team. She received her Ph.D. Degree in Civil Engineering (Structure Engineering) from Dalian University of Technology in Dalian, China. Her research is focused on the structural health monitoring of reinforced concrete/ECC structures.



Pu Jiao: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Pu Jiao received his B.S. Degree in Civil Engineering in 2016 from Xi'an Jiaotong University, China. He received his M.S Degree in Structural Engineering in 2019 from the Institute of Engineering Mechanics, CEA, China. He joined Dr. Chen's research group as a Ph.D. student in August 2019. His research interests include low-damage structures, intelligent infrastructure and damage identification for building structures and infrastructure.



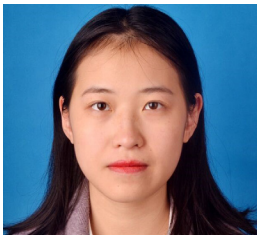
Pengfei Ma: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Pengfei (Kyle) Ma is a first-year Ph.D. student in the INSPIRE UTC group at Missouri S&T. His research topics mainly draw on structural health monitoring (SHM) and corrosion monitoring based on fiber optic sensor technology. Kyle's M.S. research area mainly focused on bridge weigh-in-motion as well as the mechanical performance of orthotropic decks under static and dynamic loadings.



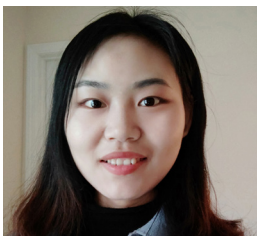
Erica Nesti: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Erica Nesti received a B.S. Degree in Chemical Engineering in 2017 from the University of Pisa, Italy and studied Material Engineering at the Polytechnic University of Turin, Italy. She has been at Missouri S&T for six months as a visiting student to work on her Master's Thesis. Her research project is to evaluate the corrosion performance of enamel coating to prevent the degradation of reinforced concrete and the influence of this coating on pipeline vibration.



Xi Wan: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Xi Wan is a visiting student at Missouri S&T from Central South University in Hunan, China. Xi received her B.S. Degree in Engineering from Wuhan University of Technology in July 2017. Her research focus is on modal parameter identification, system identification, structural dynamics, signal processing and finite element model. Currently, Xi is researching time-varying and nonlinear dynamical system identification using time-frequency analysis.



Mingxia Yang: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Mingxia Yang is a visiting student at Missouri S&T from Central South University (CSU) in Changsha, China. Mingxia received her B.S. Degree in Engineering from Zhengzhou University in July 2018. Currently, Mingxia is doing research in the area of "Health Monitoring and Performance Evaluation Methods of Bridges" with her advisor Dr. Genda Chen.



Ying Zhuo: Missouri S&T. **Research Advisor:** Dr. Genda Chen

Ying Zhuo is a Ph.D. student at Missouri S&T. Ying holds his B.S. and M.S. Degrees in Civil Engineering from Hunan University in China. When he completed his undergraduate program, he received the Excellent Graduation Design of his major. Ying recently joined the INSPIRE UTC research team and plans to focus on optic fiber sensors and probability of defect detection.

BRIDGE INSPECTION ROBOT DEPLOYMENT SYSTEMS (BIRDS)

This project aims to develop and build a solar-powered mobile test facility to support field tests at bridge sites and provide wireless communication between the bridge sites and the INSPIRE UTC at Missouri S&T. The mobile test facility is referred to as BIRDS; it houses climbing robots, unmanned aerial vehicles (UAVs), multimodal vehicles, sensors, nondestructive evaluation devices, data acquisition units, batteries, and miscellaneous tools. The BIRDS serves as a field station for data collection and transmission to the base station on the Missouri S&T campus, and as a means of transportation for an inspection crew.

This article introduces the recent development of a hybrid flying and traversing vehicle at the INSPIRE UTC. Such a multimodal vehicle was designed and prototyped for inspection of girder bridges, local repair of bridge elements near girders, and deployment of climbing robots into different parts of bridges during inspection. The hybrid vehicle is envisioned to operate for one hour or longer during inspection according to the following steps:

1. It flies to the underside of bridge deck and girders to be inspected,
2. Once in position, it grabs the bottom flange of a bridge girder with a specifically designed roller clamping system,
3. It traverses along the bridge girder, providing a stable platform for high quality imaging and nondestructive testing from on-board devices and cameras, and
4. It detaches from the bridge as it encounters obstacles, and flies to the next area of interest.

The hybrid vehicle must have an effective vehicle-bridge engagement/disengagement mechanism for smooth transition between the flying and traversing modes. Thus, design criteria of the vehicle include, but are limited to,

- In the flying mode, the vehicle is stable with necessary positioning precision and navigation guidance in a GPS denied environment.
- In the traversing mode, the vehicle with necessary positioning precision moves at a constant speed to provide a stable station for various measurements.
- In the transition period, the vehicle engages with a girder safely and efficiently.
- Overall, the hybrid vehicle must have the required payload for measurement devices or deployment of climbing robots, and the required flight time for bridge inspection and local maintenance.

The hybrid vehicle was sized and shaped mainly based on the required functions for I-girder inspection and for deployment of climbing robots. Fig. 1 shows the 1st prototype of a hybrid flying and traversing vehicle. The multimodal vehicle utilized two separate methods of transportation for flying and traversing. Such a design not only allowed a rapid development of the 1st prototype to demonstrate its concept but also increased its operation time during bridge inspection since traversing consumes less battery power.



Fig. 1. 1st prototype of the proposed hybrid vehicle.

The 1st prototype consisted of a custom-made main frame of carbon fiber materials with four plate arms, a flying system of four propellers installed at the ends of the four arms, a traversing system of two scissor clamps with two grips installed at the two ends of each clamp above the main frame, two 25V batteries together with speed and flight controllers attached beneath the main frame, and two spy cameras above the main frame for visual inspection.

For flight capability, it used four brushless 12V DC outrunner motors that were attached to the four plate arms. For traversing capability, four additional DC motors were used to engage the two scissor clamps. With the help of beveled 3D printed Onyx gears, the clamps were driven inward to pressure against the edges of the girder flange with their positions controlled by linear potentiometers. The clamps can accommodate a flange range of 38-47 cm (15-18.5 in). Each grip installed on the scissor clamps was a 3D printed onyx wheel that was overlaid with a flexible urethane coating to increase the coefficient of friction against the gripped beam to help with stability during inspection. The cameras wirelessly relayed real-time videos to the control station to assist with positioning of the vehicle.

Each 54.6 cm (21.5 in) propeller can support approximately 113 N (25 lbs), amounting to 450 N (100 lbs) for four propellers. To maintain a minimum 2:1 thrust-to-weight ratio for flight stability, the total weight on the vehicle must be below 225 N (50 lbs), which meets the maximum 55 lbs weight requirement stipulated by the Federal Aviation Administration regulations. The overall weight of the 1st prototype itself was about 118 N (27 lbs), leaving a payload of approximately 107 N (23 lbs) for other measurement devices.

A complete system test was performed to validate the BIRDS prototype in terms of flying, clamping, and traversing with a 43.2 cm (17 in) plank simulating the flange of an I-girder in bridge applications. The BIRDS launched from ground level upwards until it reached the wood plank. Once beneath the test fixture, the clamping system was successfully engaged with each wheel, as shown in Fig. 2. The traversing mechanism was tested back and forth along the wooden plank to ensure it functioned as designed. Motors were then throttled upwards as the clamping mechanism

was slowly disengaged. Once the clamps spread past the extent of the plywood plank, the throttle was lowered until the drone landed back on the ground.



Fig. 2. Laboratory tests of the 1st prototype in traversing mode.

Several observations can be made from the complete system test. The rotor arm flexibility concern was apparent during the initial takeoff and landing. Undesired flexing occurred at the cantilevered connection of the rotor arm to the main frame and at the ends of the slits in the main frame, which was cut to make room for the clamping mechanisms. This did not hinder the flight capabilities, but caused a slight bouncing motion to occur under landing impact loading and resulted in wire disconnection. Although clamping forces were not monitored during traversing, a large deflection of the wheels was not seen during the test. Therefore, the clamping mechanism can provide more than the minimum force necessary to clamp the BIRDS onto a girder and perform inspection. Using a position-controlled clamping mechanism without yet establishing a relation between flange sizes and a position on the remote controller did not cause an issue during the test conducted at a close standoff distance. On real-world bridges, this would not

be an option. If the size of a girder is unknown, a different positioning system will be needed to replicate laboratory results.

To facilitate the inspection and maintenance of river-crossing bridges, engineers often design and build a dedicated inspection platform guided between girders as shown in Fig. 3, costing over \$1M. The proposed and developed hybrid vehicle would be quite familiar to bridge engineers and inspectors, and potentially adopted in practice.



Fig. 3. Inspection platform used in practice.

In closure, the potential benefits of the developed hybrid vehicle include, but are not limited to:

- Increased operation time
- Stable measurement platform
- Ease in navigation
- Accurate positioning
- Cost Effectiveness
- Improved potential for adoption by bridge inspectors

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ABOUT THIS PROJECT

Led by Dr. Genda Chen, Professor and Abbett Distinguished Chair in Civil Engineering and Director of the INSPIRE (INSpecting and Preserving Infrastructure through Robotic Exploration) UTC at Missouri University of Science and Technology, the Bridge Inspection Robot Deployment Systems project is part of the INSPIRE UTC Research Program in collaboration with the MinerFly team who supports various Missouri S&T research activities in robotics. For more information on this INSPIRE UTC project, please contact Dr. Chen at inspire-utc@mst.edu or (573) 341-6114.



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A SIMULATION TRAINING AND CONTROL SYSTEM FOR ROBOTIC INSPECTION OF STEEL BRIDGES

Deterioration of steel structures in bridges directly costs approximately \$10B per year and costs an order of magnitude more in indirect expenses. In the US alone, more than fifty thousand steel bridges are either deficient or functionally obsolete and likely present a growing safety concern. We expect cost and safety concerns to continue increasing as our nation's bridges approach or exceed designed lifespans. However, current bridge inspection requires much human effort and time as well as expensive specialized equipment. This project leverages new advances in simulation training, autonomy, control, and sensors under the INSPIRE umbrella to more quickly, cost effectively, safely, and reliably inspect bridges using human-robot bridge inspection teams.

Our aim then is to bring together INSPIRED advances in robotics, sensors, and simulations to help human inspectors work with and manage a team of robots that reliably and safely inspect bridges quickly and thoroughly. Since robot and sensor development is ongoing, we started by developing a software simulation that can be quickly modified to integrate advances in robotics, sensors, and theory. In simulation, we can cost-effectively explore multiple ways of monitoring and managing robots and their sensors thus developing effective monitoring and control interfaces, inspection processes, and control algorithms for quick, effective bridge inspection. Furthermore, simulations have been used in operational training in many complex systems from airplane piloting and repair training to cultural awareness training. Thus, once we have explored and converged on effective inspection processes for human-robot teams, our simulator can be used in workforce training for human inspectors to learn how to work with robots and refresh their knowledge of robots, sensors, and inspection procedures.



Fig. 2 Simulation Interface Screenshot Showing Multiple Feeds Across The Bottom and Multiple Robots.

Finally, when we connect the simulated world to the real-world replacing simulated entities with real robots, the same interface that was used in simulation training controls real-world robots in an operational environment. This speeds up transitioning from training to operation further saving time and cost. Fig. 1 shows our system architecture. The simulation interface was built using the Unity game engine enabling easy running on PCs, tablets, VR-devices, and phones. To connect to real-world robots, we built a bridge to the Robot Operating System (ROS), the de-facto standard operating system and communications interface for both industrial and research robots.

Fig. 2 is a screenshot from our simulation that currently supports UAVs and climbing robots with associated sensors. Current control technology for both types of robots relies on a model that assumes one operator per robot, that is, teleoperation. Such a simple model does not work well when extended to routing and controlling multiple robots since costs increase as the number of human operators increases. Instead, we developed autonomous control algorithms that enable a single operator, with some training, to control multiple, heterogeneous robots. Human robot interaction design is key to human-robot teaming. However, interaction design depends on robot autonomy. On one end with no autonomy, we have simply teleoperation with one operator per robot. On the other end, the operator pushes a start button and fully autonomous robots inspect the complete bridge. Teleoperation is too expensive in terms of cost of human effort while full autonomy is too error prone and not within the project's scope. Instead we propose to provide inspection robots with limited cost-effective autonomy overseen and managed by a human operator. Current and prior work indicates that a surprising amount of control can be achieved by implementing two simple behaviors in robot hardware. First, climbing robots on trusses

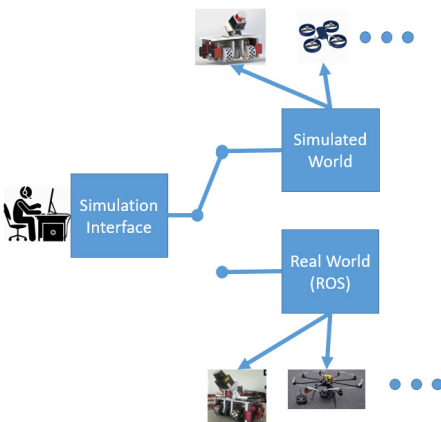


Fig. 1 Simulation Training and Control System Architecture.

need to move from one end of a truss to the other. And second, flying robots need to move to an operator supplied location. By sequencing such behaviors – commanding robots to follow a sequence of moves – we can achieve our goal of fast, cost-effective bridge inspection.

Steel truss bridges contain thousands of trusses. A human operator would find it excruciatingly difficult and tedious to pick out all traversable truss members for robots to (move-to and) inspect in optimal sequence. Instead, we need an automated routing algorithm to generate routes – a sequence of members to traverse during inspection. Our recent results indicate that

we can use genetic algorithms to automatically generate such routing sequences for a robot that covers all trusses on a bridge in minimal time. We are extending this work to multiple robots working simultaneously and speeding up the genetic algorithm to provide route generation for bridges with thousands of trusses. Table 1 shows genetic algorithm performance on a set of benchmarks for one, two, and five robots traversing all bridge members. The table shows that we are close to optimal and that the time needed to inspect a bridge can decrease linearly as we increase the number of robots.

Table 1 Performance of GA on MM k-CPP benchmark problems.

Problem	V	E	Lower Bound	Best $k = 1$	Percent Above Lower Bound	Best $k = 2$	Speedup $k = 2$	Best $k = 5$	Speedup $k = 5$
gdb1	12	22	252	270	7.143 %	130	2.077	53	5.094
gdb2	12	26	291	298	2.405 %	146	2.041	63	4.73
gdb3	12	22	233	246	5.579 %	120	2.05	49	5.02
gdb9	27	51	219	236	7.763 %	119	1.983	53	4.453
gdb10	12	25	252	260	3.175 %	128	2.031	53	4.906
gdb11	22	45	356	374	5.056 %	192	1.948	77	4.857
gdb12	13	23	334	356	6.587 %	173	2.058	70	5.086
gdb17	8	28	84	89	5.952 %	44	2.023	19	4.684
gdb18	9	36	158	164	3.797 %	80	2.05	32	5.125
gdb19	8	11	45	47	4.444 %	23	2.043	10	4.7
val4	41	69	343	381	11.079 %	194	1.964	89	4.281
val5	34	65	367	401	9.264 %	219	1.831	105	3.819
val7	40	66	249	273	9.639 %	146	1.870	78	3.5
val8	30	63	347	386	11.239 %	202	1.911	88	4.386
val9	50	92	278	309	11.151 %	169	1.828	97	3.186
Averages	-	-	-	-	6.952%	-	1.981	-	4.522

Given a route, a single human operator can select and command inspection robots to move to route start positions and then simply monitor the robots and their sensor feeds as they proceed to inspect all trusses on their route. UAVs with visual and multispectral cameras tasked with inspecting (moving to) problem areas can provide the operator with an option of re-tasking truss climbing robots to prioritize such focus areas and to take action when

robots fail. Near-real time route generation, multi-robot situational awareness for operators through our interface, and low-level relatively easy to develop autonomy for inspection robots, combine to achieve our objective of fast, cost effective, reliable bridge inspection. Videos of the system managing real and virtual robots may be viewed at <https://ecsl.cse.unr.edu/>.

ABOUT THIS PROJECT

Led by Dr. Sushil J. Louis, Professor in Computer Science and Engineering at the University of Nevada, Reno (UNR) this Simulation Training and Control System project is part of the INSPIRE UTC research program. The project was based on previous work funded by the NSF and ONR.



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INSPIRE WEBINARS

RECENT WEBINARS



DATA TO RISK-INFORMED DECISIONS THROUGH BRIDGE MODEL UPDATING

Presented: September 25, 2019

Speaker: **Dr. Iris Tien**

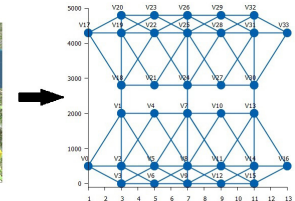
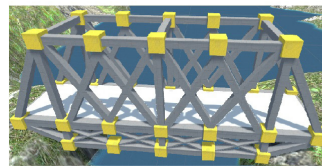
Assistant Professor, School of Civil and Environmental Engineering
Georgia Institute of Technology

A PERFORMANCE-BASED APPROACH FOR LOADING DEFINITION OF HEAVY VEHICLE IMPACT EVENTS

Presented: June 5, 2019

Speaker: **Dr. Anil Agrawal**

Herbert G. Kayser Professor of Structural/
Bridge Engineering
The City College of New York



SIMULATION TRAINING AND ROUTE OPTIMIZATION FOR BRIDGE INSPECTION

Presented: December 4, 2019, 11:00 am (Central)

Speaker: **Dr. Sushil Louis**

Professor of Computer Science and
Engineering
University of Nevada, Reno

Register: inspire-utc.mst.edu/webinars

Since the 1970s, simulation training has developed operational trainers for a variety of complex systems from pilot flight simulations to cultural awareness training simulations. When connected to the real world, such simulation training interfaces can drive real vehicles and systems. We have been building a Simulation Training And Control System (STACS) for autonomous bridge inspection that uses a simulated world to train inspectors to control a heterogeneous group of robots. The objective is that, once trained, inspectors can use the same STACS interface used in training to control multiple real robots simultaneously during a bridge inspection task. We first built a multi-robot control interface and simulated environment so that a single operator may manage at least two types of robots. Second, we developed a new optimization algorithm for automatically and quickly generating near-optimal routing for n robots to cooperatively cover every truss while minimizing inspection time. This webinar describes and demonstrates STACS, provides optimization results corresponding to time (and thus cost) saved in bridge inspection. Results show that we can significantly reduce bridge inspection time with inspection robots and that the time needed decreases in inverse proportion to the number of robots available for inspection.

UNLV PARTNERSHIP WITH TESLA GIGAFACTORY

In Summer 2019, Tesla partnered with the University of Nevada, Reno (UNR), the University of Nevada, Las Vegas (UNLV) and the Desert Research Institute (DRI). This partnership was for a Robotics Academy for K-12 teachers. INSPIRE UTC research student Blake Hament was among the instructors for the week-long program that trained 200 Nevadan middle and high school teachers. This experience led to dialog with Tesla to apply Blake's work with LIDAR scanners for robots in construction. This resulted in a task order to help monitor the construction of the Reno-based Tesla Gigafactory. Currently, a UNLV undergraduate researcher is on-site in Reno. He is being advised by Blake to develop 3D models and scans as the Gigafactory is being constructed. Such work is viewed as an important step forward in real-time construction monitoring and worker safety. Ground and aerial robots would perform scans that can mitigate delays and accelerate construction.

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RECENT KEYNOTE/INVITED PRESENTATIONS

- **"Structural System Identification and Model Updating,"** 12th Asia-Pacific-Euro Summer School on Smart Structures Technology (APESS), Sapienza University of Rome, Rome, Italy, July 2019 (Yang Wang)
 - **"Empowering and Rejuvenating Civil Engineering with Informatics, Automation and Actuation,"** Georgia Institute of Technology, Atlanta, GA, September 23-24, 2019. (Genda Chen)
-

WEBINAR ARCHIVES

- 2019
- Data to Risk-Informed Decisions Through Bridge Model Updating
By Dr. Iris Tien, Georgia Institute of Technology, September 25, 2019
 - A Performance-Based Approach for Loading Definition of Heavy Vehicle Impact Events
By Dr. Anil Agrawal, The City College of New York, June 5, 2019
 - Battery-Free Wireless Strain Measurement Using an Antenna Sensor
By Dr. Yang Wang, Georgia Institute of Technology, March 6, 2019
 - Assistive Intelligence (AI): Intelligent Data Analytics Algorithms to Assist Human Experts
By Dr. Zhaozheng Yin, Missouri S&T, January 30, 2019
- 2018
- Toward Autonomous Wall-climbing Robots for Inspection of Concrete Bridges and Tunnels
By Dr. Jizhong Xiao, The City College of New York, September 19, 2018
 - Climbing Robots for Steel Bridge Inspection and Evaluation
By Dr. Hung La, University of Nevada, Reno, June 21, 2018
 - Microwave Materials Characterization and Imaging for Structural Health Monitoring
By Dr. Reza Zoughi, Missouri S&T, March 15, 2018
- 2017
- Drone-Enabled Remote Sensing for Transportation Infrastructure Assessment
By Mr. Colin Brooks, Michigan Tech Research Institute, December 13, 2017
 - Drone-Enabled Remote Sensing for Transportation Infrastructure Assessment
By Dr. Genda Chen, Missouri S&T, September 28, 2017

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scholarsmine.mst.edu/inspire_webinars

FIRST Competition at Kaleidoscope Discovery Center

The Kaleidoscope Discovery Center (KDC) located in Rolla, MO was able to provide area children with opportunities to participate in robotics education via the For Inspiration and Recognition of Science and Technology (FIRST) program with support provided by the INSPIRE UTC. FIRST is an international organization whose mission is to inspire innovation and build skills in engineering, science, communication and leadership. During this event, KDC organized and supported four teams with a total of 30 middle school students for the 2018-2019 FIRST LEGO League competition season. Two of the teams were selected to compete at regionals in Columbia, MO. Support from the INSPIRE UTC provided a scholarship for an independent team from Rolla to attend the regional competition.



For more information, visit: thekaleidoscope.org/first-robotics

Future City Competition at Kaleidoscope Discovery Center



In Summer 2019, KDC drew inspiration from participation in the previous FLL, Jr. competition and Future City Competitions in the planning and completion of the FLL: Team Ready summer camp, with a theme of "Engineering the Future City," and several other week long camps focused on robotics education. Students work as a team with an educator and engineer mentor to plan cities using SimCity™ software, research and write solutions to an engineering problem, build tabletop scale models with recycled materials, and present their ideas before judges. KDC was pleased to host 184 children in these camps with the support from INSPIRE UTC.



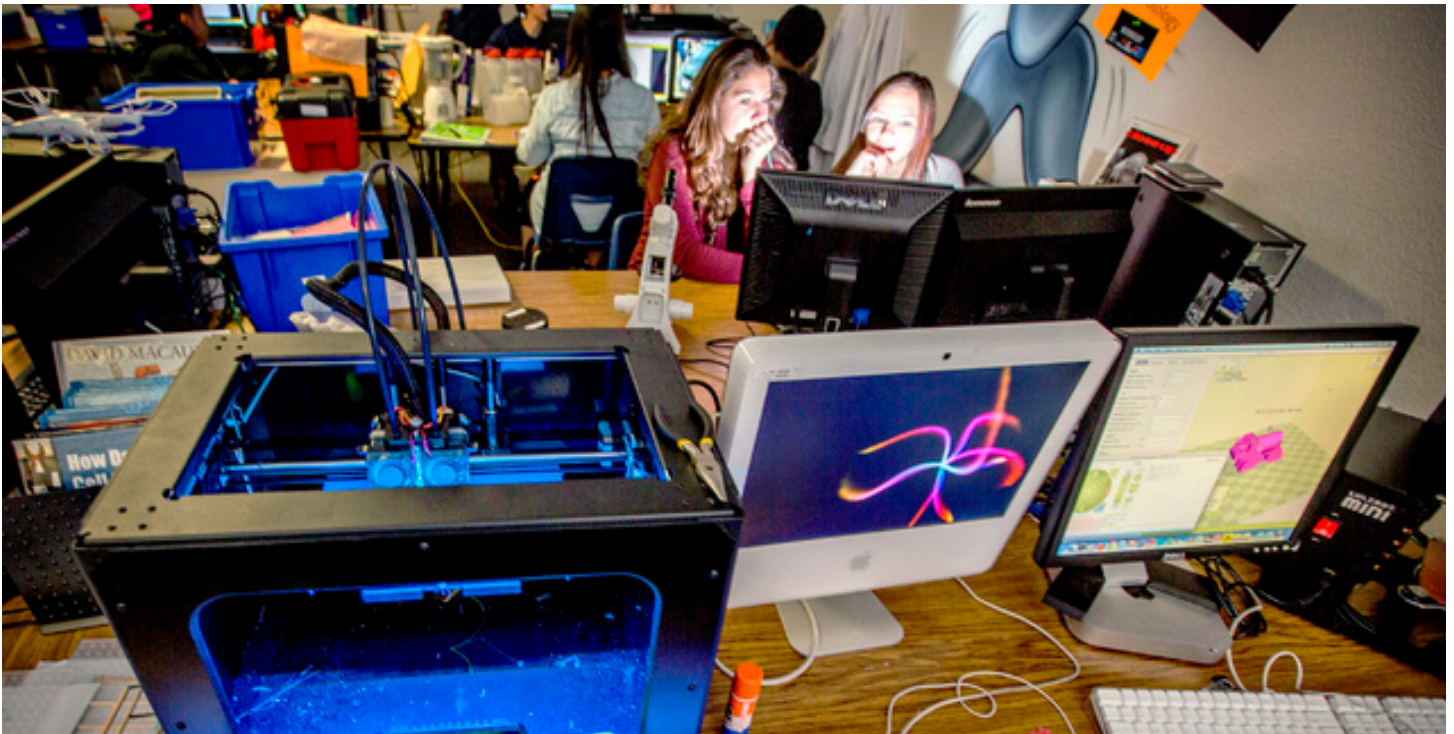
OUTREACH

UNLV Robotics Laboratory Show - Saturday K-12 Programs

The UNLV team continues to work with the neighboring Clark County Las Vegas Public Library in the Saturday K-12 programs.

Lesson plans include computer-aid-design (CAD), 3D printing, and embedded controllers (Arduino). Additionally, the team serves institutional outreach programs, namely Upward Bound. This program is UNLV's outreach to middle school students each Saturday led by hands-on STEM labs including drone (programming), augmented reality (projection mapping) and embedded control (Arduino).

The team also participated in the Nevada-wide Robotics STEM program sponsored by Tesla, which is an event brought to over 50 K-12 science teachers for intensive training.



For more information, visit: inspire-utc.mst.edu/events



OPEN POSITIONS

Center for Intelligent Infrastructure

The Center for Intelligent Infrastructure (CII) at Missouri S&T seeks to expand its research capabilities in autonomous preservation and resilience of civil infrastructure by inviting applications for the following key positions. Candidates are required to work in laboratory and field environments, doing heavy lifting and travelling long distance to job sites as needed. Interviews will begin in November 2019 and continue until the positions are filled. For more information, contact Dr. Genda Chen at gchen@mst.edu.

RESEARCH ASSISTANT/ASSOCIATE PROFESSOR IN ROBOTICS, COMMUNICATION, AND VISUALIZATION

Candidates must have an earned undergraduate degree in electrical/mechanical/computer/systems engineering from an ABET/EAC accredited program or equivalent, and an earned Ph.D. in the same or closely related field. Superior communication and interpersonal skills, and the ability to engage in collaborative and interdisciplinary research are also required attributes. Hands-on experience in system integration and robotics research experience in platform mechanics, unmanned aerial vehicle (UAV) navigation and guidance in GPS blind environment, aerodynamic stability, satellite communication system, and wireless data transmission and certification, are required. Licensure as a UAV pilot must be attained within 6 months of appointment. Interested candidates should electronically submit an application consisting of a cover letter, a current curriculum vitae, a statement of research and teaching interests and goals, and complete contact information for five references to the Human Resource Office at <https://hr.mst.edu/careers/>. Submitted materials must include a **position reference number 00075310**.

RESEARCH ENGINEER IN BRIDGE INSPECTION AND MAINTENANCE

The successful candidate must have an earned undergraduate degree in civil engineering from an ABET/EAC accredited program or equivalent, and at least 1 year of practical experience in bridge inspection and maintenance, particularly with the state department of transportation. Superior communication and interpersonal skills, leadership capabilities, and the ability to engage in collaborative and interdisciplinary research projects are also required attributes. Licensure as a professional engineer in civil engineering must be attained in the State of Missouri within 1 year of appointment. Knowledge about any bridge management software such as PONTIS is strongly encouraged. Familiarity to nondestructive evaluation and test of bridges is a plus. Interested candidates should electronically submit an application consisting of a cover letter, a current curriculum vitae, a statement of research interests and goals, and complete contact information for three references to the Human Resource Office at <https://hr.mst.edu/careers/>. Submitted materials must include a **position reference number 00075187**.

POST DOC IN ROBOT RESEARCH, DEVELOPMENT, AND OPERATION

The successful candidate will be expected to design, manufacture and test special flying and climbing robots or their combination for safe and efficient bridge inspection and maintenance. System integration of various parts from open sources and defect identification from images will be the main duties of this position. The outcomes of the related work are robots that can climb on a structural surface or fly and traverse along a bridge beam as demonstrated in both laboratory and field conditions. Fusion techniques from a set of heterogeneous data will be developed.

POST DOC IN INFRASTRUCTURE AND COMMUNITY RESILIENCE

The successful candidate will be expected to explore and develop an open-source, cloud-based, modulated digital twins of physical infrastructures overlaid with cyber infrastructure to achieve their sustainability, safety, and resilience under environmental, operational, and extreme conditions. Specific duties include, but are not limited to, the multi-scale modeling of infrastructure and community resilience, and the identification of impact that multi-scale sensing and hybrid computation/instrumentation strategies may have on the improvement of societal resilience.



INSPIRE University Transportation Center

Missouri University of Science and Technology
112 Engineering Research Laboratory, 500 W. 16th St.
Rolla, MO 65409

Connect with INSPIRE UTC:

- **FACEBOOK:** [BIT.LY/20XESW4](https://bit.ly/20XESW4)
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Contact Us

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UPCOMING EVENTS

TECHNOLOGY TRANSFER

November 22-24, 2019

Invited Presentation: "Robot-assisted Bridge Inspection and Maintenance", ICRAI 2019 Conference, Singapore
icrai.org

December 4, 2019

INSPIRE Webinar: "Simulation Training and Route Optimization for Bridge Inspection", by Dr. Sushil Louis, University of Nevada, Reno
inspire-utc.mst.edu/webinars

OUTREACH

November 15, 2019

Expanding Your Horizons Camp, Missouri S&T, Rolla, MO
<https://pce.mst.edu/youth/eyh/>

February 23, 2020

First Lego League Competition, Missouri S&T, Rolla, MO
<https://thekaleidoscope.org/product/first-lego-league/>

February 27-March 1, 2020

National Society of Black Engineers, Rolla, MO
<https://sdi.mst.edu/pci/>

News

January 12-16, 2020 TRB Annual Meeting
trb.org/Annual Meeting

June 8-10, 2020 CUTC Summer Meeting
westerntransportationinstitute.org

inspire-utc.mst.edu/events