JAMES WORTH
BAGLEY
COLLEGE OF ENGINEERING
MISSISSIPPI STATE UNIVERSITY

Annual Report 2014

CAVS

Center for Advanced Vehicular Systems

Mission

CAVS strives to be a world-class center of excellence for research, technology and education equipped to address engineering challenges facing U.S. mobility industries. Utilizing high performance computational resources and state-of-the-art analytical tools for modeling, simulation and experimentation, CAVS will provide a distinctive, interdisciplinary environment wherein next-generation engineers and scientists train alongside field experts to investigate, design, and verify novel solutions in materials, propulsion, and design for efficient human and vehicle mobility. Harnessing our broad impact research along with our state, national and international industrial alliances, CAVS will support economic development and outreach activities throughout the State of Mississippi.

Vision

The Center for Advanced Vehicular Systems (CAVS) will be a global leader in interdisciplinary education and research for the development of engineering solutions that expand and enhance the design, technology, production, and infrastructure necessary for sustainable mobility.

CAVS

Box 5405, Mississippi State, MS 39762 ▪ 200 Research Blvd., Starkville, MS 39759 ▪ Ph: 662.325.5431 ▪ Fax: 662.325.5433 ▪ www.cavs.msstate.edu

Writer/editor • *Diane Godwin, HPC²*
Designer • *Dianna Janus, HPC²*
Photographers • *Megan Bean, Russ Houston, Beth Newman ~ Office of Public Affairs, and Dianna Janus ~ HPC²*

Director's Message

In 2014, CAVS faculty and staff continued to garner notable achievements in research and we have highlighted a few of them in this annual report. In our goal to be a world-class center of excellence we are continuing to add new areas of research with a high payoff potential, as well as nurture our present strengths. This year was significant in that substantial progress was made in securing additional research funding from foundations and industry.

RESEARCH FOR PRODUCTIVE COLLABORATIONS

CAVS continued to focus on strengthening its partnership with the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg and its High Performance Computing Modernization Program. Mississippi State University (MSU), through its High Performance Computing Collaboratory (HPC2), has supported DoD high performance computing software needs since 1990. This support has been through a multitude of long term initiatives funded by NSF, DoD, and industry. This joint enterprise includes the NSF Engineering Research Center for Computational Field Simulation, the Center for DoD User Productivity Enhancement and Technology Transfer (PETT), the Simulation Based Reliability and Safety Program (SimBRS), and most recently the Computational Research and Engineering Acquisition Tools and Environments program (CREATE). Through this history of support to military high performance computing program needs and software development, MSU has developed a rich understanding of military software systems and the personnel and expertise needed to support major DoD software requirements.

RELEVANT RESEARCH FOR INNOVATION AND DEVELOPMENT

CAVS work with ERDC is to support the CREATE-GV (ground vehicle) software development. CREATE-GV had as its drivers the high acquisition costs and lengthy development period to build and field a new ground vehicle coupled with the recognition of the dynamic world conditions in which our forces may be deployed (e.g., rapidly changing technology, asymmetric warfare). These drivers spurred the recognition for a new design paradigm that would require the rapid development and fielding of weapon systems capable of adapting post deployment. The CREATE paradigm is to develop physics-based software to identify design defects throughout the acquisition process, thus substantially reducing acquisition time and cost overruns. This physics-based computational evaluation approach facilitates life cycle performance predictions (i.e., from concept to production to sustainment) of virtual prototypes. The intent is to substantially reduce acquisition costs early in the development cycle and minimize the number of expensive redesigns inherent in most large DoD acquisition systems.

RESEARCH IS STATE ECONOMIC DRIVER

To help achieve CAVS and MSU's role to be an economic development engine for the state of Mississippi, 2014 saw the inception of CAVS' sister organization the Institute for Systems Engineering Research (ISER) on the campus of ERDC in Vicksburg. ISER's mission is to improve engineering, design, and process systems by developing next-generation computational tools for new systems and products that will assist decision makers in selecting the most appropriate courses of action to resolve issue(s) related to ERDC equities or projects and reduce risk of the U.S. industrial base. The Institute's research vision is to revolutionize system engineering processes and virtual prototyping through computational science and engineering leading to a dual use capacity that will enhance innovation in the DoD and strengthen the U.S. industrial infrastructure. ISER is a collaborative effort between MSU and ERDC and complements the economic development and industry support presently given to the state through CAVS Extension in Canton, Mississippi.

RESEARCH REINFORCES MANUFACTING INDUSTRY

CAVS continues to support the state of Mississippi's industrial enterprise through multiple Manufacturing Extension Partnership projects. Plans are being developed to support the engineering and manufacturing needs of the Yokohama Tire Corporation's West Point facility once it is in production in 2015. Also, several projects to support the Toyota Blue Springs plant were initiated in 2014.

Next year holds much promise for CAVS as several of the initiatives described in this report begin to mature.

Scientists Excel at Research to Steer the 'Smart Car of the Future'

- Create a hybrid system with almost no battery, electric motor drive for control of the front and rear wheels versus using conventional drivetrain technology; check ✓
- Ensure torque vectoring to improve vehicle's fuel efficiency and traction—better handling in turns and other maneuvers; check ✓
- Confirm that the vehicle will get more than 50 miles per gallon of fuel; check ✓
- Make sure the battery is small enough not to compromise any passenger space; check ✓
- Include regenerative braking, a process which the electric motor helps slow down the vehicle when drivers brake, and recapture energy normally lost in the process to recharge battery and improve vehicle efficiency; double-check ✓ ✓
- No sacrifices in power density, in fact improve upon power density of the vehicle; check ✓
- Guarantee that emissions are within or lower than Environmental Protection Agency (EPA) standards; check ✓
- Confirm that the vehicle can run off gasoline, diesel or any alternative fuel; check ✓

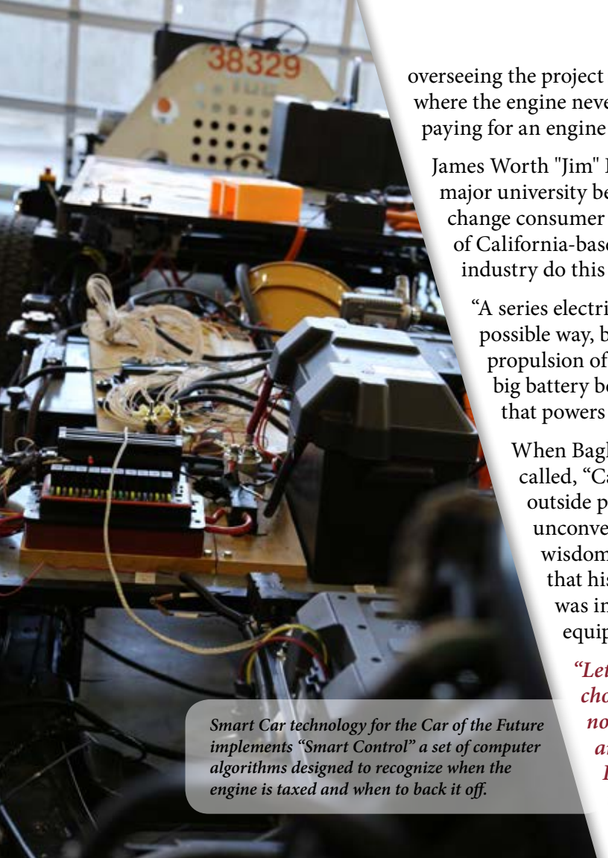
This is the checklist CAVS research engineers are completing to create "Smart Car" technology for powertrains of the future.

The Mississippi State Center for Advanced Vehicular Systems "Car of the Future" team records energy data before they put on the vehicle's frame. From left are mechanical engineering graduate student Jeremiah Hayes of HornLake; lead engineer Matthew Doude, CAVS research associate; and electrical engineering graduate student Quintin Grice of Woodland.
Photo by Russ Houston

Using supercomputers to model and simulate the developed systems and control algorithms, MSU is stepping "out of the box" to prove new hybrid technologies. The new hybrid system is a tally of preferences that most hybrid series vehicles of today don't meet. Currently, American consumer acceptance and purchase of typical hybrid cars makes-up just 3 percent of the market.

Zach Rowland, principal investigator and deputy director of CAVS said. "We are demonstrating how we can create improved energy systems that can make vehicles more affordable and efficient, without sacrificing performance or the environment."

"Most of the hybrids on the market have a huge battery that sacrifices passenger space, power density and torque—the ability to power the wheels for traction and handling," Mike Mazzola, associate director at CAVS and one of the lead scientists



Smart Car technology for the Car of the Future implements "Smart Control" a set of computer algorithms designed to recognize when the engine is taxed and when to back it off.

overseeing the project said. "They have a modest all electric range from 40 to 50 miles where the engine never turns on; it provides good fuel mileage, but consumers are paying for an engine that rarely turns on."

James Worth "Jim" Bagley, a 1961 and 1964 MSU electrical engineering alumnus and major university benefactor, wants to tap Mississippi State research expertise to change consumer acceptance of hybrid cars. The former CEO and board chairman of California-based Lam Research Corp., believes CAVS researchers can help the industry do this by creating a new hybrid series that consumers want.

"A series electric power train lets you operate the engine in its most efficient possible way, because the small electric motor is solely designated for the propulsion of the wheels," Mazzola explained. "We eliminate the need for a big battery because the engine drives a generator that produces electricity that powers the motor that drives the wheels."

When Bagley presented his visionary list and avant-garde research project called, "Car of the Future," MSU CAVS researchers, along with other outside peer professionals, considered his proposal as impractical and unconventional thinking that goes against all conventional engineering wisdom. Yet, Bagley was able to sell them on the idea by demonstrating that his father was a pioneer in the heavy equipment industry. His dad was instrumental in constructing electric drive units for heavy industrial equipment; what scientists recognize now as hybrid electric drive.

"Let's face it, Jim is right, we need to realize that the industry's first choice in producing the type of hybrid cars that are on the market now are not gaining wide scale consumer acceptance because they are expensive and the buyer has to give up too many preferences. In the meantime, no one has based designing a car using our method of hybrid electric technology," Mazzola said. "Until now."

U.S. Environmental Protection Agency Region 4 representatives visit CAVS. They are interested in the "Smart Car" technology for powertrains of the Future.

Bagley is funding the project and used his business acumen to set the standard. His goal is to enable CAVS researchers and students to take all the knowledge they gained from participating in and winning the U.S. Department of Energy's EcoCAR Advanced Vehicle Technology Competitions and put it on the road. So far CAVS researchers have been able to meet his goals for the project. And they have generated interest and partnerships with several key original equipment manufacturers and a visit by the U.S. Environmental Protection Agency. The EPA has a vested interest in providing positive steps in dealing with energy needs and prices, while protecting and solving environmental problems.

"The interest from industry and the EPA is an acknowledgement of our effort in the advancement of this technology and our relevance in this area," Rowland said.

Students working on their doctorates in engineering are currently sharing their findings of how they are improving the IQ of a hybrid series vehicle. One of their main enabling factors, "Smart Control" is a set of computer algorithms designed to recognize when the engine is taxed and when to back it off.

"Twenty years ago we wouldn't have been able to use this technology because cars didn't have the sophisticated computer platforms that are now a standard part of every car on the market," Mazzola said. "So, we're developing really smart software that fixes the problem of creating a series hybrid with small energy storage. Right now we're developing them in modeling and simulation and testing them on real cars in the lab at CAVS, so consumers can have a hybrid series car to drive the way they want and still receive the benefit of an advanced powertrain."

This project is enabling CAVS researchers and students to combine past EcoCAR culture and experiences with current cross-disciplinary knowledge and resources to prove to the world that Mississippi has the capabilities to provide a solution for the passion of driving. It also addresses the international problem of balancing energy needs with environmental responsibility.

Rowland summed it all up with, "We're developing the new technology and at the same time developing the engineers that will provide the capabilities to design the next generation of vehicles."

Research and Students 'ACEL' into the Future

CAVS scientists are designing novel engine combustion strategies for the vehicles of the future that will achieve higher fuel economy, more engine power, and are safer for the environment. This mind probing analysis is called low temperature combustion engine research. The work is supported by the creation of a new Advanced Combustion Engines (ACE) Laboratory, which when combined with MSU's research expertise in this area, is one of the finest in the southeast.

"We have a 35' x 35' lab that is filled with test beds holding engines from a variety of classes ranging from a single-cylinder, compression-ignition research engine; an automotive-size four-cylinder, diesel engine; to a 12.9 liter, heavy duty diesel," said Kalyan Srinivasan, associate professor of mechanical engineering.

The new ACE laboratory is only 4 years old and it was at this time that Sundar Krishnan and Kalyan Srinivasan began dedicating their careers to designing novel engine combustion strategies for vehicles that would improve fuel efficiency and power density, while at the same time reduce emissions. The two professors started at ground zero to build a lab and to establish themselves as credible researchers in the field. Meanwhile, federal fuel economy and pollution emission standards were on the rise. For that reason and due to a sluggish economy, engine manufacturers, trucking companies, and even everyday commuters have turned to researchers like Krishnan and Srinivasan for answers to cut engine fuel consumption and emissions as well as consumer costs.

"Since a lot of our industrial sector runs on diesel fuel for the transportation of goods this is an important area in which to conduct the research to develop technology that could save them money," said Sundar Krishnan, associate professor of mechanical engineering. "Just the exhaust after-treatment devices on truck engines can cost more than $5,000, so engine manufacturers are looking for other low-cost ways to build cleaner engines, while maintaining fuel efficiency and power density."

Although diesel engines are more fuel efficient, they have serious pollutant emissions problems. The catalytic converters that clean up pollutants created by a gasoline powered spark ignition engine do not work for diesel engines.

"Nitrogen oxides (NOx molecules) are formed in the high temperature regions in a diesel engine and they are harmful, pollutant, engine emissions." Srinivasan further explained, "What we've done is to use propane as the main fuel and ignite it using a small amount of appropriately timed diesel fuel injection. Basically, the diesel ignites the propane mixture—diesel is easier to ignite—so, we reduce the diesel amount and provide most of the fuel energy from propane. As a result, there is better diesel disbursement in the combustion chamber and that reduces the hot spots, so we try to keep those temperatures down by dispersing the diesel. Now, we don't have those hot regions where NOx form. We've cut those pollutants without any after-treatment. Another advantage—we run this whole combustion system with excess air, and that allows for the efficient use of the fuels and keeps the smoke emissions low."

Yet, Krishnan and Srinivasan will tell you there isn't the so called "silver bullet" for a solution, because while they have discovered a way to eliminate NOx and smoke pollution, the catch is, in doing so, other pollutants like unburned hydrocarbons and carbon monoxide go up. It's frustrating because both are environmental toxins and cause a loss of fuel efficiency, which is the main benefit of using diesel engines.

"It is kind of like playing the game Whack-a-mole," Srinivasan said. "We have three major things that we try to deal with in an engine, fuel efficiency, pollutants, and power density and these three don't simultaneously work together. If you devise a strategy to reduce one, the other two are going to go up or will be compromised. Our challenge is to devise a strategy to whack all three down and get them to be compliant."

A local original equipment manufacturer (OEM) of engines and the Propane Education and Research Council who fund Krishnan and Srinivasan's work realize there is no easy solution, and the achievements they have accomplished so far have brought them one step closer to the solution of building the kind of clean, fuel-efficient engines that consumers want. In the meantime, the other advantage is the investment in their research is also training the next generation of engineers who will develop the engines for the new vehicles of the future.

"Everything in our lab is student-built. That is a lot of value added to a student's resume," Krishnan offered. It's true the results of our research equate to efficient products or new combustion strategies, but it is just as important for us to remember that it is our job to ensure that these students are 'industry ready' to produce high quality work the minute they start working for a company. And we're meeting that goal. OEM's are telling us our graduates are work ready. They are not spending a lot of capital bringing our students up to speed."

Research Robot Revs Responders

Many adults and children alike have sparkled delight in the guise of movie robots named C-3PO, R2-D2 (Star Wars), Megatron (Transformers), WALL*E, and other famous mechanical creations. First emergency responders, like the rural Starkville, Mississippi, SWAT team are revved up about a robot named Brutus. This technically, advanced robot is part of a research project that aims to provide police with better tools to deal with high-risk incidents more efficiently and in a safer way for both residents and law enforcement. Cindy Bethel, director of the CAVS Robot Test Bed Facility and the Social, Therapeutic and Robotic Systems (STaRS) lab, is one of the only researchers in the country who has access to the inside intricacies of a SWAT teams' training procedures. The SWAT training excursions are when Bethel and her team study and learn the best methods of how to integrate Brutus with the tactical team.

"What makes our research unique is we're working to make Brutus autonomous, so a team member doesn't have to be taken out of the fight to basically just operate the robot," Bethel explained. "The other advantage is the access we have enables us to gather immediate feedback about the robot interfaces we're developing to convey information to the officers."

The premise of making Brutus autonomous—programming the robot to act on its own and convey back to the officers what it will do next—is to help keep rural crime fighting teams out of harm's way.

"Rural teams don't have the resources to take a person out of the fight," Bethel said. "They don't have fulltime SWAT teams. Those who are police officers also serve double-duty as SWAT team members. In rural, small-town America this is very common. We feel that what we are developing could help be a force multiplier in these rural departments that don't' have the resources of a larger city police department."

The possibility of an autonomous robot changes the way SWAT teams approach calls in hostage situations or when a person fully armed has blockaded themselves in a room. Instead of spending hours using mirrors or cameras on a pole to see around corners as officers move in behind shields to pin down a suspect's location, Brutus makes first contact and

sends high definition video and audio back to the Android player worn on the wrist that faces the inside forearm revealing the threats of the crime scene.

"We're hoping to stream audio and video feeds from Brutus onto Google glass, because what we have discovered is the glow from the Android wrist player can back light the officers," Bethel explained. "I applied for a Google grant and spoke with them. They like the idea of combining our scientific know-how with Google glass technology to enhance and add another protective function to the officers' existing safety glasses. Hopefully their excitement will give us the edge to help us secure the grant."

According to Shane Kelley, a Starkville police department sergeant, "Brutus is a lifesaving tool for us. It helps us stay out of harm's way. And it could be an economical tool that could do a lot of things to support and reinforce rural SWAT teams."

In addition to coming up with low-cost solutions like outfitting the robot with sensor and interactive software that will help provide rural officers with better information in high risk areas,

BRUTUS' Specs:

- *Two-way communication system*
- *High definition video*
- *Three cameras with pan, tilt and zoom capability, which offers 360 degree capability.*
- *Manipulator arm and sensors to offer different viewpoints.*
- *Two parallel track extensions mounted on each side of robot, which can be rotated 360 degrees allows Brutus to perform tasks such as self-righting and climbing stairs.*

Bethel is building a robotic test-bed facility where crime fighters from across the state can train and hone their skills.

"It will be a high fidelity training facility, where we will have breaching doors and room dividers to create hallways to teach safe-entry. It will have 7.1 surround sound, a high-definition projection system and theatrical lighting to create scenes with projected images like explosive devices," Bethel said. "We we are trying to create a very immersive type of environment and it will be one of the only facilities like it in the south."

If successful, Bethel's vision and hopes are that this extraordinary technology can perhaps be appropriately and responsibly harnessed to enhance security and safety at military bases, seaports, airports, borders, prisons, critical infrastructure, security checkpoints, and even be deployed in our children's schools to help keep them safe.

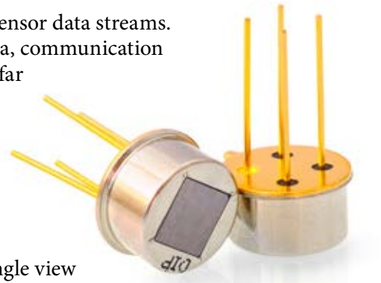
Synthesizing Sensors' Senses

John Ball and Derek Anderson are looking through a pair of pricey sensory devices they will use to help create autonomous intelligent systems based on research data generated from a well-equipped, high-tech laboratory like no other in the southeast. The assistant professors in electrical and computer engineering are building a Sensor Fusion laboratory to make multiple sensors like infrared, radar, LIDAR and hyperspectral devices work together, much like an individual uses senses of sight, sound, smell and touch to perceive and understand their surroundings.

"The CAVS Sensor Fusion laboratory will have a suite of sensors. These devices can cost as little as a few hundred dollars to as much as as several thousand each," Anderson said. "Having all these pieces of equipment located in one place will give researchers and our students a unique and huge advantage."

Each of these sensors view the world in very different ways. There are sensors that detect almost any plausible specification and a multitude of observations. There are position, proximity, pressure, heat and flow sensors to name just a few. For instance, some automobiles are programmed to monitor its own progress and if the vehicle changes lanes without a turn-signal a chime sounds to alert the driver. The smoke alarms in homes could not function without sensors.

The problem is there is a lack of integration and communication between these sensor data streams. Anderson and Ball hope to find a solution by conducting research to fuse the data, communication streams. This work is what engineers and researchers define as sensor fusion. So far Anderson has found a solution in his award winning theoretical research, which he thinks when applied will help projects like Cindy Bethel's SWAT robot, Brutus, recognize friend or foe by combining data from thermal, point cloud and hyperspectral imaging sensors. This differentiating ability will help keep SWAT members and victims out of harm's way.

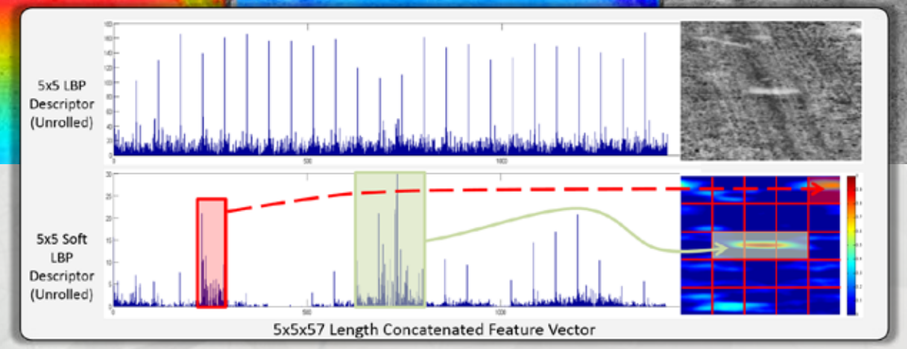


Electronic sensors

"We're really looking at a lot of different sensors that work in a lot of different environments but they all have to come together and be coherently tied into a single view of the scene, so eventually the machine can reason about what it wants to do," Ball explained.

Three dimensional scene reconstruction from a single infrared camera on a ground vehicle. Images are color coded. Blue equals smaller and red represents larger values of "depth images" for different standoff distances from the vehicle.

Detection of buried explosive hazards in infrared imagery. Top: Features (histogram of local binary patterns) extracted from the raw imagery. Bottom: Features extracted from a filtered image.



Anderson and Ball plan to work together to address the profession's existing problem of a proliferation of sensor data and not enough knowledge, by expanding their vision to include using the lab as a test bed facility to analyze and invent autonomous competencies for all sorts of mechanical devices and vehicles.

Infrared sensors

"We can also use this technology for tasks like humanitarian demining," Anderson offered. "I'd rather have an autonomous vehicle perform demining rather than a human. My multisource fusion research has been supported by the National Library of Medicine, DARPA, CEED and the U.S. Army Research Office in conjunction with the Night Vision and Electronic Sensors Directorate for scene understanding and demining. This, coupled with John's extensive radar and hyperspectral expertise in the academic and government sector puts us in a unique position to tackle big challenges in sensor fusion"

Ball added, "We already have the technology to decipher and create intelligent reasoning systems from sensing information. The key is to find the funding support to continue the research and to write the code to build intelligent systems—the core capability that could be used in variety of products."

The trend of integrating new sensing methods with computing capability and digital communications continues to grow. Global industry experts predict that the smart sensor market will rise above $6-billion by 2017.

"If we can fuse sensors with domain knowledge from humans then we can crack the problem of how machines can sense and observe and have autonomous capabilities," Anderson said. "We have everything in place here at CAVS, we just need the financial support to be the first to crack the code."

Researchers Lab-to-Fab Work could Create U.S. Manufacturing Renaissance

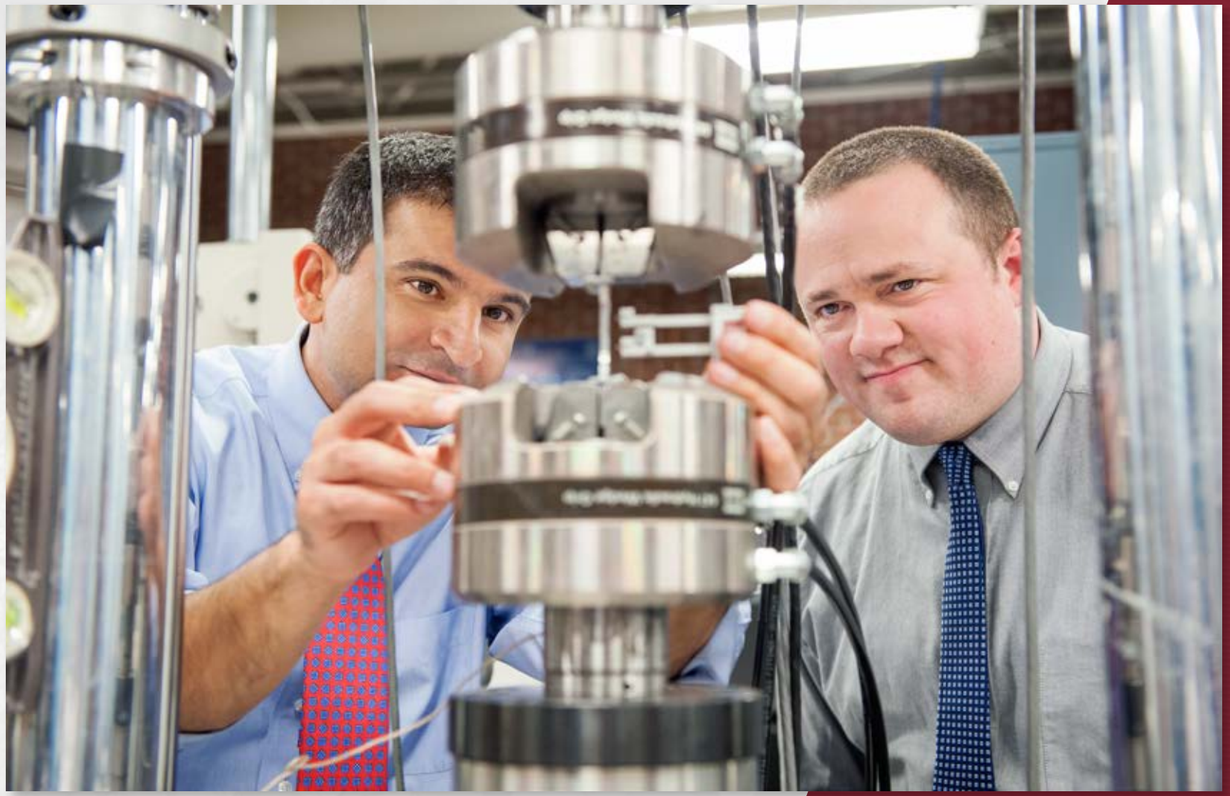
Lab-to-fab describes the work two CAVS researchers are conducting to help an emerging technology move from the laboratory to a production environment. Additive manufacturing (AM), more commonly known as 3-D printing, is mainly used to create three-dimensional prototypes from a digital blue print for engineers and designers. Researchers Scott Thompson and Nima Shamsaei are trying to discover a configuration for laser free-form technology, a type of AM process, to use metals to produce reliable parts for the automotive, aerospace and biomedical industries. If successful, the two assistant mechanical engineering professors could help to create a manufacturing industry renaissance that makes it worth the investment for U.S. companies to build products here and sell them worldwide.

"This research of how to print reliable 3-D metal parts can be a favorable economic game changer for American manufacturers and workers," Thompson said. "For instance a car dealer could download a digital file and have a customized part printed on-site, or if an airline mechanic needs a part to fix a plane it can be printed on-site rather than delaying the flight waiting on a part. It is cost effective in terms of not having to bulk manufacture the part, there are savings in inventory and shipping, plus you're adding high-tech jobs," Thompson said.

Looking long term, highly customized manufacturing is predicted to have a huge impact; industrial sales of AM products and services are forecast to exceed $6.5 billion by 2019. Experts' conclude that the technique can be more cost-effective than traditional methods.

"Conventional—subtractive--manufacturing methods carve and remove material from a solid block to create a part. Additive manufacturing uses lasers that melt metal powders that shape a part from the bottom up by adding ultrathin layer upon ultrathin layer," Shamsaei explained. "Our Laser Engineered Net Shaping (LENS) machine gives us the capability to fabricate complex geometries by adding layers with micro precision."

One disadvantage of the LENS AM system is that it can fabricate parts with structural impurities, thus impacting the



mechanical behavior of the parts. Thompson specializes in heat transfer and Shamsaei, a fatigue expert, clarified that the final product quality depends on the microstructural layering (the build—of the part), which depends on the thermal history.

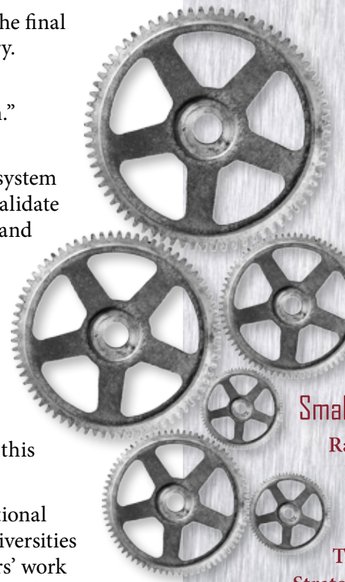
"We can monitor temperature and control the process parameters to keep the temperature at the level we want for structural integrity. This helps us optimize process parameters for producing a reliable part for its intended application." Shamsaei said.

Mississippi State University is one of only a few universities in the nation to install a state-of-the-art thermal imaging-system to help Shamsaei and Thompson monitor heat levels during LENS fabrication - helping them control the process and validate models. What is more unusual and unique is to have all this high-tech equipment including LENS as well as materials and fatigue characterization located under one roof. CAVS is one of the only research centers in the southeast to offer these kind of resources.

"There are these different variables you have to tell the machine—like how fast—there is a laser that comes down and then there is powder that is blown into the laser. How fast does the powder have to go into the laser? How fast does it have to move? There are all these print parameters, and they all have to be perfect to get the part that we can trust. So, I'm observing and modeling the thermal behavior and Dr. Shamsaei is characterizing the mechanical behavior and fatigue resistance of samples by strategically breaking them via tensile and fatigue tests. We then optimize those parameters to fabricate reliable products. Dr. Linkan Bian from Industrial and Systems Engineering is helping us with this process parameter optimization."

The current Whitehouse administration has made a national commitment to support AM research by forming the National Network for Manufacturing Innovation Institute, located in Youngstown, Ohio. It is a regional network of research universities attracting industry partners located in the Northeast part of the country. However, the two Mississippi state researchers' work in AM has caught the attention of several large, medium and small manufacturing companies, along with government and academic entities. Together they have formed the Consortium on Laser Freeform Fabrication of Engineered Products with Enhanced Structural Integrity (CLF2).

"We hope this initial 'product driven' group of more than 20 committed members led by Mississippi State will help contribute toward the AM national initiative by finding unique solutions. We want to help Mississippi become the hub in the southeast for advanced, high-tech manufacturing. And since MSU is the largest state university with the first and the largest engineering college, we should be able to support that mission," concluded Thompson and Shamsaei.



Consortium on Laser Freeform Fabrication of Engineered Products with Enhanced Structural Integrity

Medium-to-Large Industry

- **Caterpillar, Inc.** *(Peoria, IL & Corinth, MS)*
- **John Deere** *(Moline, IL)*
- **Eaton Aerospace Group** *(Jackson, MS)*

Small Industry

- **Rapid Prototype + Manufacturing** *(Avon Lake, OH)*
- **HBM-nCode Federal LLC** *(Starkville, MS)*
- **Hol-Mac Corporation** *(Bay Springs, MS)*
- **Optomec** *(Albuquerque, NM)*
- **Taylor Machine Works, Inc.** *(Louisville, MS)*
- **Stratonics, Inc.** *(Lake Forest, CA)*
- **Simufact-Americas** *(Plymouth, MI)*
- **Mechanics & Materials Consulting, LLC** *(Flagstaff, AZ)*

Government

- **Air Force Research Laboratory** *(Dayton, OH)*
- **Engineering Research & Development Ctr** *(Vicksburg, MS)*
- **NASA Marshall Space Flight Center** *(Huntsville, AL)*
- **National Research Council** *(Ottawa, Canada)*
- **Oak Ridge National Laboratory** *(Oak Ridge, TN)*

Academia

- **Mississippi State University** *(Starkville, MS)*
- **Georgia Institute of Technology** *(Atlanta, GA)*
- **Texas A&M University** *(College Station, TX)*
- **University of Arizona** *(Tucson, AZ)*
- **University of Toledo** *(Toledo, OH)*

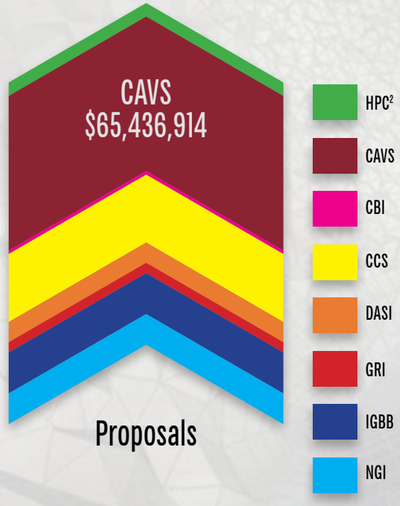
Not-For-Profit Organizations

- **ASTM International** *(West Conshohocken, PA)*

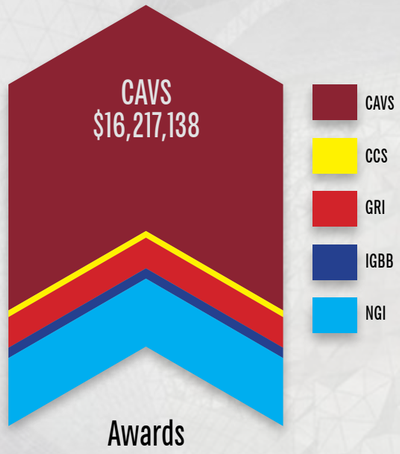
"This research of how to print reliable 3-D metal parts can be a favorable economic game changer for American manufacturers and workers," Thompson said.

Research Funding Portfolio

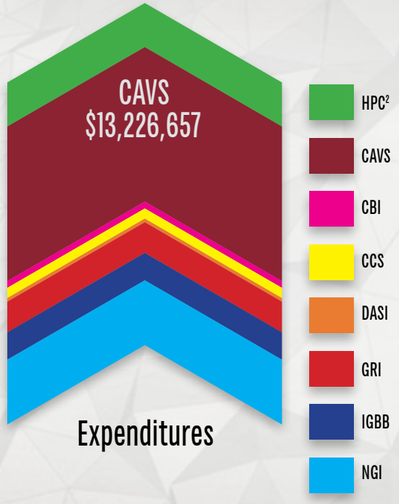
Awards by Sponsor



Proposals



Awards



Expenditures

MORE INFO

Interested in how your business, company or organization can partner with CAVS, please contact:

Dr. Roger King at rking@cavs.msstate.edu or visit www.cavs.msstate.edu.

CAVS is an HPC² member center. Mississippi State University is an equal opportunity institution.

MISSISSIPPI STATE
UNIVERSITY

CAVS

Box 9618, Mississippi State, MS 39762 • 200 Research Blvd.
Starkville, MS 39759 • Ph: 662.325.5431 • Fax: 662.325.5433