College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

FALL 2023 NEWSLETTER

MECHANICAL ENGINEERING

MAKING CONNECTIONS

Our transdisciplinary research enriches graduate education

Greetings from Madison!

I am excited to bring you the latest highlights from the department. The first notable highlight is that, as of fall 2023, our department is now home to two popular undergraduate programs: mechanical engineering (ME) and engineering mechanics with an aerospace option (EMA).

A special thanks to the numerous faculty and staff, led by Associate Chair Riccardo Bonazza, who helped integrate the EMA programs into the ME department over the past year. We now have the tremendous opportunity to integrate and expand our educational offerings for the more than 1,400 undergraduate students we serve across two programs.

A second highlight is that the department now has nearly 50 faculty members, reflecting a 47% growth in our faculty size over three years. Amongst this group are two extremely talented faculty, James Pikul and Lei Zhou, who joined us in fall 2023 and are providing students new opportunities in electrochemistry, microbatteries, robotics and precision mechatronics.

A third highlight is our growing, innovative research enterprise. Our faculty, staff and students conducted an impressive $25+ million in funded research this past fiscal year. This level of support underscores our position as a hub of innovation and discovery across a range of real-world challenges involving energy systems, advanced manufacturing, biomechanics, robotics, sensors, materials and computational engineering. To support all this research, we have been aggressively upgrading our facilities and have recently opened new state-of-the-art lab spaces for soft robotics, nanoscale thermal transport and battery research.

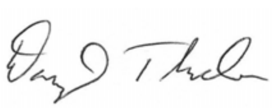
Finally, it is a pleasure to highlight our students' incredible ingenuity and creativity. Over the spring and summer, we had more than 100 students participating in national design competitions including the University Rover Challenge in Utah, the Intercollegiate Rocket Engineering Competition in New Mexico, and the Electrek Formula Sun Grand Prix competition in Kansas.

Our ME spring senior design symposium featured 42 teams exhibiting their solutions to challenging problems from industry, research and the community. Included in these projects was a full-size electric boat, a rocket thruster energy generation system and a thermophotovoltaic test facility, which won best overall design project. The symposium was followed by a memorable outdoor banquet on a beautiful spring day, providing a platform for students, faculty and alumni to connect, exchange ideas and celebrate our shared passion for mechanical engineering. I invite you to join us when we reconvene for the senior design symposium in spring 2024.

On a sad note, we lost two long-time members of the mechanical engineering community over the past few months. Professor Emeritus John Uicker passed away on April 25. John, who taught in the department for 40 years, was internationally known for his pioneering work in computational dynamics and remained extremely active in the department even after retiring in 2007. Professor Emeritus Ed Lovell passed away on June 7 at the age of 84. Ed was on the faculty at UW-Madison from 1968 to 2008, serving as chair of the Department of Engineering Mechanics and Astronautics and producing more than 230 publications on fundamental and applied aspects of structural mechanics. We appreciate the tremendous dedication and service that John and Ed provided to the department and are grateful for the opportunity to continue their legacy of excellence.

Thank you for your support of our department, which continues to help our research and educational programs in countless ways.

On, Wisconsin!



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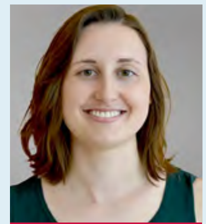
Grad student lands NSF fellowship

Graduate student Vanessa Barton earned a prestigious 2023 National Science Foundation Graduate Research Fellowship.

As a member of Assistant Professor Joseph Andrews' Laboratory for Printed Electronics and Sensors, her research focuses on developing new flexible pressure sensors using an interdigitated co-planar capacitive sensing scheme in conjunction with an enhanced overlaid elastomeric composite. Barton's goal is for these wearable sensors to provide real-time detection of impact force, direction and duration to help researchers more precisely understand traumatic brain injury so they can ultimately design and build better protective equipment.



Vanessa Barton

This project is part of the UW-Madison-led PANTHER program, an interdisciplinary research initiative made up of both academic labs and industry partners that are focused on understanding, detecting and preventing traumatic brain injuries.

"One of the aspects that I enjoy about this project is its interdisciplinary nature, as it combines mechanical, electrical and materials science engineering all for a biomedical application. I'm looking forward to doing more research on this topic and working to develop other sensors in the future," Barton says.

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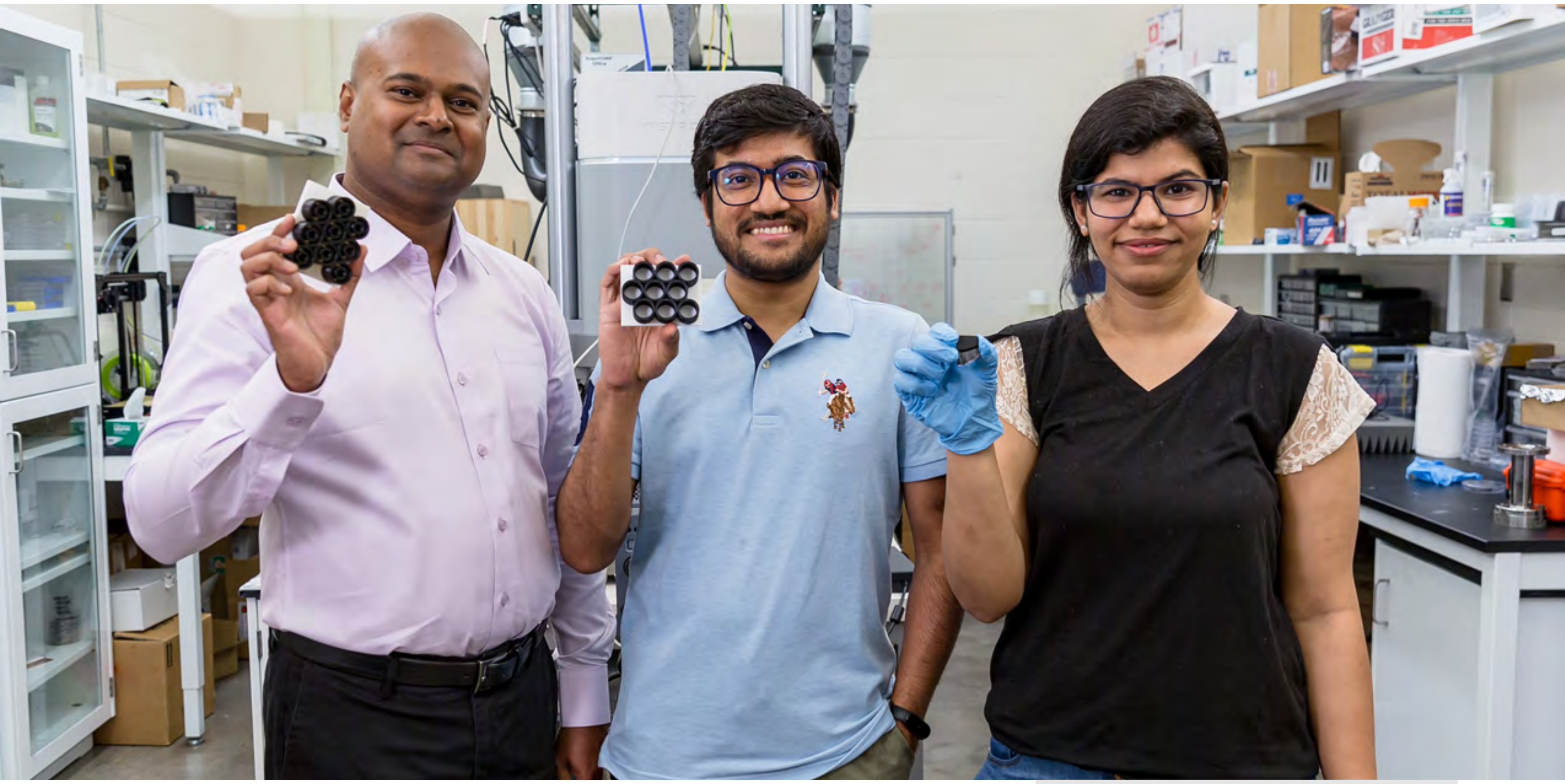
Cover photo: Assistant Professor Lei Zhou, who joined the department in August 2023, is teaching a new undergraduate course called *Introduction to Mechatronics*. Photo: Joel Hallberg.



Assistant Professor Ramathasan Thevamaran (left), PhD student Abhishek Gupta (center), and postdoctoral research associate Komal Chawla (right), found a way to greatly reduce the density of their ultra-shock-absorbing foam material–while crucially retaining much of the material's exceptional properties. Photo: Joel Hallberg.

Discovery opens door to ultra-lightweight protective materials

In November 2022, UW-Madison engineers garnered widespread attention when they announced the creation of an ultra-shock-absorbing foam material that could dramatically improve helmets.

The researchers' material, an architected, vertically aligned carbon nanotube foam, can absorb significantly more energy from impacts than the foam currently used in U.S. military combat helmet liners. It also is much stronger and stiffer.

As a helmet lining material, the researchers' foam holds tremendous potential for helping to mitigate, or even prevent, concussions and other traumatic brain injuries, according to Assistant Professor Ramathasan Thevamaran, who led the research.

Now, Thevamaran and his team have discovered a way to greatly reduce the density, and thus the weight, of their foam material—while crucially retaining much of the material's exceptional properties.

"Typically, materials with a higher density will have better mechanical properties. So, it's very challenging to achieve superior mechanical properties in a material with a low density," Thevamaran says. "For example, think of a piece of solid metal. Poking holes in the metal would reduce its density but also cause its properties to severely degrade."

To achieve this breakthrough, the researchers tailored the design of their vertically aligned carbon nanotube foam to have unique structural features across multiple length scales. Their material has a novel architecture that consists of closely packed thin concentric cylinder structures at the micrometer scale, with each cylinder made of many carbon nanotubes—which themselves have a concentric cylindrical structure in the nanometer scale. These structures give the material its outstanding properties.

In this new study, the team investigated a variety of design parameters and discovered the internal gap between the concentric cylinders plays a key role in determining the material's overall properties. They varied the material's density by changing the internal gap, and then observed how those changes induced different types of deformation in the material when compressed. Ultimately, the researchers discovered that increasing the internal gap, up to a certain point, led to better structural stiffness at low densities.

"In this work, we achieved a desirable linear scaling between properties and density in vertically aligned carbon nanotube foams designed with our unique architecture," Thevamaran says. "We were able to create that linear scaling by tailoring the gap between the concentric cylinder rings. This allowed us to simultaneously improve our material's damping capacity and energy absorption efficiency while also allowing the material to be extremely lightweight."

The researchers are patenting their technology through the Wisconsin Alumni Research Foundation.

This research is part of the PANTHER program, an interdisciplinary research initiative led by UW-Madison that aims to better understand, detect and prevent traumatic brain injuries.

FOCUS ON NEW FACULTY

James Pikul is redefining what we use to generate and store energy

A robot, hard at work, runs low on power. Instead of needing to be plugged in and waiting to recharge, the robot simply "eats" some nearby metal, which provides power to top off its battery.

This is just one of the "disruptive" energy storage technologies developed by James Pikul, who joined the department as the Leon and Elizabeth Janssen Associate Professor in August 2023.

In his research, Pikul aims to make transformative advances in energy storage and robotics by understanding and exploiting electrochemistry and soft matter physics.

"Electrochemistry is a science that connects chemical reactions with electricity, and that's exciting because we can use our amazing control over electricity to control the chemical and physical world we live in," Pikul says. "Or we can do the reverse—use chemistry to control electrons. That interface is what we're studying, and we can use it to make better batteries, build intelligent materials, and enable more capable robots."

Pikul has developed a device that, when it comes into contact with a metal surface, catalyzes the rust reaction, allowing the robot to extract energy from the freed electrons. It could enable metal-eating robots that can power themselves by scavenging while conducting search-and-rescue missions. This technology also has the potential to make shipping more sustainable, where sheets of metal could essentially function like fuel cells to power a ship. Pikul has founded a startup company, Metal Light, to commercialize the technology.

"Although my lab focuses on robots as a motivating theme, many of the technologies we develop are broadly useful for improving energy storage and efficiency," Pikul says. "Energy storage technology is becoming such a global necessity for many areas, including grid storage that can back up our renewables as well as for sustainably powering electric vehicles, aviation and shipping."

In addition, Pikul studies the mechanics of soft robots with the goal of making robots that can safely and comfortably assist humans. He has been using this work to reduce the number of injuries experienced by nurses.

Pikul earned his bachelor's degree, master's degree and PhD (2015) in mechanical engineering from the University of Illinois at Urbana-Champaign. He comes to UW-Madison from the University of Pennsylvania, where he was an assistant professor in the Department of Mechanical Engineering and Applied Mechanics.

Lei Zhou is breaking down boundaries in precision mechatronics

Lei Zhou uses her interdisciplinary precision mechatronics research as a powerful tool for solving problems in various application areas, including semiconductor manufacturing equipment and robotics. With a systems focus, she develops novel and high-performance mechatronic solutions by exploiting the synergy between precision machine design, electric machines, and control algorithms.

Most of today's mechatronic systems are designed sequentially—designing mechanical systems and actuators first, followed by control. However, this approach may lead to conservative results, according to Zhou. For example, when control engineers begin working on the system, they might be unable to implement the best control solutions due to the mechanical and electrical engineers' earlier decisions on the machine and actuator design.

That's why Zhou emphasizes a synergistic "co-design" approach in her research, where important aspects of machine design, electromagnetic design, and control are considered simultaneously from a system perspective. Zhou says this approach allows researchers to develop more innovative solutions and achieve better performance in mechatronic systems.

"One unique thing about my lab is that I train my graduate students to work on all the key aspects of a mechatronic system. So, they do modeling, machine design, electromagnetic design, control algorithms, and implementation, and this helps to break down some disciplinary boundaries," says Zhou, an assistant professor who joined the faculty in August 2023 with a joint appointment in ME and ECE. "The students learn how to work from a system perspective, which enables them to solve bigger, more complex challenges."

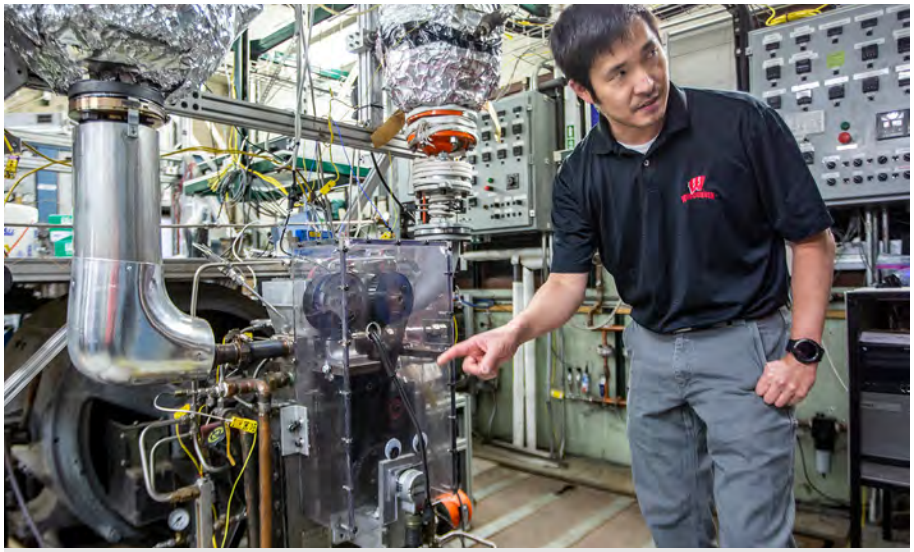
She is also an associate director of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC).

Zhou earned her PhD in mechanical engineering from Massachusetts Institute of Technology in 2019. She received her bachelor's degree in control and instrumentation engineering from Tsinghua University in China and her master's degree in mechanical engineering from MIT. Prior to joining UW-Madison, Zhou was an assistant professor in the Walker Department of Mechanical Engineering at the University of Texas at Austin.

One of Zhou's current research projects focuses on designing precision positioning systems for high-throughput semiconductor chip manufacturing. She's also working on developing novel actuation, sensing and control solutions for high-performance robots used in manufacturing factories. Specifically, she's focused on designing robotic hands or grippers that can work interactively and safely with objects, other robots and humans.

In fall 2023, Zhou is teaching a new undergraduate course called *Introduction to Mechatronics* that will provide students with many hands-on learning opportunities.

Trees may hold the solution for keeping engines running smoothly and efficiently



Researcher Stephen Sakai explains the workings of a spark-ignition engine used to test properties of biofuel additives in a lab of the Engine Research Center. Photo: Matthew Wisniewski/Wisconsin Energy Institute.

UW-Madison engineers have discovered that when blended with gasoline, methylbutenol, a type of alcohol produced by pine trees, produces less air pollution and is more effective than other alcohols at reducing engine knock, an annoying and sometimes destructive phenomenon that happens when fuel ignites when it's not supposed to.

Their findings suggest methylbutenol is a promising low-carbon biofuel that could be mixed with gasoline.

"Everything we've seen has been very, very favorable," says Robert Lorenz Professor David Rothamer.

With support from the Great Lakes Bioenergy Research Center, a federally funded research hub based at UW-Madison, Rothamer and his graduate student Stephen Sakai investigated how three types of alcohol perform when mixed with gasoline in an internal combustion engine.

They compared ethanol with isobutanol and methylbutenol, which contain more carbon atoms, making them more similar to gasoline than ethanol. With higher energy content and corrosion resistance, these next-generation biofuels are considered "drop-in" fuels that can replace gasoline without the need for modifying engines.

The researchers used a single-cylinder engine connected to monitoring equipment in the Engine Research Center to test the performance of each of the biofuel additives mixed with gasoline. They found that methylbutenol produced less soot and was better at resisting engine knock than ethanol or isobutanol.

Methylbutenol hasn't been widely studied as a fuel additive. Rothamer says the findings indicate that terpene alcohols like methylbutenol merit a closer look.

With transparent machine learning tool, engineers accelerate polymer discovery

Ying Li

Using the power of prediction, UW-Madison mechanical engineers have quickly discovered several promising high-performance polymers out of a field of 8 million candidates.

The aerospace, automobile and electronics industries use these polymers, known as polyimides, for a wide variety of applications because they have excellent mechanical and thermal properties—including strength, stiffness and heat resistance.

Right now, there's a limited number of existing polyimides because the process of designing them is costly and time-consuming.

However, with their data-driven design framework, the UW-Madison engineers are leveraging machine learning predictions and molecular dynamics simulations to dramatically speed up the discovery of new polyimides with even better properties.

"Our design strategy is much more efficient compared to the conventional trial-and-error process and can also be applied to the molecular design of other polymeric materials," says Associate Professor Ying Li, who led the research.

Polyimides are produced through a condensation reaction of dianhydride and diamine/diisocyanate molecules. For their study, the engineers first collected open-source data of the chemical structures of all the existing dianhydride and diamine/diisocyanate molecules, then used that data to build a comprehensive library of 8 million hypothetical polyimides.

Database in hand, the team created multiple machine learning models for the thermal and mechanical properties of polyimides based on experimentally reported values. Using a variety of machine learning techniques, the researchers identified chemical substructures that are most important for determining individual properties.

"We incorporated techniques that essentially explain how our machine learning model behaves, so our model isn't a black box," Li says. "We've built a transparent box that allows human experts to immediately understand why the machine learning model made a certain decision."

Applying their well-trained machine learning models, the researchers obtained predictions for the properties of the 8 million hypothetical polyimides. Then they screened that whole dataset and identified the three best hypothetical polyimides with combined properties superior to those of existing polyimides.

To check their work, the researchers built all-atom models for their top-three candidates and conducted molecular dynamics simulations to calculate a key thermal property. "The simulations were in good agreement with the predictions from the machine learning models, so that gives us confidence that our predictions are quite reliable," Li says.

Researchers in the UW Autonomous & Resilient Controls Laboratory (ARC Lab) test their control algorithms using a drone. From left: Graduate students Yujie Wang, Yuhao Zhang, Sushen Kashyap, Sequoyah Walters, and Assistant Professor Xiangru Xu. Photo: Joel Hallberg

With NSF CAREER Award, Xiangru Xu aims to improve safety of autonomous systems

Despite years of development, truly autonomous technologies such as self-driving vehicles and delivery drones continue to remain elusive, largely due to safety and reliability concerns.

Meanwhile, thanks to advances in artificial intelligence, neural networks—a type of machine learning algorithm—have become an indispensable component of modern autonomous systems, especially in their perception capabilities. In autonomous vehicles, neural networks use data from sensors to map the environment and recognize objects such as traffic signs.

However, these machine learning components greatly increase the complexity of the overall autonomous system, making it much more difficult to design the system and analyze its behavior.

That's why Assistant Professor Xiangru Xu will use his National Science Foundation CAREER Award to establish a theoretical framework and design control algorithms to ensure the safety of autonomous systems with machine learning components. He is focused on safety-critical systems in which any safety failure will break the product or cause human injury.

"Results from surveys show that the American public is very skeptical of autonomous systems," Xu says. "But, in the future, if there were a self-driving car that came with provable performance guarantees for safe and reliable operation on our streets, it could boost the public's trust in this technology, which is a very important factor in determining the role of autonomous systems in our future society."

He says there are many fundamental problems in machine learning that he will need to consider as he designs control algorithms. For one, neural networks are very sensitive, so there's a risk that a small change to the input can lead to an incorrect result for image recognition.

Xu is leveraging his expertise in control theory to tackle this challenge.

"A neural network is basically a function that maps input data to output data, and the areas of controls and optimization have a lot of principled methods for analyzing complicated dynamics and functions," Xu says. "This expertise will allow me to look at the system in a holistic way so we can design safe trajectories more efficiently. Ultimately, I expect to be able to provide insight on how to design better autonomous systems."

New center aims to expand the role of semiconductors

Unlike any other in the world, the new Wisconsin Center for Semiconductor Thermal Photonics at UW-Madison will combine research in photonics, thermal science and quantum science to understand how semiconductors could be used to control the flow of heat. That understanding will be beneficial as researchers seek to develop new types of power generation, energy conversion, refrigeration, advanced sensing and other next-generation applications.

Assistant Professors Dakotah Thompson and Eric Tervo are among six co-principal investigators in the center, which brings together faculty from multiple engineering and physics backgrounds. The researchers say the confluence of several events makes this an ideal time to launch the center.

When quantum mechanics was developed more than a century ago, thermal radiation was one of the first phenomena explained by the then-radical new theory. Now, there is big resurgence in research in the manipulation and applications of thermal radiation, with researchers like Thompson, Tervo and ECE Associate Professor Zongfu Yu using new techniques and tools to focus on fundamental questions and new technologies. For example, Tervo is developing ways to actively control the flow of heat by manipulating thermal radiation in nanostructured materials.

Additionally, the U.S. CHIPS and Science Act, which passed in summer 2022 and aims to bolster the country's semiconductor manufacturing and research, is opening up new funding sources and multi-institution research collaborations. UW-Madison has a strong convergence of people working in semiconductors, optics and thermal and quantum research, making it an ideal place to investigate this less-explored side of semiconductor science and technology.

Assistant Professors Eric Tervo (left), Jennifer Choy (center) and Dakotah Thompson (right) are bringing expertise in quantum mechanics, thermal emissions and measurement techniques to the new Wisconsin Center for Semiconductor Thermal Photonics. Photo: Joel Hallberg.

Badgerloop team wins American Solar Challenge Rookie of the Year Award

The Badgerloop team at the American Solar Challenge Electrek Formula Sun Grand Prix 2023 in Topeka, Kansas. Submitted photo.

After shifting its focus from the hyperloop to solar car racing, the UW-Madison Badgerloop team took home the Rookie of the Year Award at the American Solar Challenge Electrek Formula Sun Grand Prix 2023 competition in July. The competition involved three days of racing on the 2.5-mile road course at Heartland Motorsports Park in Topeka, Kansas.

ME student and outgoing Badgerloop mechanical director Jay Yoo says the team faced challenges transitioning to a solar car racing team, in which the students had to start from square one to develop and gather the knowledge needed to build a solar car and have it perform reliably.

“Due to our lack of knowledge, resources and experience with solar car racing, our goals this year were pretty simple and we took baby steps to get here today,” Yoo says. “Our main goals were to design, build and test a working solar car; pass scrutineering and dynamic testing; and learn as much as we can in preparation for the following years. I can say proudly that we’ve been able to do all of those things.”

ME student Brooke Ehle, incoming Badgerloop mechanical director, says she’s very proud of what the team accomplished at the competition. “Over the three-day track race we were able to start and end the race with all of the other teams on the track and managed to drive 230 miles on the track (92 laps),” she says. “On top of being able to complete these laps we were also awarded Rookie of the Year due to the fact that out of all the first-year teams there, our car was the only complete original.”

The UW-Madison team successfully launched and recovered a rocket carrying a quantum magnetometer as a payload at Spaceport America Cup 2023. From left: Students Kyle Adler, Cam Schultz, Avery Kendall, Violet Suhrer, Frank Nobile (mentor), Julia Thormann, Isaac Becker, Eugene O’Brien, Sam Conway, and Scott Russell at the competition. Submitted photo.

Students compete at Spaceport America Cup in New Mexico

Students from the UW-Madison chapter of the American Institute of Aeronautics and Astronautics (AIAA) competed for the first time at the 2023 Intercollegiate Rocket Engineering Competition (also known as Spaceport America Cup) in New Mexico, placing 34th overall out of 158 teams.

The Spaceport America Cup is the world’s largest intercollegiate rocket competition. Teams are evaluated based on the performance of their rockets, as well as a scientific payload.

The UW-Madison team successfully launched and recovered a rocket carrying a quantum magnetometer as a payload. Despite high-wind conditions, the team received bonus points for launching early, with its rocket reaching an apogee altitude of 8,233 feet. The rocket was recovered in the desert without damage, along with an intact and still-functioning scientific payload.

The event was a culmination of more than nine months of hard work in which additional students from AIAA also contributed to the rocket design, construction and testing and provided regular reporting to the competition.

The team was accepted into the competition in October 2022 after spending a month designing its rocket. “We were all so elated when we found out we got in. After that, it was straight to work,” says Julia Thormann, AIAA president and competition structures co-lead. “We had a total of three project update reports and a final technical report to submit, as well as a safety review video conference.”

Competition team lead Kyle Adler says that when the time finally came for the competition launch days, the team quickly learned all of the ways Murphy’s Law applies to rocketry. After an entire morning of preparing the rocket, the team’s first launch was canceled due to wind.

“Disappointed but determined to launch the second day, we woke up well before sunrise to give us the best chance,” Adler says. “Another five hours of preparation and several broken switches later, we finally found ourselves loading the rocket onto the pad. The most memorable moment soon came, as our team was called over, and we confirmed GO for launch. Seconds later, we lost GPS tracking and watched our rocket soar into the clouds. The successful recovery of our rocket was a perfect example of the importance of backup measures and planning for the worst, something none of us will soon forget.”

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Graduate student Tyler Bennett lifts a case overhead with help from an exoskeleton. Exoskeletons have rigid supporting structures that make it easier for users to perform certain actions, which may prove useful in the construction field. Photo: Joel Hallberg.

Exosuits may ease strain on construction industry

The construction industry workforce is aging and facing major shortages to keep pace with demand across the United States. According to the Associated Builders and Contractors, almost a quarter of the construction workforce is older than 55—and the industry needs to hire more than half a million additional workers on top of normal hiring in 2023 to close the gap.

While meeting this massive construction worker shortfall will take a much broader effort, researchers at UW-Madison are studying how wearing EXOs (a general term including both exosuits and exoskeletons) can help existing workers do more. EXOs can increase the ability of a single worker, and potentially help all workers have a better experience and protect their health and safety while going about their jobs.

Graduate students Tyler Bennett (ME) and Wei Han (CEE) are studying three passive EXOs, which use springs and tension to support movement. The team is focusing on suits that aid with back and shoulder support. Exosuits are made of soft, flexible fabric, while exoskeletons contain rigid supporting structures.

"A lot of work-related musculoskeletal injuries are in the back," Bennett says. "So, we wanted to find one that really focuses on alleviating lower back strain. We also wanted to add options providing shoulder support because a lot of construction work involves overhead work."

Bennett and Han have collaborated with employers from the national construction firm Mortenson since January 2022 to test the EXOs while workers perform various tasks like pushing a gondola or raising an object overhead.

"EXOs aren't yet well-developed or prepared to be used in construction sites," Han says. "By doing these feasibility studies, we hope to assess which ways they can be helpful in construction sites, or what should be modified and improved to really get to the point where they can be viable tools."