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STEM Degrees: 1 **STEM Participants:** 5

Major Goals: Rapidly recoiling materials controlled by latches generate the fastest, repeated-use movements on the planet. These systems are found in diverse organisms ranging from cavitating crustaceans to jaw-jumping ants. They are of great interest to engineering, because they leverage material deformation to control the flow of energy through structures. This enables these mechanisms to both rapidly release energy for high acceleration movements while also avoiding self-destruction that commonly results from extreme energy release. Therefore, central to the research in this area of ultrafast movements is the visualization of ultra-rapid movements and their underlying mechanisms generated by an extreme flow of energy from actuator to energy storage, and, most importantly, from energy storage to the kinetic energy of the output motion powered by material recoil. This acquisition of a new, cutting-edge, high speed imaging system resolves the pressing technical need for improved visualization capabilities to experimentally test and model the energy flow through materials that enable extreme mass-specific power outputs without self-destruction. This ultrafast high speed imaging system was acquired for use by two labs that are part of two different ARO-sponsored MURI teams operating at Duke University and are focusing on visualization of rapid systems and deforming materials.

Visualization of these systems operating real-time enables measurement of the pathways for mitigating and making use of energy flow and energetic losses in these systems and their components. This facilitates translation of interdisciplinary principles and biological discoveries into practical biological experimental frameworks and synthetic test systems. These generalizable experimental frameworks coupled with technical visualization now empower researchers presently working on ultrafast systems and even broader communities that are tackling the design and experimental challenges of extremely fast, repeatable movement at small scales. Improved visualization capabilities substantially move us toward our primary goals of this work, specifically to:

(1) establish how internal system loss mechanisms are overcome or leveraged to yield dynamic, precise, and repeatable movement at small sizes via analysis of biological, synthetic, and mathematical models of elastic recoil and latch-mediated energy release;

(2) establish how energy flow between ultrafast mechanisms and substrates enables impulsive, high performance outcomes through energy recapture and control, while ensuring repeated use through strategic energy dissipation;

and,

(3) establish how latch mediated spring actuation enables system-level control of multi-dynamic systems by both taking advantage of and overcoming losses inherent to ultrafast, small systems.

Accomplishments: We received the new high speed imaging system in November, 2022. To our knowledge, we are the first academic research group in the world to use this system, called the Pharsighted camera (Model E9-80S, Photron). This imaging system has unprecedented light sensitivity at extremely high frame rates. In the few months since receiving the camera, we have successfully filmed a diversity of ultrafast organisms, materials, and fluids. In particular, we have filmed, with unprecedented precision, the rapid recoil of the 3D elastic head exoskeleton of trap-jaw ants. We have imaged the fastest, smallest organism, the snapping amphipod crustacean, now with sufficient precision that we can measure their energetics. We have captured the full resolution of elastic propulsion of snapping shrimp snaps. Also, in collaboration with the Horstmeyer Lab (engineering optics) we are now at the cusp of installing a new, custom-designed, multi-lens imaging system onto the new high speed imaging system to fully resolve small scale deformations across the full field of recoiling structures, such as the trap jaw ant head. These accomplishments are significant and offer the first fully resolved measurements of motion and, as we move forward with the projects, dynamics, of energy flow and control in ultrafast, spring-driven, repeated use systems.

Training Opportunities: We have involved the following individuals in the training and use of the high speed imaging system:
Research scientist: Dr. Zanne Cox
Graduate students: Justin Jorge, Clare Cook
Undergraduates: Yasuhiko Komatsu
Post-baccalaureate associates in research: Ben Schelling, Sophie Hanson

Results Dissemination: Inaugural Charlotte Mangum Lectureship by S. Patek, William and Mary College

Durham School of the Arts (local public high school) all-day science class visits to present high speed imaging data by B. Schelling and S. Hanson

Honors and Awards: PI Patek:

Few-Glasson Alumni Society Inductee for individuals “who have distinguished themselves through their career accomplishments, the potential of their current endeavors, or their support for graduate students and graduate education at Duke”.

Inaugural Charlotte Mangum Lectureship, William and Mary College

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: S. Patek
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: S. Craig
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: S. Cox
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: J. Jorge
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
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Project Contribution:
National Academy Member: N

Participant Type: Non-Student Research Assistant
Participant: B. Schelling
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A high speed imaging system for research on ultrafast, repeated-use materials and systems

Abstract

The smallest, fastest, repeated-use movements on the planet are generated by organisms. Such extreme, non-destructive performance is achieved through tuned, dynamic interactions of multiple integrated components, specifically through the loading of energy into elastic deformation of materials, control of energy loading and release through latch mechanisms, and the generation of extreme accelerations powered by elastically recoiling materials. At sub-millisecond and sub-millimeter scales, the dynamics of energy flow and control of these systems have been invisible or just barely resolved even with state-of-the-art high speed imaging. As such, engineers striving to match the performance of these fast systems and scientists attempting to experimentally solve their ultrafast dynamics are regularly thwarted by the "simple" process of visualization. Rigorous analysis, modeling and synthesis require sufficiently resolved temporal and spatial dynamics. Effective visualization of whole system output and component interactions is now feasible with the acquired high speed imaging system (Pharsighted imaging system, Model E9-80S, Photron). The ultra high-speed imaging system is entirely new to the market and, according to the company, is "the world's first backside-illuminated, full-frame high speed camera". The camera has extreme light sensitivity, which is the crucial piece for working with organisms and resolving subtle optical shifts. In addition, it has incredible resolution and frame rates, such as, 640 x 480 pixels at 272,000fps; 640 x 384 pixels at 336,000fps; 640 x 256 pixels at 492,000fps; 640 x 128 pixels at 918,000fps; 2,457,000fps at 640 x 32. We are able to film previously invisible movements without any exceptional additional lighting. These capabilities more than triple the usable frame rate and pixel resolution of the high speed imaging systems currently in use. This technological advance has transformed the experimental, modeling, and synthesis work of ARO-sponsored MURI teams as well as research groups beyond the MURI teams which are examining the control pathways and integrated tuning of dynamic components of impulsive biological and synthetic systems and materials. This imaging technology will transform other research initiatives establishing the outer extremes of repeatable ultrafast movement, materials synthesis and energetics. The technology also enhances ongoing educational initiatives in biomechanics and bio-inspired systems.

Objectives:

1. Establish how internal system loss mechanisms are overcome or leveraged to yield dynamic, precise, and repeatable movement at small sizes via analysis of biological, synthetic, and mathematical models of elastic recoil and latch-mediated energy release.

2. Establish how energy flow between LaMSA mechanisms and substrates enables impulsive, high performance outcomes through energy recapture, dissipation, and control.
3. Establish how LaMSA enables system-level control of multi-dynamic systems by both taking advantage of and overcoming losses inherent to ultrafast, small systems.

Findings and Accomplishments:

1. Establish how internal system loss mechanisms are overcome or leveraged to yield dynamic, precise, and repeatable movement at small sizes via analysis of biological, synthetic, and mathematical models of elastic recoil and latch-mediated energy release.

We received the new high speed imaging system in November, 2022. To our knowledge, we are the first academic research groups in the world to use this system, called the Pharsighted camera (Model E9-80S, Photron). This imaging system has unprecedented light sensitivity at extremely high frame rates. In the few months since receiving the camera, we have successfully filmed a diversity of ultrafast organisms, materials, and fluids. In particular, we have filmed, with unprecedented precision, the rapid recoil of the 3D elastic head exoskeleton of trap-jaw ants. We have imaged the fastest, smallest organism, the snapping amphipod crustacean, now with sufficient precision that we can measure their energetics. We have captured the full resolution of elastic propulsion of snapping shrimp snaps. Also, in collaboration with the Horstmeyer Lab (engineering optics) we are now at the cusp of installing a new, custom-designed, multi-lens imaging system onto the new high speed imaging system to fully resolve small scale deformations across the full field of recoiling structures, such as the trap jaw ant head. These accomplishments are significant and offer the first fully resolved measurements of motion and, as we move forward with the projects, the dynamics of energy flow and control in ultrafast, spring-driven, repeated use systems.

2. Establish how energy flow between LaMSA mechanisms and substrates enables impulsive, high performance outcomes through energy recapture, dissipation, and control.

We have begun filming organisms in their natural environments, such that we can measure the dynamics of energy exchange between the ultrafast movement and the environment. In particular, we have visualized the flow field around snapping shrimp cavitation formation and we are working on the amphipod flow field measurements.

3. Establish how LaMSA enables system-level control of multi-dynamic systems by both taking advantage of and overcoming losses inherent to ultrafast, small systems.

Work on this objective will begin in the next few months, as we analyze the new energetics and dynamics data of spring actuation using our new multi-lens optical rig installed on the new imaging system and then move into resolving latch mediation during spring actuation as the next step.