Research and Reports on Metals

Editorial

Heavy Mining Machinery and Intelligent Control Systems Research at Missouri S&T

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Missouri S&T is advancing cutting edge research initiatives in heavy mining machinery and intelligent control systems. Heavy machinery problems have become critical in the production of strategic and critical minerals and materials for technological advances in manufacturing, construction, defence, health, energy, agriculture and transportation applications. Current operations use large-capacity and capital-intensive production equipment. Higher energy costs, tougher environments and high production targets create acute problems that must be addressed to achieve higher machine availability, reliability and maintainability. Current research includes (i) formation excavation science and engineering; (ii) machine dynamics, fracture and fatigue failure; (iii) coupled thermo-mechanical stress simulation of ultra-large truck tires; (iv) DEM modelling of formation microstructures; (v) machine vision and dynamics control; (v) machine and whole-body vibrations; (vi) machine-road interactions and design; and (vii) mine safety, health and hazards engineering.

Formation Excavation Science and Engineering

Material excavation is an engineering frontier with challenges in several areas including material extraction, construction, tunnelling, shaft boring, hydraulic fracturing of reservoirs and lunar applications. The excavation process entails the dislocation of materials from naturally occurring environments in which the equipment motion is constrained by formation geology, workspace and cutting tool geometries and machine breakout force. A major excavation problem is the variability of material diggability, resulting in varying mechanical energy input and stress loading of cutting tool. Thus, excavation results in severe wear and fatigue failure of structural components of excavator. Current research advances excavation science in soft formations with embedded hard and abrasive boulders and provides the basis for the intelligent curved blade excavation (ICBE) technologies for solving these problems. The ICBE technologies capture and transmit longitudinal and axial stress waves generated from excavator- formation interactions. The transmitted stress waves are used to characterize the nature and condition of the formation for making real-time decisions on hardness and fragmentation (Figure 1).

Machinery Dynamics, Fracture and Fatigue Failure

The dynamics of heavy mining machinery comprise three major components, including inertia matrix, Coriolis and centripetal forces and gravity. This dynamic function is equivalent to the difference between the breakout force and resistive force due to formation. The upper structures of excavators are fixed, and thus, the kinematics and dynamic models are related to the front-end assembly. The Lagrange or iterative Newton-Euler methods are used to develop the dynamic equations of excavators because they lend themselves to efficient software implementation and provide detailed information on all links and joints for stress and strength analysis. The von Mises stress profiles are created using FEA analysis in ANSYS and compared with shovel material properties to identify critical stress fields for failure against yield strengths. The stress fields form the basis for fatigue failure and life-expectancy analysis of the front-end assembly. Fracture mechanics techniques are used to estimate stress intensity factors (SIFs) at pre-defined semi-elliptical cracks. SIF-crack length relationships are used to generate the crack-propagation curves and to estimate the life of dipper components (Figure 2).

Machine-Terrain Interactions and Haul Road Design

The key to sound machine health is proper understanding of the haul road bed structure and bearing capacities, truck-road interactions, and road deformation mechanics. Haul road conditions have pronounced effects on haulage efficiency and costs. Research will focus on contact stress waves generation and deflection, subgrade bearing capacity and maximum machine load using Newton-Euler-Lagrangian theory and FEA modelling techniques. Virtual prototype simulation is used to create haul road simulator for experimenting under varying load and road conditions (Figure 3).

Thermo-Mechanical Stress Simulation of Ultra-Large Truck Tires

Tires are critical components of haul trucks for terrain engagement, stability and maneuverability. Tires are subjected to mechanical and thermal stresses whose combined effects lead to truck wear and tear and fatigue failure. This research provides a basis for modelling, analysis and managing the thermo-mechanical stresses under dynamic impact loading. Current research uses a general nonlinear finite-strain time-dependent theory to model rubber materials. Finite deformation constitutive model, based on the Lagrangian strain tensor, captures the nonlinear stress-strain behaviour of the cord-rubber composite.
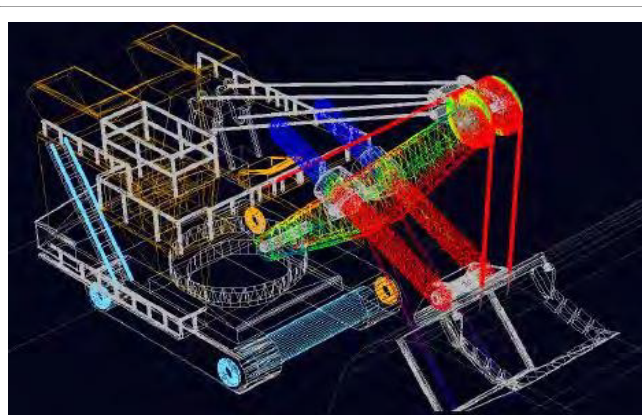
*Corresponding author: Samuel Frimpong, PhD, PEng, Professor and Robert H. Quenon Endowed Chair Director, Heavy Mining Machinery Research Laboratory, Member, APLU Board on Natural Resources, Missouri University of Science and Technology (Missouri S&T), Rolla, MISSOURI, USA, Tel: (573) 341-7617; Fax: (573) 341-6934; E-mail: frimpong@mst.edu

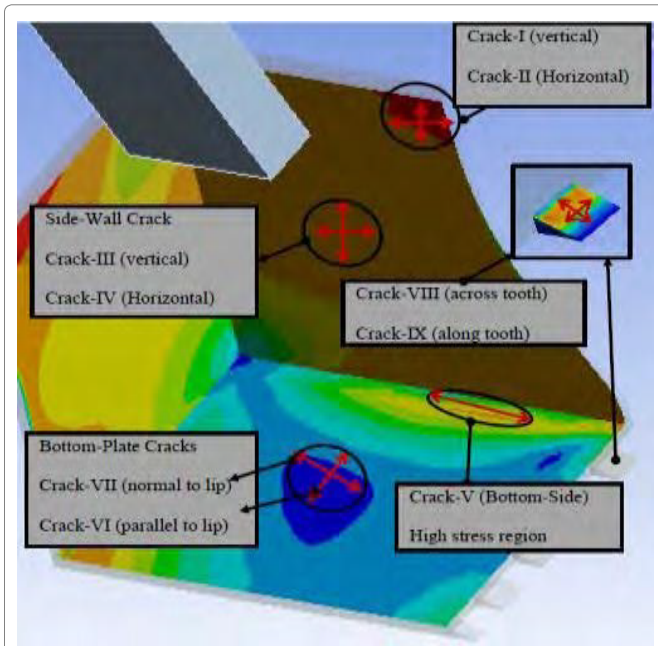**Figure 1:** Formation excavation science and engineering.

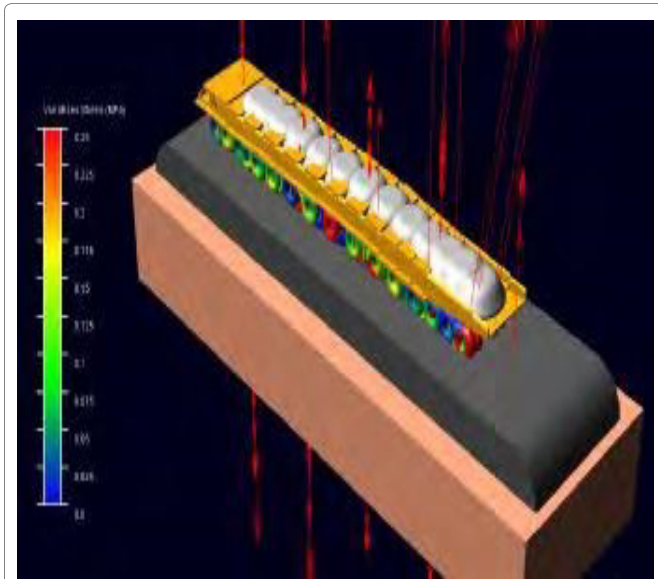**Figure 2:** Machinery Dynamics, Fracture and Fatigue Failure.

Figure 3: Machine-Terrain Interactions and Haul Road Design.

A theoretical model of the viscoelastic properties of tire cord-rubber composite is used to provide an in-depth knowledge of wide range temperature effects on the tire. FEA is used to study the kinematics of the rolling tire under the truck's weight, contact with the haulage terrain, haul distances, and truck velocity (Figure 4).

Augmented Visualization and Collision Avoidance

Haul truck operators face challenges in interacting with mine layouts. Two interrelated challenges are an operator's limited vision due to extensive "blind" areas around the truck and the truck stability during an operator's response to intrusive dangers. These problems may be augmented by the presence of ice or snow, mud, pot holes and tire tread wear. An operator may over-speed, swerve, slow down or stop to avoid collision. Depending on prevailing conditions, vehicular control in response to perimeter sensing can be very challenging. The challenges can result in steering control losses and fatal accidents with corresponding human injuries and deaths, and equipment and production losses. This research deploys a global array of sensors and vision systems to capture the interactions among machines, humans and operations, thus providing a platform for multi-modal sensor suite selection and data fusion for real-time situational awareness and collision avoidance in cyber-physical enabled surface mining environments (Figure 5).

Machine and Whole-Body Vibrations

The use of large machinery in surface mining operations has resulted in high-impact shovel loading operation (HISLO). In extreme cases, shovels load large trucks with $\geq$ 100-ton passes generating high-impact forces under gravity. HISLO generates high-frequency shockwaves that cause extreme vibrations exposing operators to whole body vibrations (WBV) and injuries. In most cases, the operator's lower torso, lower back, legs, feet and hands are exposed to these high-frequency shockwaves. The operator seat, lumbar and cervical regions are severely impacted by high WBV levels and require attention to sustain operator health and safety. The primary research objective is to reduce significantly or completely eliminate the impact of RMS accelerations due to vibrations, and to promote workplace and operator health and safety. Specific objectives include: (i) a re-engineered operator seat; (ii) an optimum impulse force that reduces the magnitudes of generated shockwaves; (iii) enhanced engineered add-on suspension systems to absorb shockwaves; and (iv) aging truck suspension efficiency calibrator to examine aging truck response to generated shockwaves (Figure 6).

Broader Impact: Research Capacity Expansion

Missouri S&T is leading a nationally and internationally recognized research in heavy mining machinery and intelligent control systems. The proximity of the university to the surface mining industry of Missouri, Illinois, Wyoming, Kentucky and the support from the industry are significant advantages. In addition,
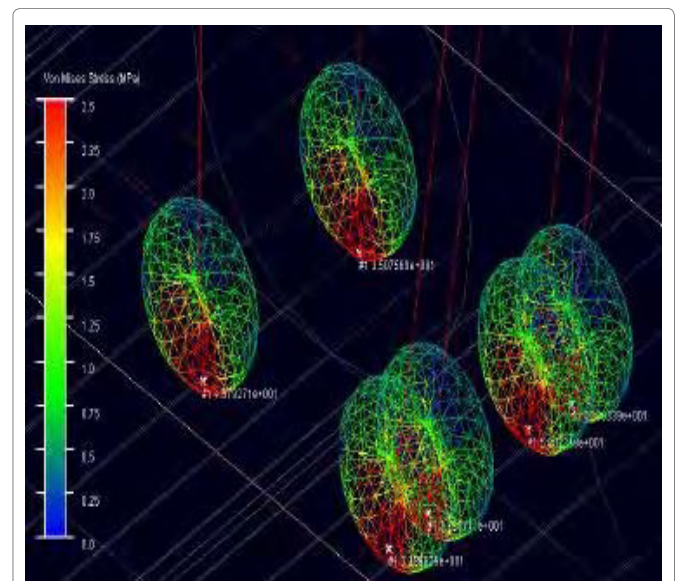

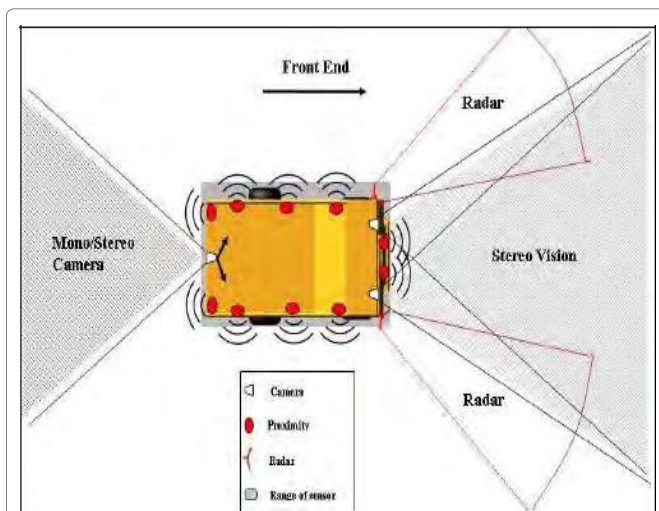**Figure 4**: Thermo-Mechanical Stress Simulation of Ultra-Large Truck Tires.

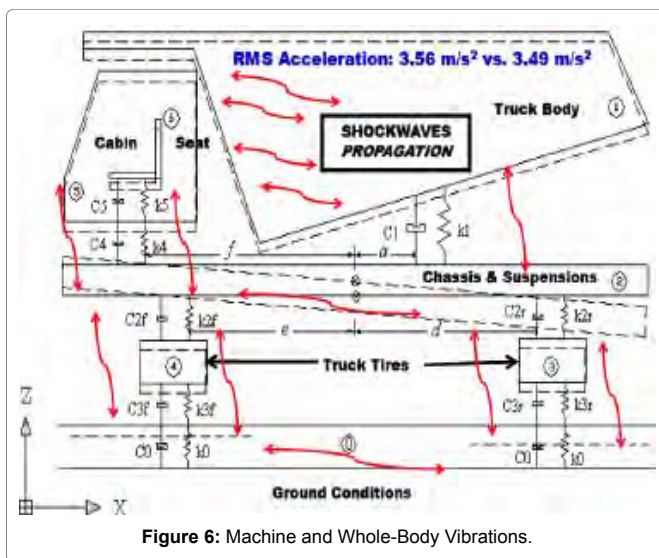**Figure 5:** Augmented Visualization and Collision Avoidance.

Figure 6: Machine and Whole-Body Vibrations.

the existence of surface mining research expertise, the research culture of excellence and the established research collaboration with industry make Missouri S&T a unique institution to lead this research effort. As part of its growing support for Missouri S&T, the mining industry endowed The Robert H. Quenon Endowed Chair, with strong emphasis on research in heavy mining machinery and intelligent control systems. This funding is allowing the researchers to build on the foundation and pillars raised by Missouri S&T and the mining industry toward a reputed centre of research excellence in this strategic area. It will also strengthen the graduate and undergraduate programs through access to well-equipped laboratories, research exposure, training and developing faculty and funding for research initiatives.

Broader Impact: Expanding Research Frontiers and Knowledge

The research initiatives are advancing knowledge and frontiers in excavation, vision and dynamic control and intelligent control systems through fundamental and applied research. In collaboration with the Departments of Electrical and Computer Engineering and Mechanical Engineering at Missouri S&T, the researchers are addressing fundamental problems in machine excavation and materials haulage in surface mining. These research areas cover a broad spectrum of research areas including formation excavation science and engineering, machinery dynamics, fracture and fatigue failure, engineering process control systems, machine vision and kinematics control, machine vibrations control and operator safety, machine-road interactions and road design and maintenance.

Broader Impact: Developing the Next Generation of Researchers

Researchers are attracted to well-developed laboratories and challenges that spur them on to grow and mature in their research endeavours with rewarding experience of new knowledge and frontier advances. The research efforts will allow Missouri S&T to attract and retain highly qualified researchers to participate in its research endeavours. The research programs will create environments for executing fundamental and applied research; where researchers initiate and complete collaborative projects with availability of relevant resources; and the challenges to grow to new heights will be spurred with rewarding recognition for excellence. Graduate students, postdoctoral fellows, research associates and other faculty will interact in the pursuit of knowledge to provide a healthy backbone for an important industrial sector of global economies. These researchers will acquire new skills and training in the pursuit of their research endeavours. These skills will have direct impact on the global economies in the areas of minerals and materials production.

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