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ACTIVE VEHICLE STABILIZATION FOR RECONNAISSANCE AND COMMAND CONTROL ON THE MOVE

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ABSTRACT

Reconnaissance of distant targets with long reaching sensor technology demands a stable platform upon which to operate. Traditionally this requires vehicles deploying mast mounted sensors to remain stationary while collecting data. Pairing electronically controlled active Electromechanical Suspension System (EMS) technology developed by The University of Texas Center for Electromechanics (UT-CEM) with current reconnaissance vehicle platforms creates highly mobile intelligence gathering systems capable of operating on the move over rough and unimproved terrain. This report documents the establishment of criteria by which to judge sensor platform stabilizing performance of EMS and then uses these metrics to evaluate performance improvements over conventional passive vehicles. Based on this analysis it may be possible to operate effectively over cross-country terrains at speeds of 10 to 15 mph while collecting useful reconnaissance data.

INTRODUCTION

Reconnaissance of distant targets with long reaching sensor technology demands a stable platform upon which to operate, traditionally this requires vehicles deploying mast mounted sensors to remain stationary while collecting data. This opens the possibility of the recon teams lagging from their optimal positions to be able to best collect the most relevant and current data on targets of interest. Giving intelligence gathering equipment operators the ability to collect data while on the move opens the possibility of seeking out targets otherwise missed due to terrain or other obstacles, while at the same time evading detection from adversaries. Pairing electronically controlled active Electromechanical Suspension System (EMS) technology developed by The University of Texas Center for Electromechanics (UT-CEM) with current reconnaissance vehicle platforms creates highly mobile intelligence gathering systems capable of operating on the move over rough and unimproved terrain. This report documents the establishment of criteria by which to judge sensor platform stabilizing performance of EMS and then uses these metrics to evaluate performance improvements over conventional passive vehicles. Based on this analysis it may be possible to operate effectively over cross-country terrains at speeds of 10-15 mph while collecting useful reconnaissance data.

This study was performed by first modifying models previously developed during a Phase I Office of Naval Research (ONR) funded effort to design EMS for the LAV 25 to represent the Coyote Reconnaissance Vehicle based on unclassified information available on the internet. This involved adding a mast and representative sensor suite payload, in addition to modifying weight distribution and chassis mass to match available information. Figure 1 shows a representative image used in developing the model and identifying components to include for illustrative purposes.

Figure 1: Coyote LAV with sensor mast deployed

CEM has a 15-year history of wheeled and tracked commercial and military vehicle hardware demonstrations using the proven approach of modeling and simulation with low-level laboratory testing and high-level field hardware verification. The same fundamental approach has been used on every advanced UT-CEM suspension program. Modeling and simulation of the vehicle platforms, actuator hardware, and control system is accomplished through the coupled use of the Dynamic Analysis and Design System (DADS) package from LMS International (Leuven, Belgium) and Matlab-Simulink from Mathworks (Natick, Massachusetts, USA). DADS is a high-order advanced multi-body simulation tool specifically tailored to vehicle simulation that provides advanced elements that can represent controlled actuators, complex tire models, road-tire contact models, system sensors, passive springs, system losses and damping, non-linear kinematics and dynamics, physical constraints, mass properties, and terrain profiles. It interfaces with Simulink to accept force commands from the modeled controller and output appropriate sensor information.

Simulink is a highly flexible high-level programming interface that allows the construction of complex models in a graphical manner that are then numerically solved concurrent with the linked DADS kinematic simulation. Figure 2 shows the top level of the Simulink model used in this study. The suspension control software is fully contained in the EMS control unit block, all other blocks perform various other functions to segregate sensors, handle steering and speed control, or format inputs and outputs to interface with DADS. In previous programs that progressed to a vehicle demonstration, the controller algorithms contained in the EMS control unit block are directly transferred, without reprogramming or modification, into the vehicle prototype using auto code generation tools and hardware from dSPACE (dSPACE GmbH, Paderborn, Germany). This facilitates a straightforward transition from simulation to prototype demonstration to production hardware. Controller cycle time in the simulation environment is strictly enforced to ensure realism and guarantee controller performance when transitioning to hardware. This approach has been successfully demonstrated in over 10 vehicle active suspension programs (including six full-vehicle demonstrations) using the same core controller.

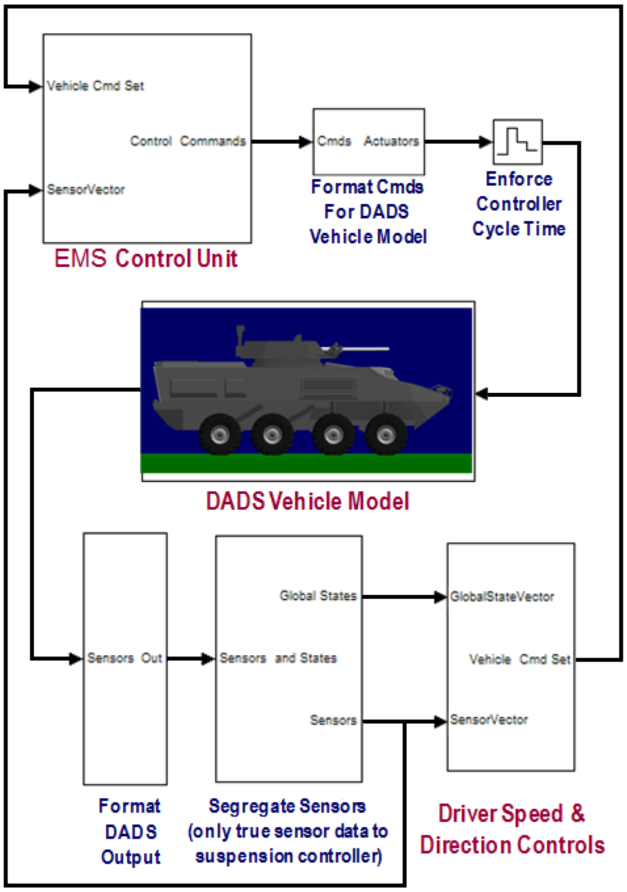


Figure 2: Simulink model of Coyote LAV controller

Model verification is accomplished at many levels during the suspension development process. Component level testing (Figure 3) and characterization comparison (Figure 4) in the lab verifies assumptions and equations used to represent components. Low-level measurements such as actuator length (Figure 5) and high-level processed measurements such as Driver Absorbed Power (Figure 6) demonstrate very comparable results and provide a high level of confidence in the accuracy of the modeling results.

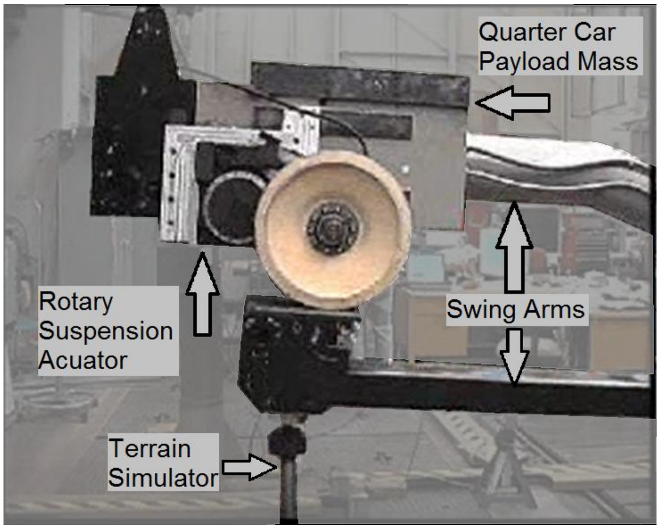


Figure 3: Rotary actuator testing with quarter car simulator rig

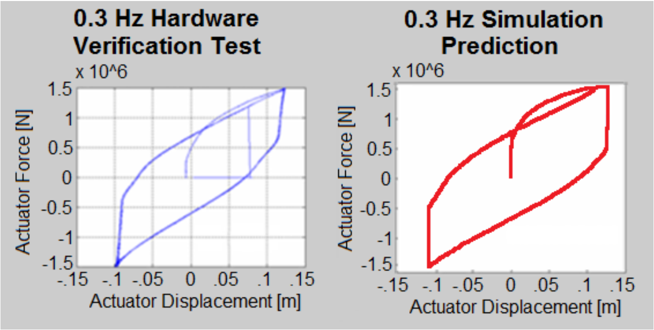
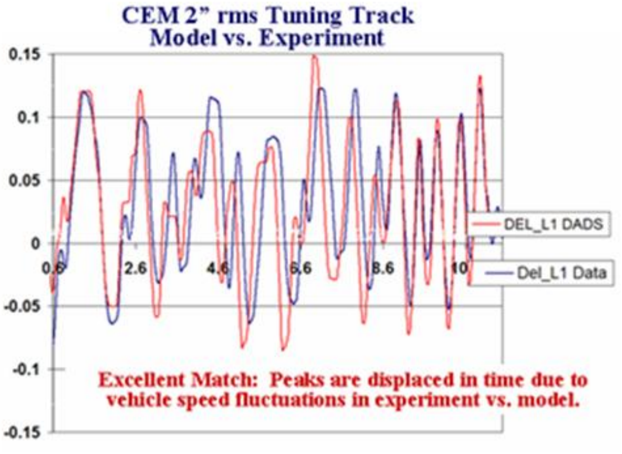


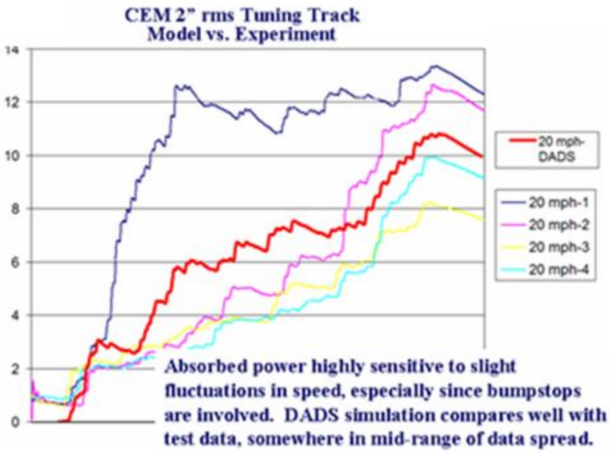
Figure 4: Actuator hysteresis comparison



CEM 2" rms Tuning Track
Model vs. Experiment

Excellent Match: Peaks are displaced in time due to vehicle speed fluctuations in experiment vs. model.

Figure 5: Comparison of actuator length between simulation and collected data



CEM 2" rms Tuning Track
Model vs. Experiment

Absorbed power highly sensitive to slight fluctuations in speed, especially since bumpstops are involved. DADS simulation compares well with test data, somewhere in mid-range of data spread.

Figure 6: Comparison of driver absorbed power between simulation and collected data

The model began with the partially validated CEM model for the 40,000 lb gross vehicle weight (GVW) LAV 25. Based on information obtained from the internet, the following assumptions were made regarding the construction of the Coyote Reconnaissance vehicle: the stock passive vehicle is modeled with a 28,000 lb GVW, weight scaled torsion bars in the rear, weight scaled coil springs in the front, stock shock absorbers on all 8 wheel stations, and a Will-Burt Stiletto 6 m mast. The mast was mounted to the floor of the vehicle 4.30 m back from the center of the front tire contact patch, 0.56 m left of the vehicle centerline, and 0.75 m from the ground at nominal ride height. It was assumed that full extension would be the worst-case scenario so the model was built to represent as such. The mass distribution and inertia were represented with a simple hollow cylinder with similar apparent dimensions as the Stiletto mast. Density was assumed uniform and the mass of the mast assumed to be 95 kg. The payload was modeled as a small dense cube measuring 0.5 m x 0.5 m x 0.5 m and assumed to be 120 kg. The mast is assumed inflexible and rigidly attached to the chassis.

Based on our history in modeling and simulation, the general trends should be applicable to a wide range of vehicle classes. Specific sensor performance and corresponding integral stabilization systems were not modeled as detailed information was not readily available. However, specific sensor models can be easily simulated at a later time if warranted and relevant data provided.

NEW PERFORMANCE METRICS

Evaluating the performance enhancement potential of EMS on mast mounted sensor packages requires the development of additional performance metrics beyond the typical driver absorbed power as developed by Lee, Pradko and Lins [1-5]. Driver absorbed power is chiefly concerned with the vertical motion of the driver's seat in narrow frequency ranges. Pitch motion is only captured if the driver is seated sufficiently far from the vehicle's center of mass to be displaced vertically as the pitch angle changes. For a device sitting 6 m above the floor of the vehicle, pitch motion will be a dominating factor in determining the potential performance of any line of sight based reconnaissance system. Heave and body rolling motions are assumed to be less detrimental to sensor performance. Peak vertical, lateral, and longitudinal accelerations of the mast payload are of lower significance to sensor performance, but still provide valuable insight into the isolation performance of the suspension system.

Power spectral density (PSD) of the mast payload accelerations was also selected as an additional performance metric to evaluate the effects of EMS on spectral content. Methods described by Ashmore [6] were used in generating the PSD results per the sponsor's request. Data was sampled at 100 Hz and a Hanning window was applied to reduce leakage. PSDs were calculated from acceleration signals having a zero DC offset so no detrending was required. A window length of 256 samples was used resulting in frequency bins 0.39 Hz apart which corresponds to wavelengths up to 128 ft at 30 mph. A 50% overlap was used to minimize signal loss due to the Hanning window.

Transfer functions for the terrain input to mast accelerations output were calculated per the sponsor's request. Welches Averaged periodogram method was used to determine the quotient of the cross power spectral density of input and output and the power spectral density of the input. The transfer function was normalized to make it dimensionless by dividing the amplitude of each frequency bin by the bin frequency squared.

The standard test plan was modified to create tests that would excite rolling motions into the vehicle. Typical testing procedures separate dynamic handling maneuvers from off-road straight-line performance. Combining the two tests provides an opportunity to better understand and demonstrate the platform stabilizing abilities of EMS. The vehicle will now be required to execute a NATO lane change while traversing a bump course. The intent is to have the vehicle encountering bumps at angles other than perpendicular to excite rolling motions and allow the EMS systems to prove their superior performance over passive.

CONTROLLER OPTIMIZATION RESULTS

Simulations began with exploring the parameter space to determine appropriate controller gain adjustments that would most enhance the stabilization of a mast mounted sensor package. In the interest of brevity, vehicle performance was evaluated over three courses at fixed speeds: Yuma Proving Grounds 4 (YPG 4) at 25 mph, Aberdeen Proving Grounds 29 (APG 29) at 20 mph, and Perryman III (PER III) at 20 mph. The courses and speeds were selected based on prior experience with the LAV 25 vehicle and anticipated performance of the Coyote model.

Four suspension topologies were evaluated for optimal controller gain settings: Standard EMS active (involves full active suspension of all eight wheels), enhanced force active (EMS with a different actuator configuration), semi active, and a hybrid (EMS Active on the four corners and semi active multistate on the interior wheel stations). Control gains were modified one at a time while holding the others constant to determine the optimum balance of parameters. With the primary focus on stabilizing the pitch motion of the chassis, it is not surprising that controller parameters responsible for counteracting vehicle pitching were the most significant in improving performance. It is worth mentioning that this effort did not include any attempt to develop new control algorithms that would provide ultra stability at low speeds, the controller used in this study shows its best performance at high speeds for which it was developed. The performance improvements shown in this study can be further enhanced through the development of a controller intended for the purpose of optimal stability at low speed.

SUSPENSION PERFORMANCE ANALYSIS

Six suspension configurations were evaluated on six different terrains at six different speeds for both straight-line and NATO lane change simulations. This required 432 simulations to fully populate the test permutation matrix. The simulated suspension configurations were stock passive 28k Lb GVW, passive 40 klb GVW with soft air suspension, 8 Wheel Active (Standard EMS) 40 klb GVW, hybrid active – semi active 40 klb GVW, enhanced force active 40 klb GVW, and semi active 40 klb GVW. The two passive models are the stock 28k Lb with stock springs and a 40K Lb vehicle with very low frequency air springs. The standard EMS system is an eight-wheeled fully active system. The hybrid active has active actuators on the front and rear axles and Semi-Active multi discrete state actuators on the second and third axle. The enhanced force active is a similar system to the standard EMS Active with a different actuator porting that provides for higher extension force with reduced retraction force. The semi active system was modeled with limitations representative of a MagnetoRheological fluid based actuator. All active systems were set with an arbitrary bi-directional force limit of 3000 Lbs in addition to any other force limit imposed by the air spring design and burst pressure capabilities. Due to the proprietary nature of the modeled suspension systems and ITAR controls governing their use and distribution, further technical discussion regarding the specifics of actuator topology and detailed comparisons with conventional passive suspension hardware are not permissible given the potential audience of this paper. The courses simulated were YPG #3, YPG #4, APG #29, and Random Wave Spectrum courses “Washboard and Pothole”, Trail, and Cross Country. Speeds ranged from 5 to 30 mph in 5 mph increments.

Rather than present hundreds of plots comparing various performance parameters across the six vehicle configurations negotiating individual courses at various speeds, representative averaged plots will be shown as many of the trends from course to course are fairly similar. Results will be given in the following order: max pitch angle, driver absorbed power, absorbed power at rear crew station, and peak payload acceleration. These will be presented in and along the X, Y, and Z directions where X corresponds to longitudinally with the direction of travel, Y laterally across the vehicle width, and Z vertically. Results will be presented for both the straight-line and NATO lane change runs, peak roll angle and yaw angle will only be presented for the NATO lane change runs.

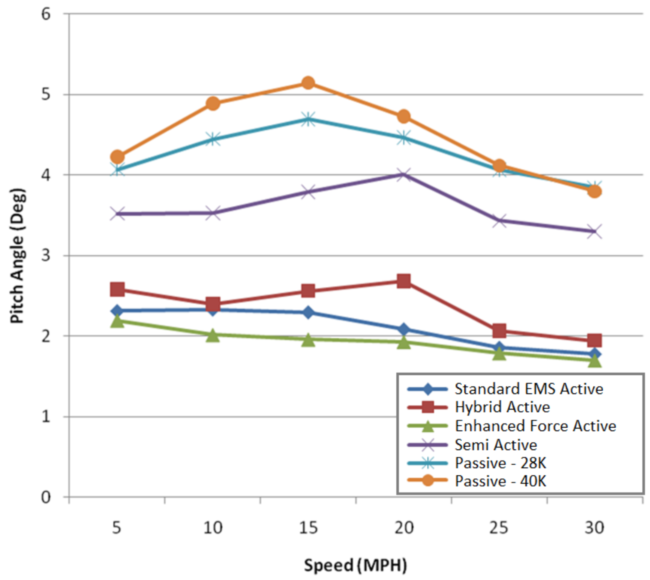


Figure 7: Averaged peak pitch angle for all straight courses

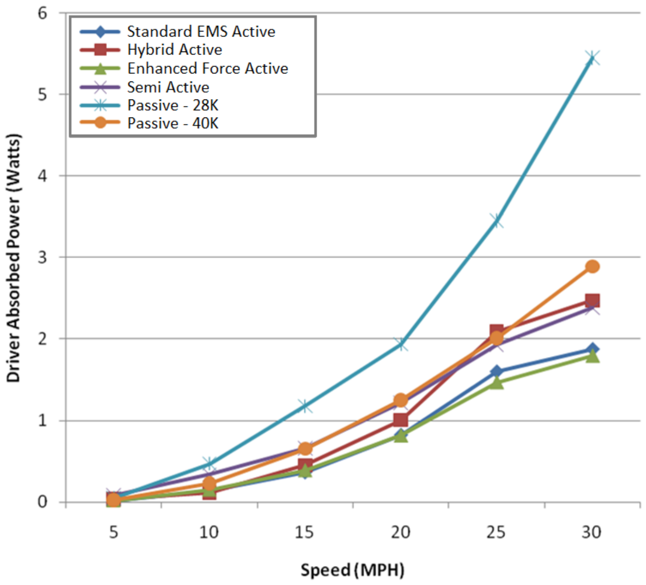


Figure 8: Averaged driver absorbed power for all straight courses

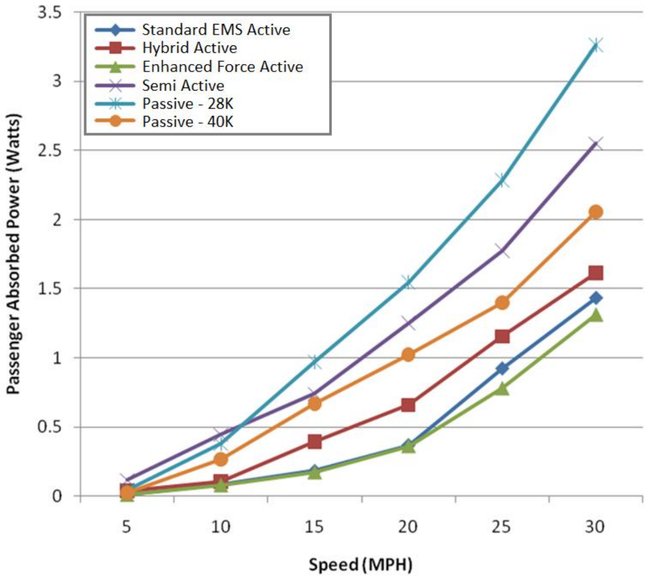


Figure 9: Averaged passenger absorbed power for all straight courses

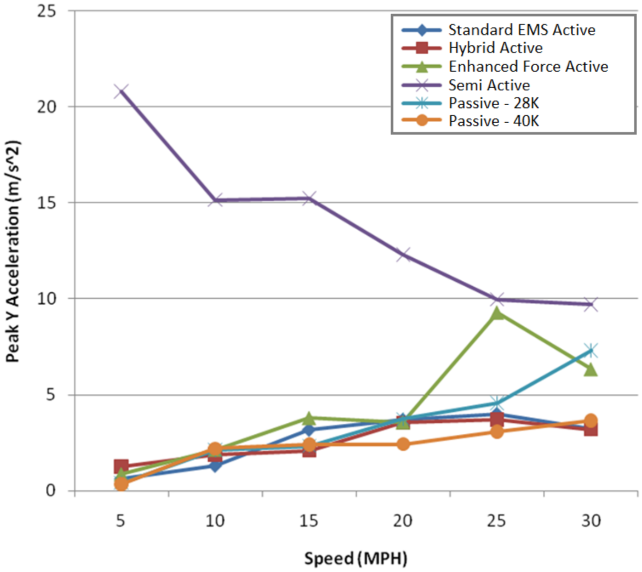


Figure 11: Averaged peak lateral (Y) payload accelerations for all straight courses

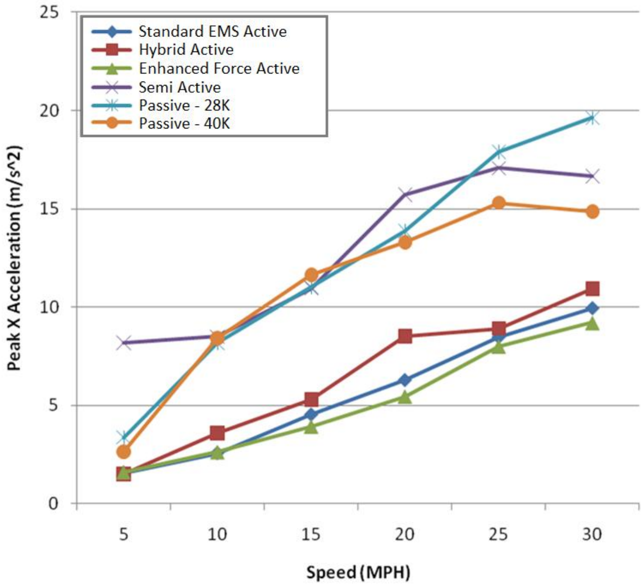


Figure 10: Averaged peak longitudinal (X) payload accelerations for all straight courses

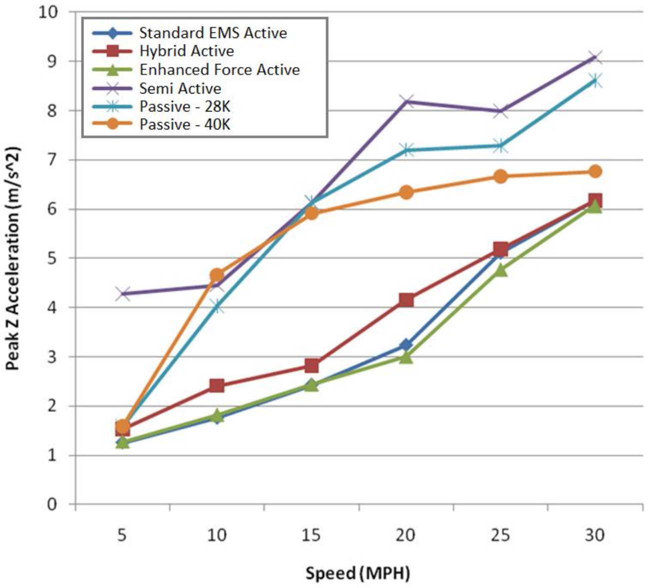


Figure 12: Averaged peak vertical (Z) payload accelerations for all straight courses

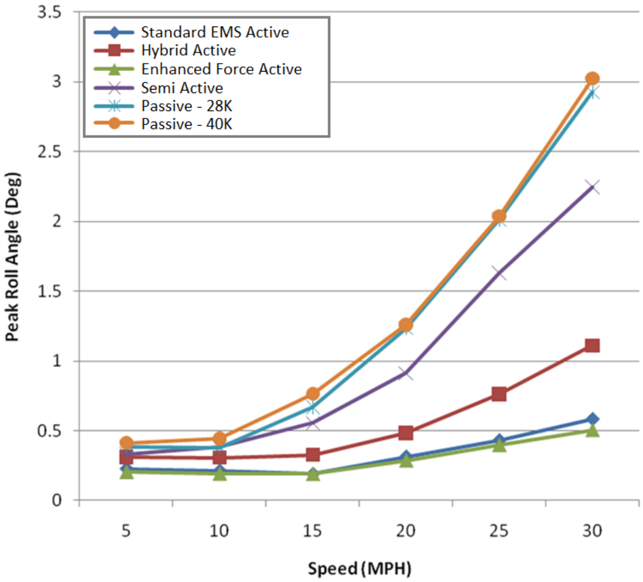


Figure 13: Averaged peak roll angle for all NATO LC courses

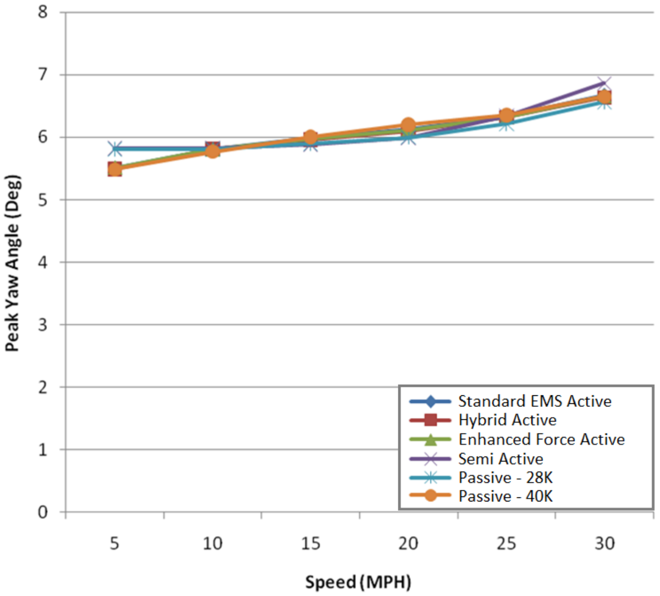


Figure 15: Averaged peak yaw angle for all NATO LC courses

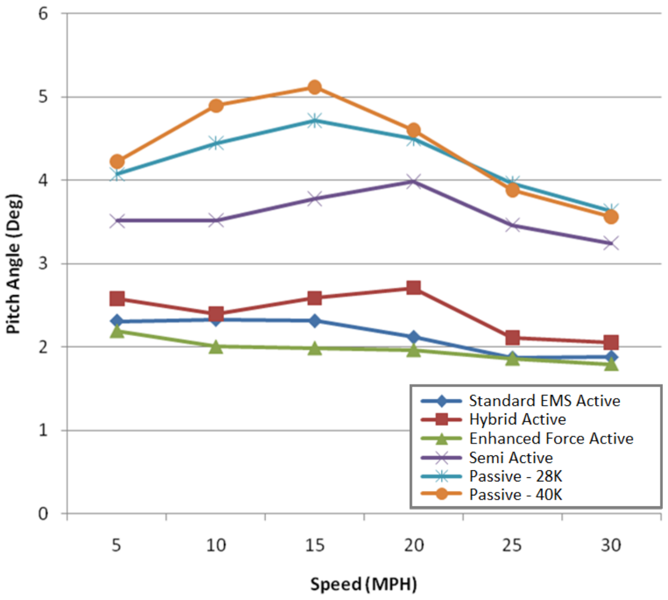


Figure 14: Averaged peak pitch angle for all NATO LC courses

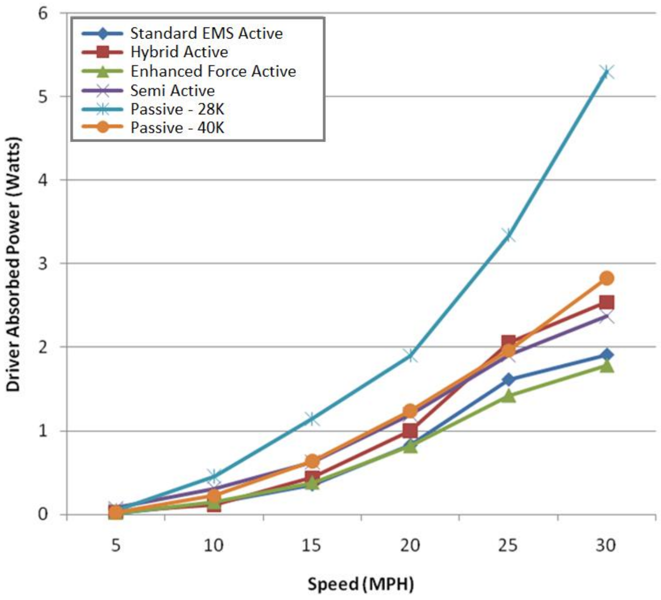


Figure 16: Averaged driver absorbed power for all NATO LC courses

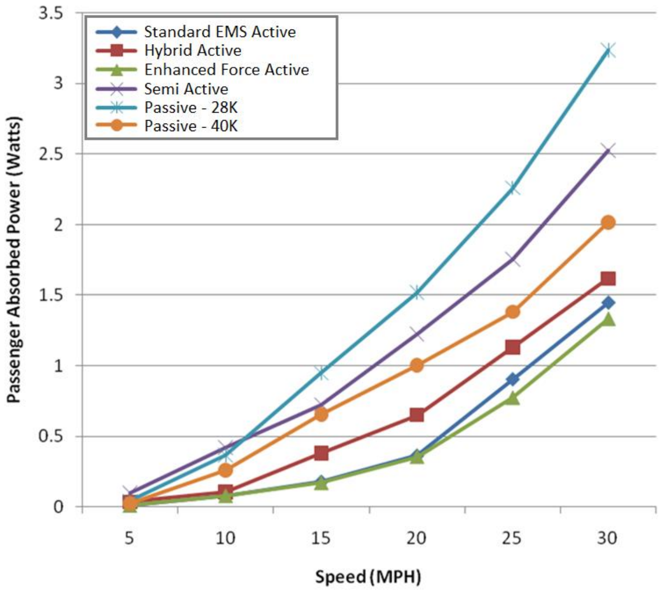


Figure 17: Averaged passenger absorbed power for all NATO LC courses

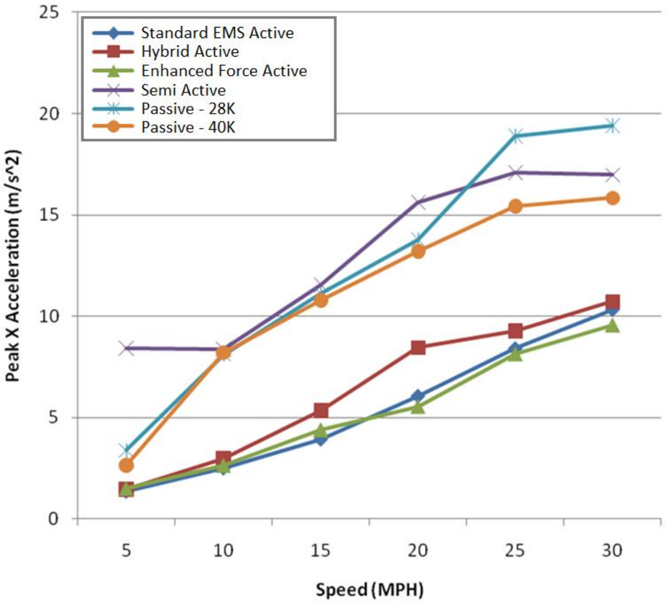


Figure 18: Averaged peak longitudinal (X) acceleration for all NATO LC courses

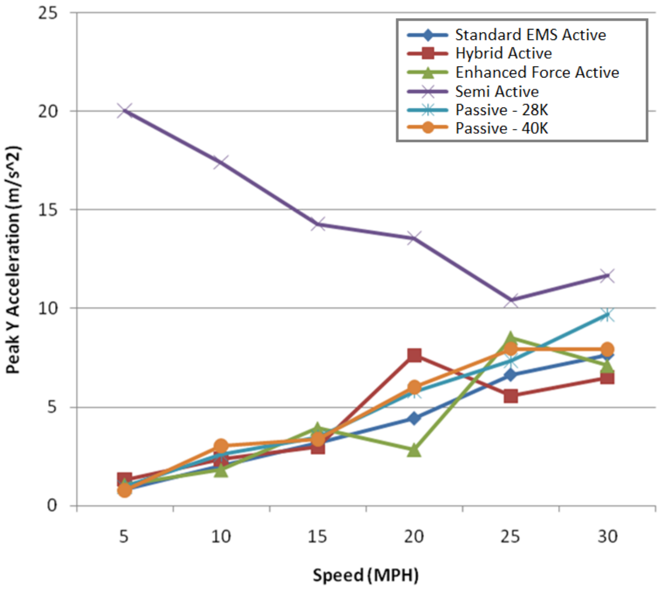


Figure 19: Averaged peak lateral (Y) acceleration for all NATO LC courses

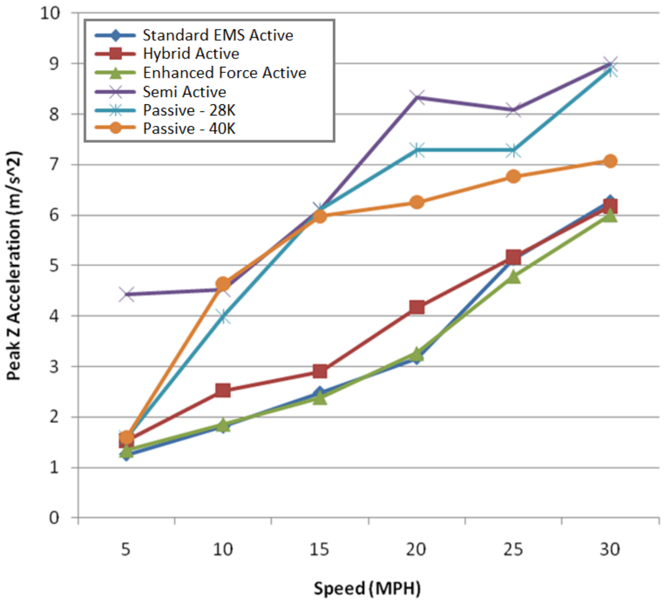


Figure 20: Averaged peak vertical (Z) acceleration for all NATO LC courses

PEAK PERFORMANCE RESULTS

The divorced nature of the active suspension systems demonstrates its superior capability to isolate the chassis motion from terrain inputs. In every performance metric other than peak yaw angle during the NATO lane change and peak lateral (Y) acceleration, the active suspension systems significantly outperformed the stock passive vehicles. In the metrics where performance was not improved, it was not diminished from stock capacity as factors other than suspension performance likely dominate its intensity. Steering harshness proved to be a significant source for lateral acceleration and yaw angle variability. The highest performing system was the enhanced force active; its higher extension force authority provides for more control in the most aggressive terrains. The standard EMS was the next best performing and in most of the lower amplitude courses was indistinguishable from the enhanced EMS. Hybrid active was next in line performance wise, typically coming within 10% to 20% of the standard and enhanced systems.

The semi active performance split the difference between the passive and full active systems for pitch control and driver absorbed power. In other metrics it was only slightly better or approximately the same as passive. In the lateral (Y) acceleration, it was significantly worse than passive. This is due to the manner by which the controller was operating to represent the semi-active actuator. There was no attempt to design a controller to avoid the potential for harsh high frequency switching near zero speed operation where the commanded force is rapidly changing sign to account for the inability of the actuator to generate positive powers in the system. This can lead to a magnification of minor harshness that would otherwise be insignificant. In this case the minor corrections the steering controller was constantly making were reflected in the recorded lateral acceleration data and contributed to this apparent performance degradation.

The heavy passive with soft air springs performed nearly identical to the stock passive with stock springs, only in peak Z acceleration and driver and passenger absorbed power was there any improvement.

The results of the deviation from the normal test plan to include a NATO lane change over the bump course were less significant than initially hoped. Minor differences in body roll angles were noted but were less significant than expected. This is another area where further test development would be worthwhile.

PSD AND TRANSFER FUNCTION ANALYSIS

Discussion of the PSD results will be focused on YPG #3 while traveling at speeds of 10 mph. This will provide a lower bound to improvements offered by EMS since EMS improvements increase with speed. Higher speeds are interesting for consideration, but concerns of overhead obstacle avoidance may provide speed limitations aside from sensor performance capabilities.

Figure 21 shows the PSD of the mast longitudinal (X) component of acceleration while traversing YPG #3 at 10 mph. The harshness of the semi-active system can clearly be seen in its departure from the family of curves around 10 Hz, it is understood that alternate control strategies exist to mitigate these artifacts however they were beyond the scope of this study. The hybrid active also shows some performance degradation above 30 Hz, however it is less significant that the pure semi active system. The transfer function of longitudinal acceleration to vertical acceleration shown in figure 22 shows similar trends to the PSD results.

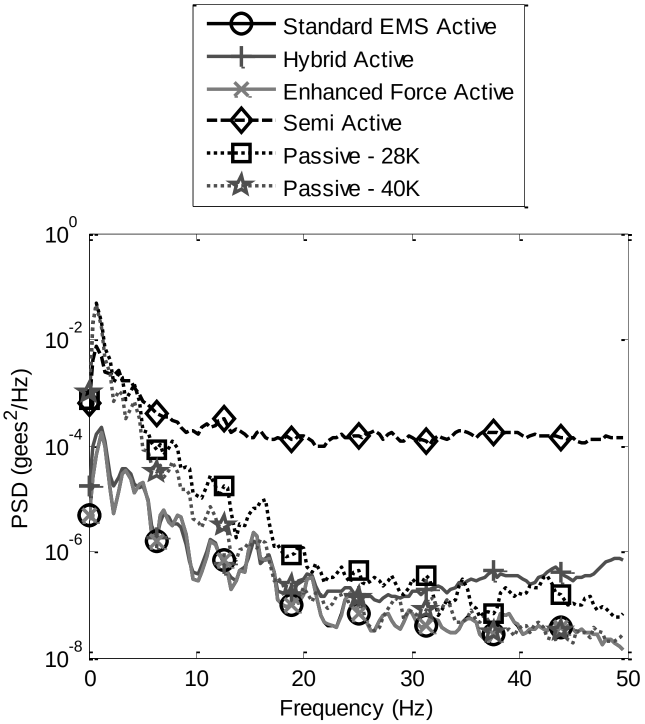


Figure 21: Mast longitudinal acceleration PSD for various vehicle configurations while traversing YPG RMS #3 at 10 mph.

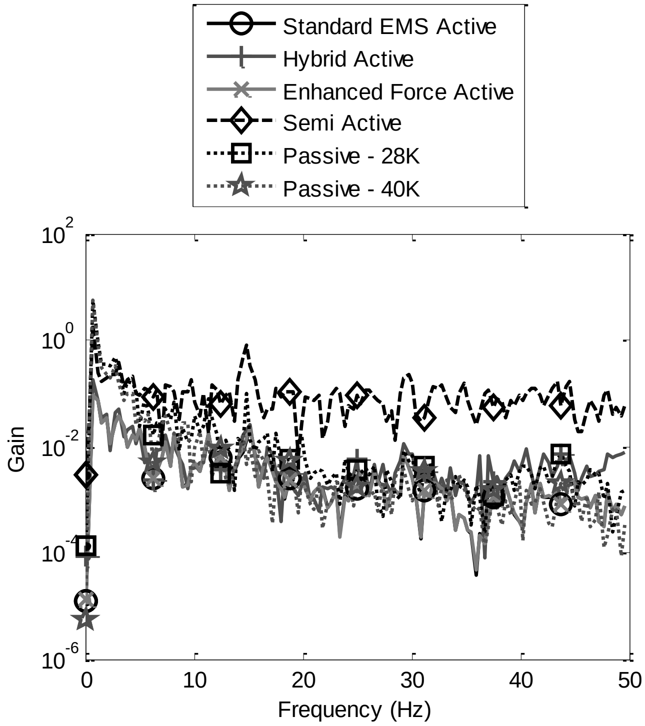


Figure 22: longitudinal acceleration vs. terrain vertical acceleration transfer functions while traversing YPG RMS #3 at 10 mph.

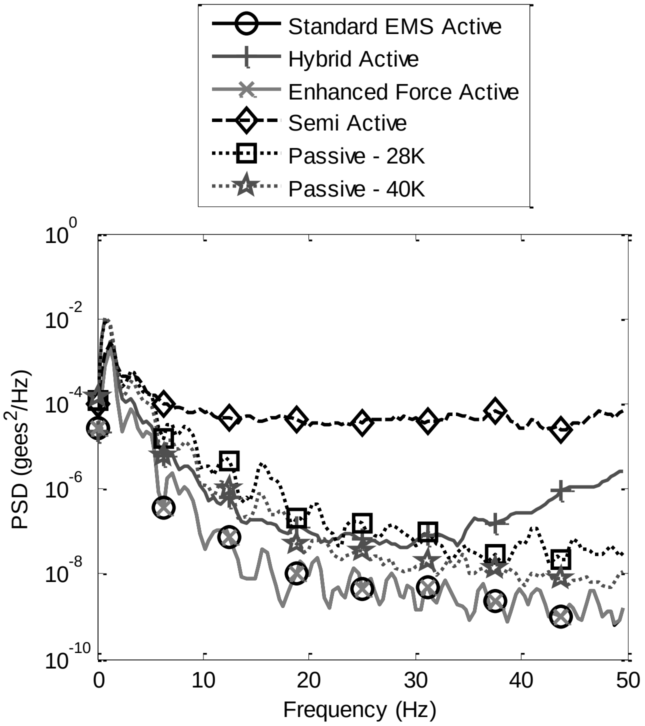


Figure 23: Mast vertical acceleration PSD for various vehicle configurations while traversing YPG RMS #3 at 10 mph.

Figure 23 shows an approximate order of magnitude improvement in vertical response of the Standard and Enhanced Force EMS systems. As seen in the longitudinal acceleration PSD plot, the Semi Active and Hybrid Active performance drops off at higher frequencies. Figure 24 shows the transfer function for the vertical acceleration with respect to the terrain vertical acceleration. Again the trends are similar to the PSD plot.

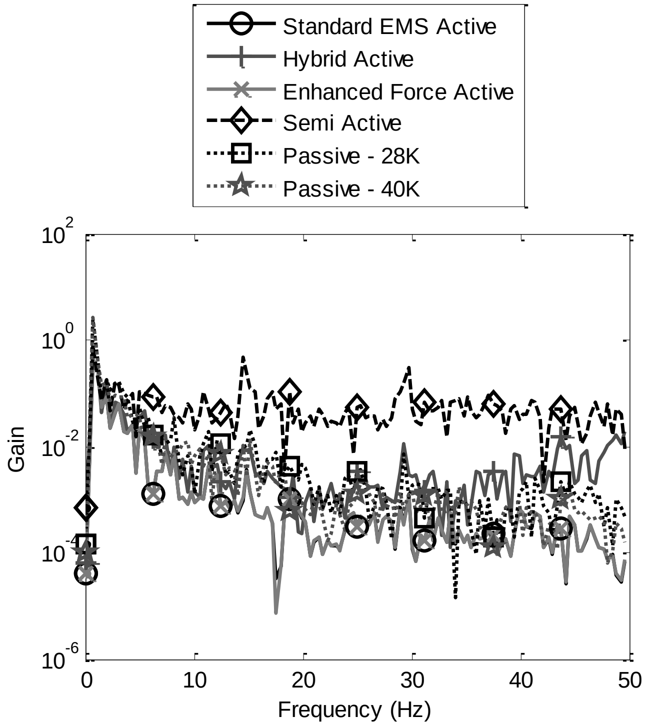


Figure 24: Vertical acceleration vs. terrain vertical acceleration transfer functions while traversing YPG RMS #3 at 10 mph

DISCUSSION / CONCLUSION

The two fully active systems proved their superior performance over hybrid active, semi active, and stock passive systems in both peak performance metrics and PSD analyses. Typical improvements of 80% to 90% lower than stock passive were seen in the fully active systems in peak body response measurements and accelerations over aggressive off-road terrains. Orders of magnitude improvements were seen in PSD and Transfer function analyses. From these results it may be possible to reliably operate mast mounted reconnaissance equipment on the move at speeds of up to 15 mph.

Additional controls development is key to fully demonstrating systems capable of true platform stabilization. The current control system was developed and optimized to minimize driver-absorbed power off road, and maximize on road stability during dynamic handling events. Both of these regimes focus on enhancing the driver experience. At speeds appropriate for mobile data collection the driver experience will not be a limiting factor, thus the system can focus on aggressively stabilizing the vehicle platform and give secondary consideration to comfort and control. Further development could realize tuned gain scheduling to optimize system performance under all operating regimes depending on the mission focus.

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