2015 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 4-6, 2015 - NOVI, MICHIGAN

INTEGRATED CONTROL OF ACTIVE CHASSIS SYSTEMS FOR MILITARY VEHICLE APPLICATIONS

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ABSTRACT

Future wheeled and tracked military vehicles will be equipped with multiple active chassis control systems, as systems currently in widespread use on passenger and commercial vehicles such as brake-based electronic stability control are implemented on military vehicles. It is essential that these systems work in an integrated fashion to avoid negative interactions between systems. The approach currently used to achieve integrated control in the passenger and commercial vehicle segments requires extensive tuning and development of the individual systems through cooperative efforts of the vehicle and active chassis system manufacturers, an approach that would generally not be feasible in the military vehicle segment. This paper presents a simple approach for achieving integrated control of multiple active chassis systems that is tailored to the unique commercial and developmental challenges faced by military vehicles.

INTRODUCTION

Future wheeled and tracked military vehicles will be equipped with multiple active chassis systems, ranging from anti-lock braking to active suspension and active steering. Integrated control of these systems is essential to maximize performance and eliminate negative interactions between systems. This paper provides an overview of the work performed by Ricardo, Inc. and the Office of Naval Research (ONR) to develop a method of integrated control for multiple active chassis systems that is tailored to the unique operating and development environment of military vehicles.

The challenge associated with integrating multiple active chassis systems is a current research and development topic both in the automobile industry, where high-end automobiles are frequently equipped with several active chassis systems, and in aircraft, where flight control systems must integrate multiple control effectors. In the auto industry, extensive, multi-year development programs are conducted to tune the individual active chassis systems to ensure they perform well together while in aircraft, complex control algorithms with full access to the end effectors are used to address interactions between effectors. For military ground vehicles, neither of these approaches are feasible: development budgets and timelines are limited, and direct interaction with end effectors is not possible since ground vehicle chassis control systems are generally “black boxes” purchased from external suppliers.

To develop an approach suitable for military vehicles, the team made two fundamental decisions, both focused on addressing the challenges in working with “black box” active chassis systems. First, since we would have little to no opportunity to tune the individual active chassis systems to work together, we decided that a higher level supervisory controller would be necessary to regulate the behavior of the individual systems. Second, we realized that communication with the individual systems would be limited, so we focused on simplifying interaction between the supervisory controller and the controllers for the individual active chassis systems. Accordingly, in contrast to existing supervisory control approaches that rely on continuous, closely coupled control of active chassis systems, our approach instead simply selects different modes for the individual systems (on/off, high/low, active/passive, etc.)

and then lets the individual systems perform their intended function with minimal intervention.

To determine the appropriate operating mode for each active chassis system, the state of vehicle dynamic behavior is first determined; states can include understeer/oversteer, rough road/smooth road, braking/accelerating, etc. Once the current state is determined, modes for each active chassis system are set based on a pre-determined logic. This logic is developed using a novel approach based on a House of Quality, an analytical tool widely used in product quality development that can be readily adapted to control system logic development. A House of Quality matrix is developed for each vehicle dynamic state the vehicle is expected to encounter, rating the stand-alone effectiveness of each active chassis system in modifying the vehicle behavior as well as identifying interactions between each system. The ratings can be established both through objective approaches (test or simulation) or subjectively. The completed House of Quality matrix is then used to establish the optimum combination of active chassis system modes for each vehicle dynamic state.

This paper will review the development of the aforementioned approach during a multi-year program conducted by ONR and Ricardo. We will first review current approaches for integrated control and discuss how we arrived at our approach. We will next review the set of active chassis systems that were used for both simulation and in-vehicle activities. Then, we will provide a detailed description of our integrated control approach, including a discussion of how the House of Quality is used to develop integrated control logic, as well as a review of simulation results using the integrated controller. Finally, we will discuss the demonstration vehicle and in-vehicle test activities.

INTEGRATED CONTROL OF ACTIVE CHASSIS SYSTEMS

To achieve integrated control of multiple active chassis systems, the basic problem to be resolved is redundant or over-actuated control. For example, on a vehicle equipped with multiple yaw control active chassis systems such as brake-based electronic stability control, active steering, and driveline torque vectoring, it is important to determine how to apportion a given yaw command between the different systems so that each system does not try to achieve the same yaw objective, creating redundancy and inefficiency. Furthermore, it is critical that the systems not perform conflicting actions as they attempt to change the vehicle yaw. Overall, the challenge is to effectively coordinate the different active chassis systems to achieve the optimal response.

Four basic types of integrated control of multiple active chassis systems can be realized, as shown in Figure 1. In each case, multiple actuators and their respective controllers are shown. In *hierarchical control*, information is exchanged between controllers in one direction only, meaning that one controller acts independently and the other controllers act in response to actions of the independent controller. In *cooperative control*, information can be exchanged in both directions between controllers. It is worth noting that cooperative control is the most common method of integrated control for current production automobiles, with limited information such as which systems are active and which are inactive exchanged between controllers over the vehicle network.

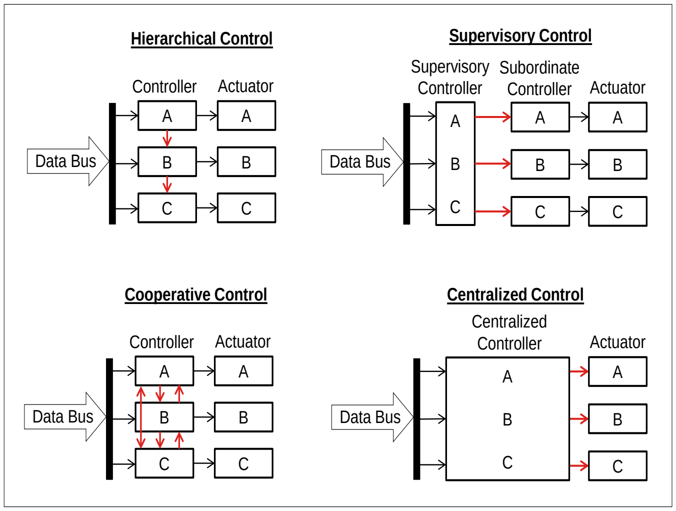


Figure 1. Integrated control methods using inter-controller communication *(left)* and controller addition/combination *(right)*

While hierarchical and cooperative control preserve the basic structure of the network and rely on communication between existing controllers, other approaches add additional or combine existing controllers. *Supervisory control* adds an additional, higher-level controller that manages the existing controllers while *centralized control* combines all functions into a single controller.

To determine the appropriate integrated control approach for this effort, the team considered two primary factors: (1) development effort and complexity, and (2) accessibility/transparency of existing controllers. Relative to development effort and complexity, both hierarchical and cooperative control require considerable work to ensure controllers function effectively together. Centralized control also requires significant development effort, including implementation of a high-bandwidth interface with all existing actuators. Relative to accessibility of existing controllers, both hierarchical and cooperative control require development-level access to the individual active chassis controllers to establish interfaces with other controllers and to tune/revise the control strategy to work with the other controllers installed on the vehicle. Since central control eliminates existing controllers, transparency of existing controllers is not an issue; however, sufficient knowledge of actuator characteristics to effectively control them must be somehow acquired.

Based on the above considerations, the team chose a supervisory control strategy. A supervisory control strategy provides nearly the level of authority of centralized control with greatly reduced development effort, and also minimizes the development and corresponding level of access required of individual active chassis controllers inherent in cooperative and hierarchical approaches. As previously mentioned, this is a key consideration for military vehicles, since chassis control systems are typically provide by vendors due to the relatively low volumes.

To further simplify system development, the team chose a moding approach for communication between the supervisory controller and the subordinate controllers. In this approach, the supervisory controller only commands the desired mode of operation of subordinate controllers instead of detailed, real-time commands. This approach minimizes interface requirements between subordinate controllers and the supervisory controller.

OVERVIEW OF TESTBED VEHICLE AND INSTALLED ACTIVE CHASSIS SYSTEMS

Vehicle Description

For this effort, a High Mobility Multipurpose Wheeled Vehicle (HMMWV) M1151 variant was selected as the testbed vehicle, for both simulation and vehicle demonstration. The HMMWV represents an ideal candidate vehicle for the installation of multiple active chassis systems, since it is widely used and its legacy design can benefit greatly from the addition of active chassis systems.

Active Chassis System Description

The team had the freedom to select the most relevant active chassis systems for the effort. The guiding principle in selecting the active chassis systems was to control all vehicle degrees of freedom and to illustrate the “art of the possible” for a vehicle equipped with multiple active systems. Accordingly, the team selected the following active chassis systems:

1. Brake-based electronic stability control (ESC)
    - Enhances stability by applying a yaw moment to the vehicle through the braking system
    - Uses steering angle and vehicle speed to determine driver target yaw rate; compares this to measured yaw rate and attempts to match target
    - Tends to reduce vehicle speed since only braking forces are applied, not accelerating forces
2. Semi-active damping
    - Employs “skyhook” or similar algorithm to control semi-active corner dampers
    - Reduces unwanted body motion leading to improved stability and ride
    - Keeps tires in closer contact with ground
    - Changes damping curve based on road profile and body motion
    - Primarily intended for ride performance but also can impact handling performance
3. Electronic limited slip differential (ELSD)
    - Uses a clutch to modulate differential from fully open to fully locked based on wheel slip and yaw control algorithms
    - In low traction conditions, the clutch can transfer torque from wheel with lower adhesion to wheel with higher adhesion, providing significant traction improvement
    - Can also reduce vehicle oversteer during handling events

Active Chassis System Performance Assessment Simulations

Performance simulations were conducted for all selected active chassis systems, using a high-fidelity HMMWV vehicle dynamics simulation model equipped with model representations of the various active chassis systems. The simulations were used to understand both the performance of the active systems individually as well as interactions between the systems, providing information that was used to develop the integrated control logic.

Two maneuvers were selected, one for assessment of performance on smooth roads and one for assessment of performance on rough roads. For smooth roads, the FMVSS 126 Sine w/ Dwell maneuver was selected; this maneuver is used for evaluating the capability of ESC systems to prevent vehicle spinout on all new US passenger vehicles. In this maneuver, the vehicle is driven at a constant 50 mph speed. The vehicle is steered in one direction and then rapidly back

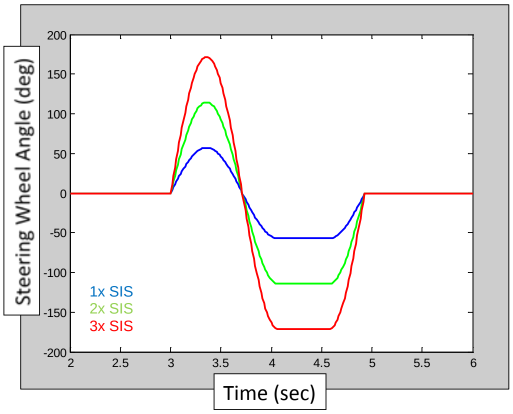


Figure 2. Typical steering inputs for Sine w/ Dwell maneuver

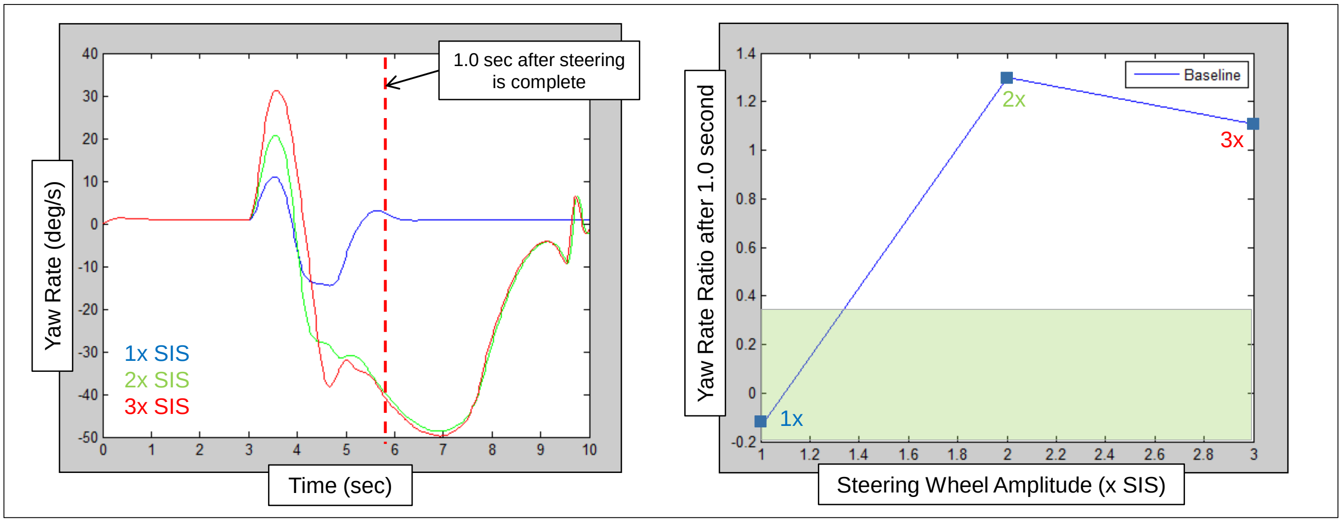


Figure 3. Performance criteria for Sine w/ Dwell maneuver: *left*, primary criterion is ratio of yaw rate 1 second after steer to peak yaw rate during steer (Yaw Rate Ratio); *right*, Yaw Rate Ratio for all steer amplitudes must be less than 0.35

in the other direction Figure 2. The steer is held in the second direction for a dwell of 0.5 sec. and then steering is returned to straight ahead. Test runs are performed at increasingly higher steering amplitudes until the vehicle spins out or until the steer angle for a given run exceeds 270 deg. For simplification, only three steer amplitudes are shown, labeled as N x SIS where SIS is the steer amplitude required to achieve 0.3 g lateral acceleration during a 50 mph constant speed, increasing steer maneuver and N is an integer multiplier.

Performance criteria for the Sine w/ Dwell maneuver are shown in Figure 3. The Sine w/ Dwell maneuver produces vehicle yaw in one direction and then the other; if spin occurs, the yaw rate will generally take much longer to decay. This is tracked by the Yaw Rate Ratio, which is the ratio of the yaw rate 1 sec. after steer is completed to the maximum value during steer; a value greater than 0.35 is indicative of vehicle spin out. The vehicle shown in Figure 3 spins out for the two larger steer inputs (2x and 3x) but not for the smaller 1x input.

Simulations for the Sine w/ Dwell maneuver were conducted both with standalone, individually operating systems as well as combinations of multiple systems. Results for the simulations, expressed as Yaw Rate Ratios, are shown in Figure 4. From the left plot in Figure 4, it is clear that only the ESC system is capable of preventing vehicle spin up to the maximum steer angle. ELSD provides some benefits at lower steer angles but is not effective at higher

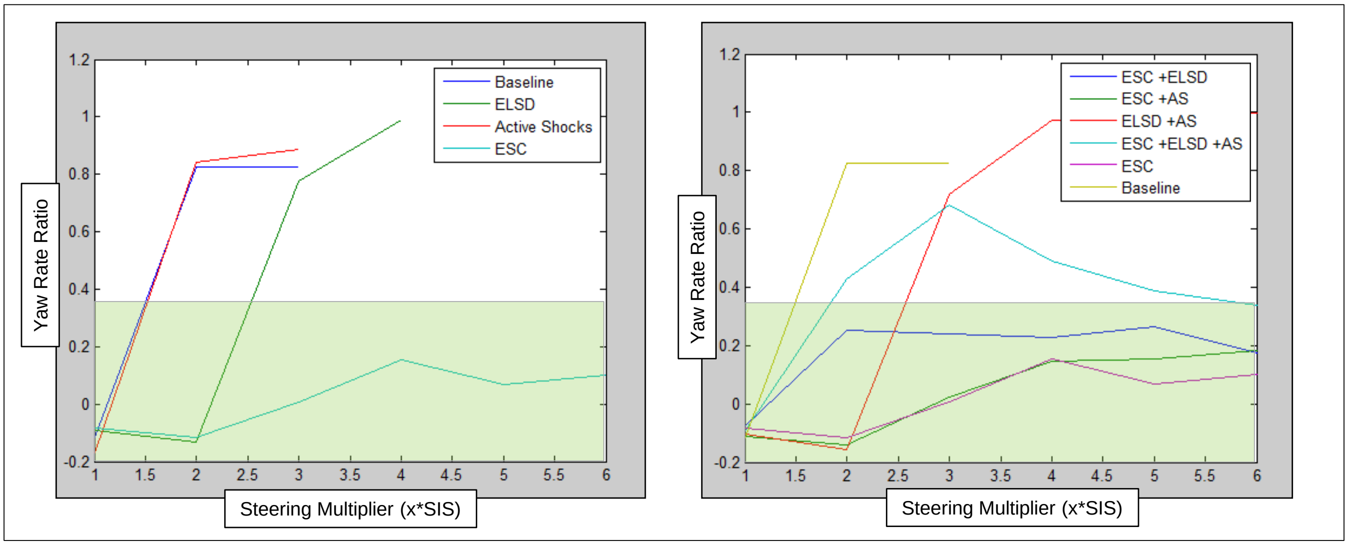


Figure 4. Individual *(left)* and combined *(right)* effects for selected active chassis systems in Sine w/ Dwell maneuver

steer angles; semi-active damping (labeled "Active Shocks") provides little additional yaw control over the baseline.

The right plot in Figure 4 illustrates the potential negative interactions between the active chassis systems. ESC with the addition of semi-active damping (ESC+AS) shows little degradation over ESC alone. However, the combination of ESC with ELSD shows significant degradation due to interactions between the ELSD and ESC. Essentially, the ELSD limits the ability of the ESC system to control individual wheel slip by locking the inner and outer wheels together through the differential. The addition of semi-active damping (ESC+ELSD+AS) further degrades system performance.

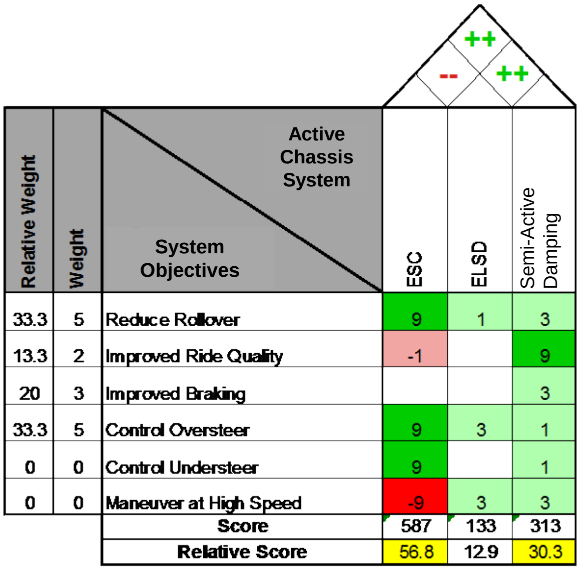
INTEGRATED MOBILITY CONTROLLER DEVELOPMENT

As previously discussed, a supervisory control architecture was selected. In this approach, a high level supervisory controller regulates the actions of the subordinate individual chassis system controllers, preventing negative interactions and maximizing the performance benefits of the systems. The supervisory controller combines data from its own sensors with data received from the active chassis system controllers to determine the vehicle state. Then, based on the vehicle state and its internal logic, it determines how to regulate the behavior of the subordinate systems.

House of Quality Controller Logic Development

The internal logic used to react to vehicle states is developed using a House of Quality decision making process. A House of Quality is most commonly used in product quality improvement to analyze the effects of different treatments on multiple quality objectives, capturing both the relative effectiveness of each treatment on the objectives as well as interactions between treatments. In this case, our objectives are instead desired vehicle dynamic attributes and our treatments are the different active chassis systems.

An example House of Quality for this effort is shown in Figure 5. The overall vehicle dynamic system objectives are listed on each row of the matrix, while the active chassis systems are listed in each column. Each objective is weighted based on its importance. Effectiveness of each active chassis system on each objective is assigned a rating from the set {-9, -3, -1, 1, 3, 9}, with -9 indicating the system is very detrimental to the objective and 9 indicating it is very beneficial to the objective; a null rating is assigned if the system has no effect on the objective. The "Roof" of the House of Quality illustrates interactions between systems, with positive or reinforcing interactions indicated by a ++ symbol and negative interactions indicated by a -- symbol. Ultimately, based on the effectiveness rating and weighting for each objective, a score for each active chassis system can be calculated, providing guidance for which system should be used. Note that the use of *Relative* indicates that the values in a row or column have been normalized so that their sum is 100.



Relative Weight	Weight	Active Chassis System / System Objectives	ESC	ELSD	Semi-Active Damping
33.3	5	Reduce Rollover	9	1	3
13.3	2	Improved Ride Quality	-1		9
20	3	Improved Braking			3
33.3	5	Control Oversteer	9	3	1
0	0	Control Understeer	9		1
0	0	Maneuver at High Speed	-9	3	3
		Score	587	133	313
		Relative Score	56.8	12.9	30.3

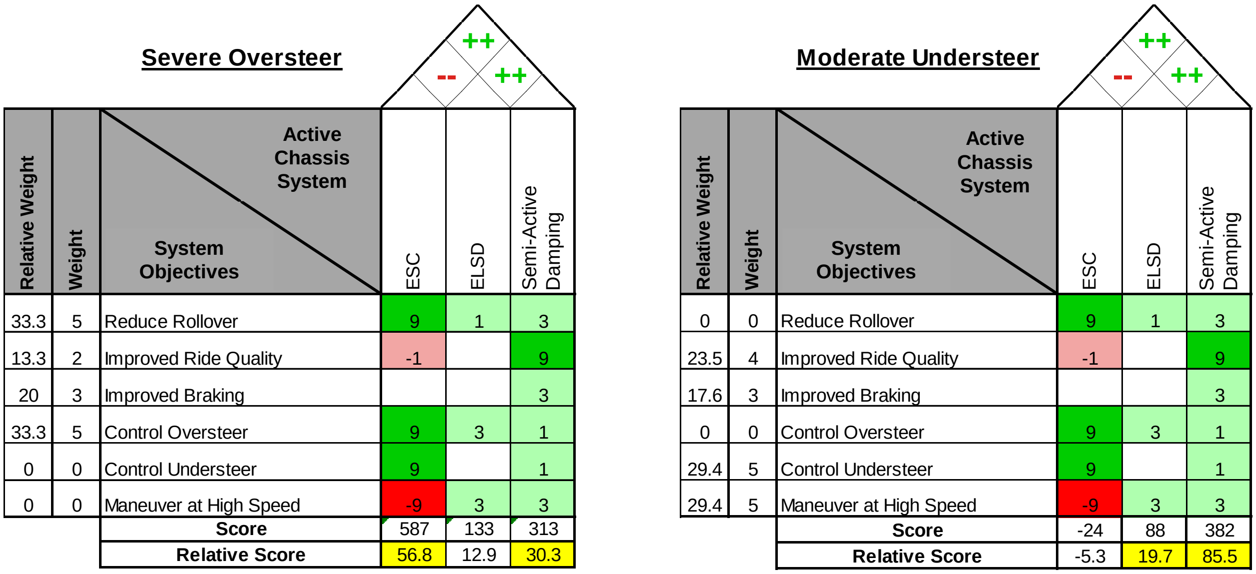
Figure 5. Example House of Quality used for controller strategy development

The system objectives for this effort were developed with a focus on end user needs and were either safety-based or performance-based and included the following: reduce rollover, improve ride quality, improve braking, control oversteer, control understeer and maneuver at high speeds. The effectiveness rating for each active system on each objective can be assigned in many different ways including simulation, testing, or historical experience. In this case, the simulation results discussed previously in this paper were used to rate the effectiveness of each individual system acting alone as well as to evaluate interactions between the systems. For example, as illustrated in Figure 4, ESC is very effective at controlling yaw rate and hence oversteer so it receives a 9 rating for the *Control Oversteer* objective. Figure 4 also shows that ELSD reduces the effectiveness of ESC, indicating that a negative interaction exists, leading to a -- rating in the House of Quality Roof for the interaction between ELSD and ESC in Figure 5.

A House of Quality rating matrix is created for the different states of vehicle dynamic behavior that the vehicle may be experiencing. The states for this effort were focused on vehicle handling response and included Moderate Understeer, Severe Understeer, Moderate Oversteer and Severe Oversteer. These states were determined from the difference between the target and actual yaw rates, with the target yaw rate calculated based on vehicle speed and driver steer angle. These four states were further categorized by whether the vehicle was on a smooth road or a rough road, since road roughness has a significant effect on behavior of the active chassis systems.

The effectiveness and interaction ratings for each objective and active system were generally similar for all states of vehicle behavior with minor differences between ratings for smooth road vs. rough road. On the other hand, the importance weightings for each objective varied significantly for each state. For example, if the vehicle is in the Moderate Understeer state, less weight is assigned to *Reduce Rollover* since the vehicle is not at significant risk of rollover in that state. However, if the vehicle is in the Severe Oversteer state, there is a greater possibility of rollover so the *Reduce Rollover* objective is assigned a higher weight. This difference in weightings between the Severe Oversteer and Moderate Understeer states is shown in Figure 6.

The end result of the House of Quality process is an overall effectiveness score for each active chassis system at achieving the weighted system objectives for a given vehicle state. A higher score means the effector system is more effective in achieving the objectives while a negative score means the effector system will hinder the vehicle control system in achieving the objectives. The overall score, together with the interaction values, is used to determine the optimal combination of systems for each state which ultimately provides the foundation for the integrated controller logic.



Severe Oversteer

Relative Weight	Weight	Active Chassis System System Objectives	ESC	ELSD	Semi-Active Damping
33.3	5	Reduce Rollover	9	1	3
13.3	2	Improved Ride Quality	-1		9
20	3	Improved Braking			3
33.3	5	Control Oversteer	9	3	1
0	0	Control Understeer	9		1
0	0	Maneuver at High Speed	-9	3	3
		Score	587	133	313
		Relative Score	56.8	12.9	30.3

Moderate Understeer

Relative Weight	Weight	Active Chassis System System Objectives	ESC	ELSD	Semi-Active Damping
0	0	Reduce Rollover	9	1	3
23.5	4	Improved Ride Quality	-1		9
17.6	3	Improved Braking			3
0	0	Control Oversteer	9	3	1
29.4	5	Control Understeer	9		1
29.4	5	Maneuver at High Speed	-9	3	3
		Score	-24	88	382
		Relative Score	-5.3	19.7	85.5

Figure 6. House of Quality matrix for two different states illustrating weighting differences for system objectives (note difference between *Reduce Rollover* weighting)

Overall Integrated Controller Architecture

The logic of which active chassis system(s) to use based on the vehicle state is then used directly to determine what mode to set each active chassis system to. In general, for each state the most beneficial systems will be in a fully functioning/fully active mode and the least beneficial systems will be in a passive/shutdown mode. The overall controller layout is summarized in Figure 7, illustrating the various modes each system can be in.

The control strategy is implemented in the supervisory controller using Matlab Simulink and Stateflow. A Stateflow block corresponding to each vehicle state is used to command the active chassis system modes. As the vehicle state changes a different Stateflow block is used, changing the active system control based on the established House of Quality logic.

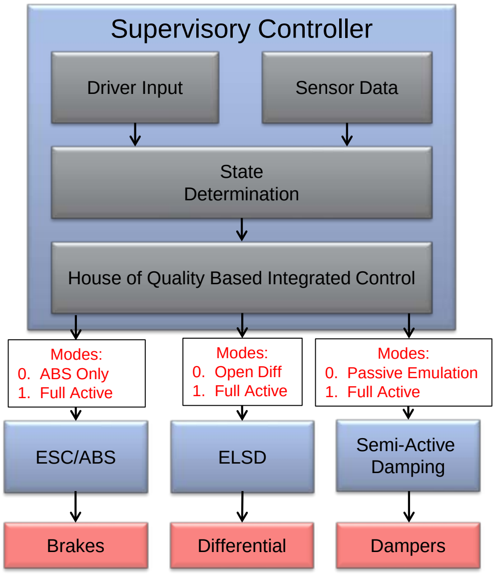


Figure 8. Diagram of Supervisory Controller function and interaction with subordinate controllers

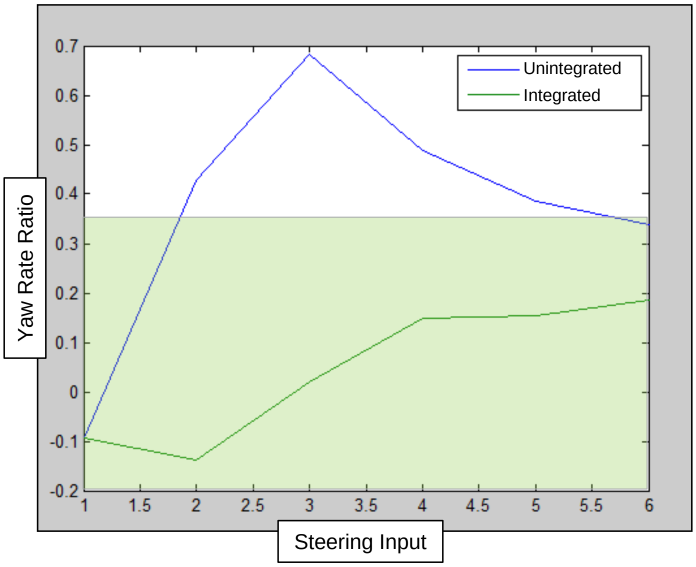


Figure 7. Sine w/ Dwell Yaw Rate Ratio plot showing significant improvements for vehicle with integrated control

The effectiveness of the overall integrated strategy was demonstrated in simulation by comparison of an integrated and unintegrated vehicle with the same active systems. The Sine w/ Dwell on smooth road and Double Lane Change on rough road maneuvers were used for the assessment. The vehicle with integrated control showed significant improvement over the unintegrated vehicle for all maneuvers. For instance, in the Sine w/ Dwell maneuver, the Yaw Rate Ratio of the integrated vehicle is substantially lower than the unintegrated vehicle, with the Yaw Rate Ratio of the integrated vehicle well below the maximum allowable value while the unintegrated vehicle fails the test Figure 8.

The vehicle with integrated control also performs better in the Double Lane Change on a rough road when compared to the unintegrated vehicle by increasing the exit speed while still successfully performing the maneuver. Shown in Figure 9, the integrated and unintegrated control vehicles both have substantially higher entrance speeds then the baseline vehicle with no active systems. However, the integrated control vehicle has a much higher exit speed than the unintegrated control vehicle, with an 8 mph increase on the 1” RMS and a 7 mph increase on the 2” RMS. This is a direct result of the integrated control coordinating the actions of the ESC and ELSD systems to prevent them from counteracting each other, resulting in less braking intervention by the ESC system and ultimately less vehicle deceleration during the maneuver.

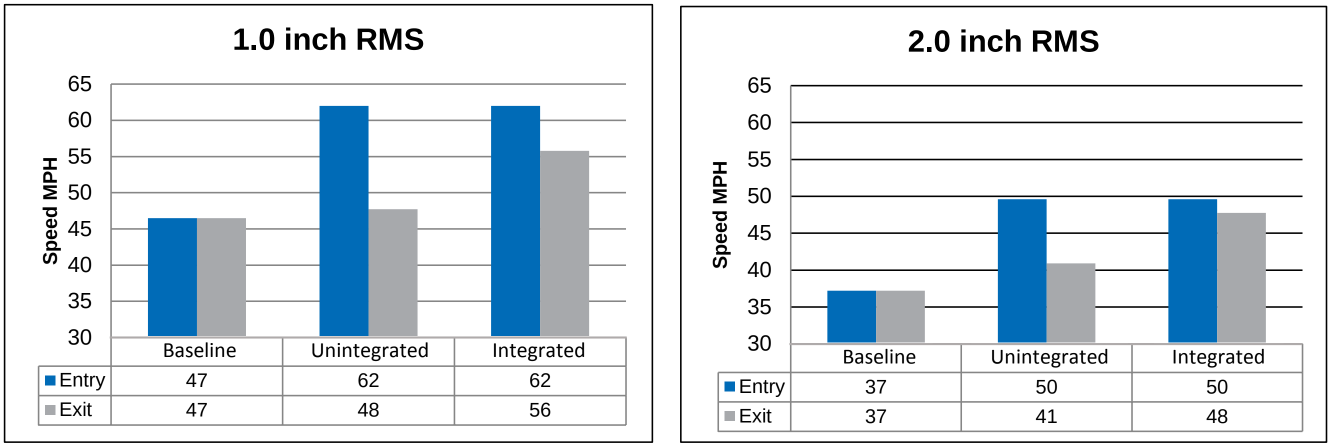


Figure 9. Double Lane Change Improvements for the Integrated Vehicle over Two Levels of Rough Road

DEMONSTRATION VEHICLE BUILD AND TESTING

To further validate the developed integrated control approach, a HMMWV M1151 demonstration vehicle was built up and tested Figure 10. Just as with the simulation-based assessment, the HMMWV was equipped with brake-based electronic stability control, electronic limited slip differentials, and semi-active damping. The integrated control strategy was implemented on a low cost, off-the-shelf electronic control unit using the Simulink models developed in the simulation phase.

Figure 11. HMMWV M1151 Demonstration Vehicle

The integrated control strategy was validated by performing a variety of on- and off-road maneuvers. The basic strategy and logic developed using the House of Quality approach was carried over with minimal changes to the demonstration vehicle. Vehicle test results illustrate that the integrated control strategy was performing as intended. Figure 11 shows performance for a NATO Double Lane Change. The left plot of the vehicle with integrated control shows the House of Quality logic in operation, with the ELSD shut off in periods of significant oversteer to avoid negative interaction with the ESC system; oversteer is indicated by the actual yaw rate being greater than the target yaw rate. The right plot shows that integrated control, by shutting off the ELSD when the ESC is active, reduces the amount of work the ESC needs to perform, evidenced by the lower required brake pressures for the vehicle with integrated control vs. unintegrated control.

CONCLUSION

This paper has outlined a simple, robust approach for developing integrated control for multiple active chassis systems that is tailored to military vehicles. The approach dynamically determines the optimum combination and operating modes of multiple active chassis systems based on the vehicle state. It can be easily modified to include any number of vehicle states and can also accommodate as many performance objectives as necessary. Furthermore, additional active chassis control systems can be readily added by simply inserting another column into the House of Quality.

Overall, the approach developed here minimizes the integration effort required for individual systems, focusing integration and development on a supervisory controller and the use of a simplified mode-based communication strategy between the supervisory controller and the subordinate active chassis controllers. Despite the simplicity of the strategy, it is still adaptive enough to accommodate more complex requirements. Future research areas include integrating the House of Quality calculations into the controller instead of hardcoding the results, creating an opportunity for adaptive algorithms that have the ability to modify the controller logic based on changes in the environment or the vehicle.

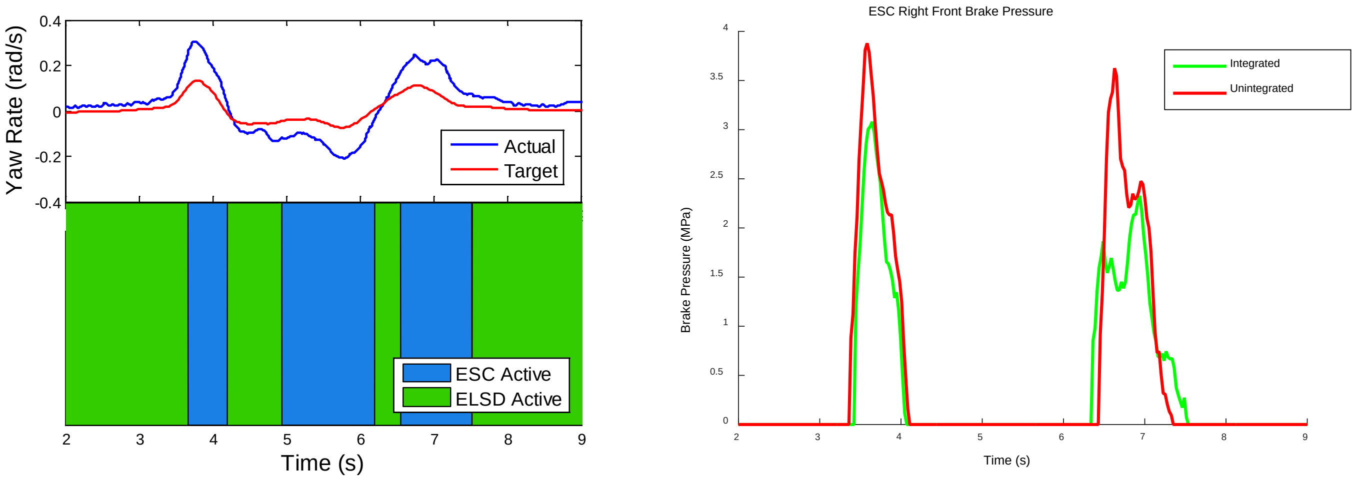


Figure 10. Results for NATO Double Lane Change at 60 mph with Demonstration Vehicle