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14. ABSTRACT This report outlines progress on the DARPA M3 Program, project "Directional and Attitude Stability Kit" for the period 08/01/2013 to 05/1/2014. It is produced by appending the quarterly reports already produced for DARPA. There were only two active "quarters" in this reporting period: Q1 = 08/01/2013 – 02/13/2014 Q2 = 02/14/2014 – 05/01/2014					
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Report Title

Directional and Attitude Stability Control Kit
Final Progress Report

ABSTRACT

This report outlines progress on the DARPA M3 Program, project “Directional and Attitude Stability Kit” for the period 08/01/2013 to 05/1/2014. It is produced by appending the quarterly reports already produced for DARPA. There were only two active “quarters” in this reporting period:

Q1 = 08/01/2013 – 02/13/2014

Q2 = 02/14/2014 – 05/01/2014

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received

Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

ReceivedBook Chapter**TOTAL:****Patents Submitted****Patents Awarded****Awards****Graduate Students**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Alonzo Kelly	0.05	
FTE Equivalent:	0.05	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

⁶
Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Micheal George	0.25
Michel Laverne	0.10
Dane Bennington	0.10
FTE Equivalent:	0.45
Total Number:	3

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attachment

Technology Transfer

Directional and Attitude Stability Control Kit

Final Progress Report, Jul. 1, 2014
National Robotics Engineering Center
Carnegie Mellon University

***Alonzo Kelly, Michael George, Michel Laverne,
Dane Bennington***

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Statement of Problem Studied¹⁰

- We address the problem of maneuver-induced rollovers of ground vehicles in theatre. A bolt-on kit is sought with the following characteristics.
 - Add-on Kit for Existing Vehicles
 - Minimal/Common Sensing
 - Adaptive to Payload/Personnel Variations
 - Prevent loss of directional or attitude stability.
 - (Maybe) Record black-box data for post-crash investigations.



MRAP Concept¹¹

- MRAPS (Mine Resistant Ambush Protected) vehicles are rolling over at high rates in theatre.
- 12,000 of these vehicles are fielded.
- They are tall, heavy (14 to 30 tons). Most have a raised Chassis, and V-Shaped Hulls.
- Therefore.....
 - **Rollover risk is high.**



MRAP Cat-1 Navistar



BAE CAIMAN MRAP

Human Factors Issues¹²

- The human factor is hard to fix:
 - Most recruits get no training before deployment.
 - Many have never driven a large vehicle.
 - Vehicles are deceptively easy to drive.
 - Driver is most junior person on the team.
 - Bar armor reduces visibility of road edge.



MRAPs



FMTVs

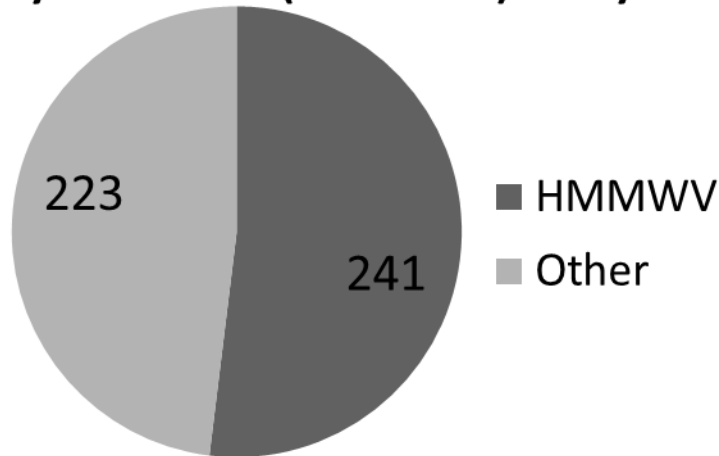


Up Armored HMMWVs

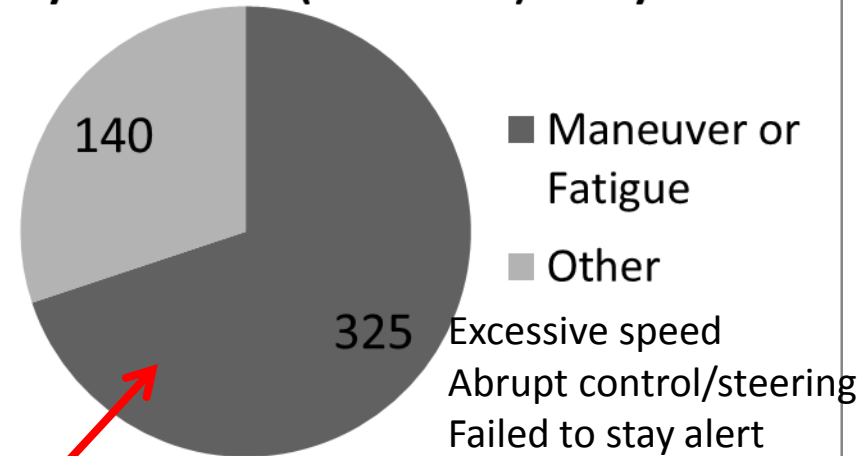
In the 3 years right before significant numbers of MRAPs were deployed:

- a) more than ½ of the rollover events were for HMMWVs
- b) almost ¾ of them were due to various forms of unsafe driving.

Army 2003-2006 (Pre MRAP) Study



Army 2003-2006 (Pre MRAP) Study

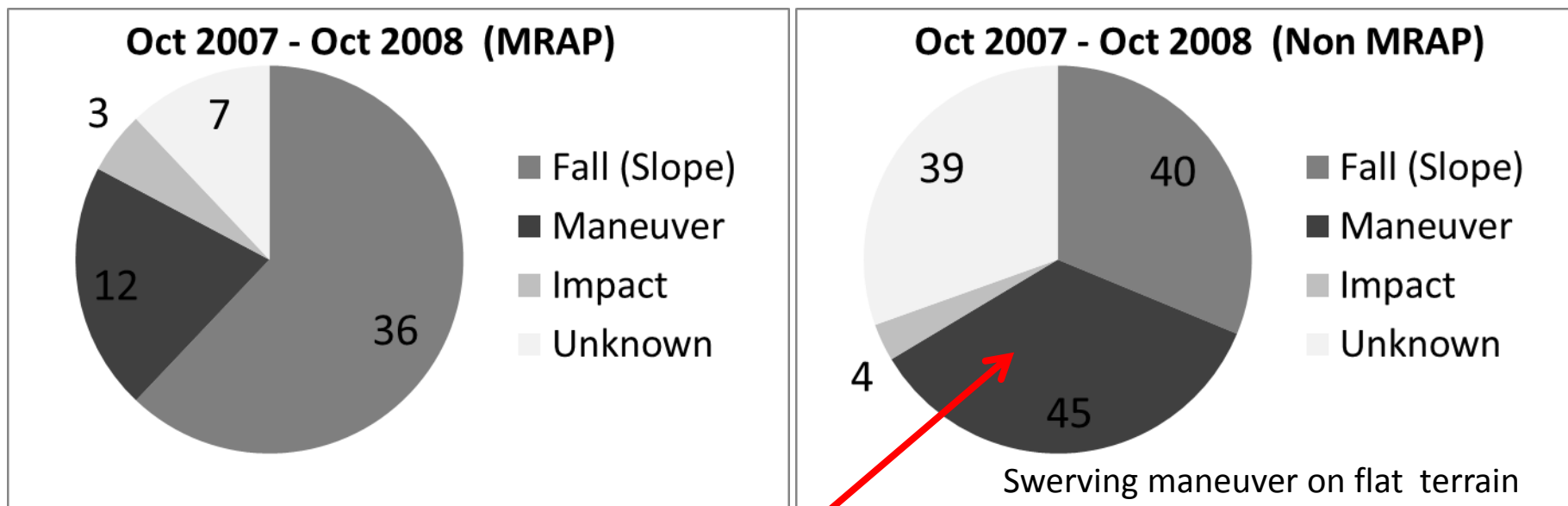


70% of Rollovers caused by Maneuver / Other Human Error

1: Joint Military Vehicle Working Group Army Tactical Vehicle Rollover Analysis, PowerPoint briefing by Mr Alfred Rice, Deployments and Operations Task Force (DOTF) (undated)

Recent Vehicle Rollover Stats¹

In more recent years, MRAPs are rolling primarily due to soft road edges and unsound bridges. However, at least 36% of rollovers are caused by unsafe driving and some of the “Fall” events are rollovers and some of the “Unknown” events are probably maneuver induced as well.



Technology may not help with Fall Rollovers. However, at least 36% caused by swerving maneuvers.

MRAP Fall initiated rollovers have often occurred from unimproved roads that may be near bodies of water where the road shoulders are soft. The weight of the MRAP and the road conditions in theater have resulted in a number of vehicle “fall initiated” type rollovers. To date almost half of MRAP rollovers have been fall initiated from operating along roads near ditches, or bridges and culverts incapable of handling the heavy weight of the MRAP.

1: Marine Corps Center for Lessons Learned, “MRAP Safety Best Practices”, Oct 2008,

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Summary for Q1¹⁶

- In this quarter we retrofitted the vehicle with both representative sensors for rollover prevention and a ground truth system to allow us to do development.

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 - Ground truth implementation
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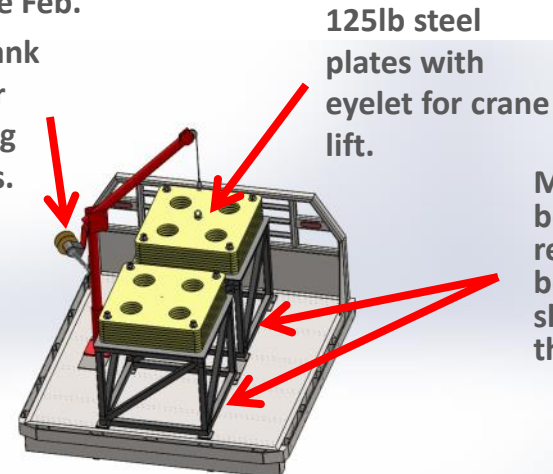
Vehicle Purchase and Retrofit

- NREC purchased a 2002 Ford F-250 pickup truck which will be leased to the project on a monthly as-needed basis. This vehicle was selected for the following characteristics:
 - Large payload relative to empty mass (2930/5870 lbs)
 - Offroad capability
 - Commercial vehicle as similar as possible to an MRAP.
- We previously reported that we would mount payload using a Kargo Master Heavy Duty Pro II steel rack, which is an off-the-shelf accessory. We mounted this rack and assessed its claim of 1700lb maximum payload and decided it was not a safe option.
- We designed a custom rack to mount the payload and subjected it to finite element analysis with maximum loads measured by an IMU on the vehicle.
- Payloads can be mounted safely in 4 locations on the vehicle in increments of 125lb up to the max payload limit (~2000lbs).
- Rack is currently in fabrication, expected completion is late Feb.



7/6/2014 F250 w/ Commercial Cargo Rack Installed

Hand crank
crane for
mounting
payloads.



125lb steel
plates with
eyelet for crane
lift.

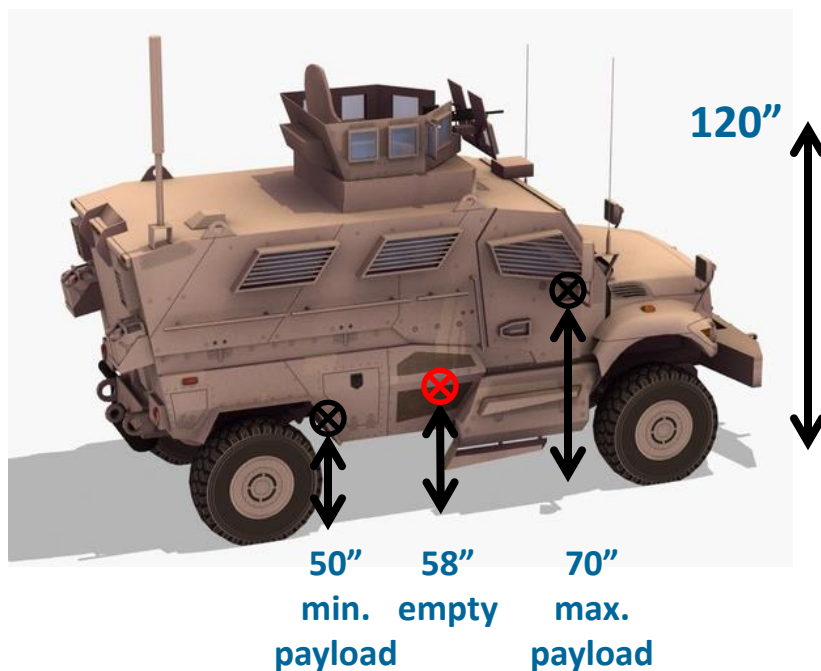
Mount can be moved
between forward and
rear locations and can
be elevated (as
shown) or level with
the tray.

Custom Payload mount with removable crane.

Recap: F-250 v MRAP ¹⁹Weights and CG's

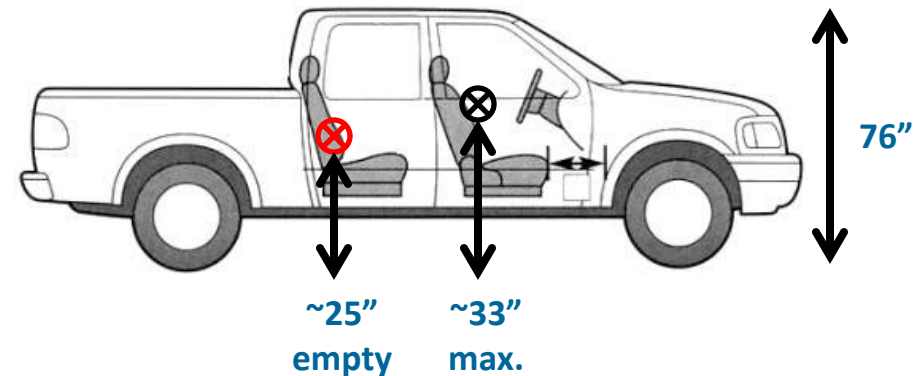
• Cat I MaxxPro Plus MRAP

- 53,000 lbs GVWR -
- 38,900 lbs curb weight
- 14,100 lbs passengers + payload



• Ford 2002 F250 Crew Cab

- 8,800 lbs GVWR -
- 5,870 lbs curb weight
- 2,930 lbs passengers + payload



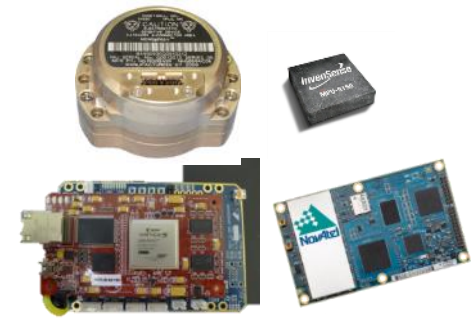
In simulation studies (See July 2013 report) cg locations can be resolved to 0.5". We designed the experiments such that the true change in c.g. is much larger than this in anticipation of greater noise levels in real data.

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- **Statement of Problem Studied**
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Vehicle Sensors²¹

- We previously reported on the sensors selected for the add-on kit. They have been integrated into a single unit to be mounted on the tray of the vehicle alongside the payload.
- Hardware interfacing to the add-on kit sensors and ground truth sensors has been implemented in firmware on an FPGA inside the unit.
- Data will be logged and post-processed **but algorithm is fast enough to run in real time.**



Individual sensor elements

Sensing module (rendered left, fabricated right) contains two IMUs, an FPGA processing unit, a GPS receiver (antenna can be seen on top) and can interface to laser ride-height, wheel encoder and engine diagnostics.

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Ground Truth²³ Sensors

- We previously reported on the selection of ground truth sensors.
 - We prefer our convenient bolt-on wheel encoder assemblies.
- They have been retro-fitted to the vehicle to enable us to monitor vehicle orientation relative to terrain, speed and location.



Laser range finder

Laser range finder plus magnetic vehicle mount. One sensor per wheel allows precise determination of vehicle roll and pitch relative to the terrain.



Wheel encoders give precise speed information. The two rear wheels are instrumented.

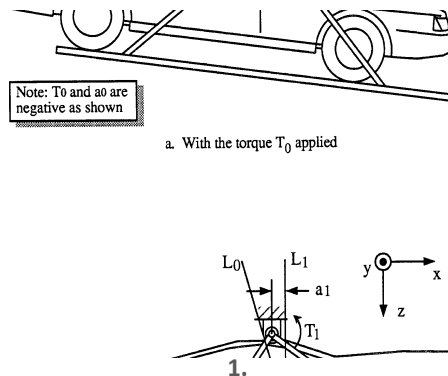
Ground Truth Calibration²⁴

- We need a ground truth reference for vehicle cg and mass in order to understand the accuracy of the proposed system. Mass and lateral/longitudinal cg are easily measured by scales at each wheel. Vertical cg is significantly harder to measure.
- There are two basic alternatives, an instrumented tilt table or an ad-hoc procedure involving scales and a crane or hydraulic lift. We will use the second procedure which has been used at NREC previously on ground robots. It is less accurate than the first procedure but only requires readily available equipment.
- Research commissioned by the Motor Vehicle Manufacturer's Association (1) discusses these procedures in detail and suggests that the accuracy and variability of the proposed procedure is between 0-4 inches which is a significant fraction of the expected change in cg location given maximum payload conditions.



2.

Tilt table systems.



1.

Scales and hydraulic lift.

1. Winkler, C. et. al. Center of Gravity Height: A Round-Robin Measurement Program. U. Mich. Transportation Research Institute Tech. Report UMTRI-91-4. 1991.
2. <http://trailer-bodybuilders.com/truck-bodies/how-tilt-test-fire-apparatus>, accessed Feb. 13, 2014.

Conclusions²⁵ for Q1

- **Main results in this review period are:**
 - Retrofit sensors and computing have been purchased and installed.
 - A safe method for mounting large payloads has been designed and is in fabrication.
 - Software development is complete.
 - Hardware and expertise for calibration vertical cg of a vehicle has been borrowed from within NREC.
 - Testing will be occur in February in Pittsburgh.

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Summary for Q2²⁷

- This quarter achieved the main program result of demonstration of mass adaptation on a real vehicle.

Add-On Kit Design²⁸

An existing INS was repurposed.



Honeywell HG1930 IMU

Acceleration, angular rate
Chassis pitch and roll



OBDLink SX

SAE J1939 Engine Interface (OBD II)
RPM, Throttle, Load, Air flow, Speed



NovAtel OEM6 GPS Receiver

Ground truth Position, velocity
For movies



- **Cost: ~\$20,000**
- **Internal computing**
- **IP67 rated**

Additional Reference Sensing



Baumer OADM lasers (x4)

Chassis to ground distance.

Terrain relative pitch and roll via trigonometry.



Hohner Series XX wheel encoders (x2)

Wheel speed

Vehicle speed

Vehicle acceleration via numerical differentiation

- Used for reference and ground truth

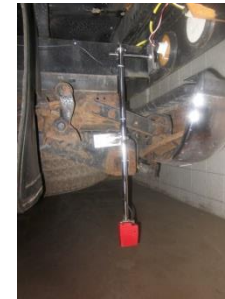
Vehicle Retrofit³⁰



Add-on Kit



Payload mounts



Laser ranger



Wheel encoder



OBDLink SX

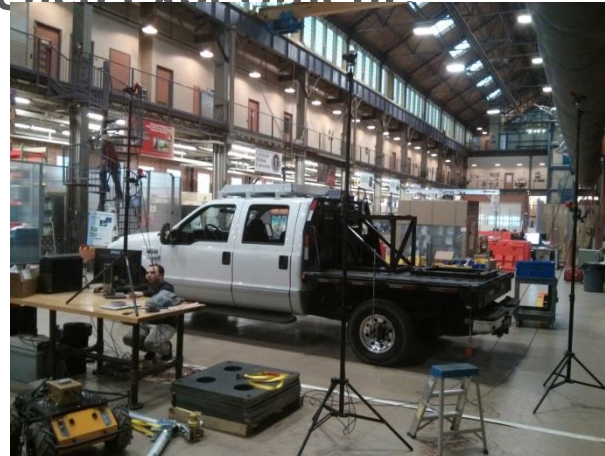
- 2002 Ford F250 Super Duty Pickup
 - Custom modifications
 - **360kg usable payload**

Ground Truth³¹

- Contracted SEA Inc. for baseline cg, mass and inertia calibration.
 - Provider for the NHTSA NCAP program testing.
- Motion capture calibration for payload mount points.
- Analytic modification of baseline numbers based on known payloads and mount points for each experiment



Baseline cg calibration at
SEA Inc.



Motion capture dimensional
calibration at NREC.

Results accurate to 5 mm and 5 kg.

Retrofit - Video³²

DARPA M3

Directional & Attitude Stability Kit

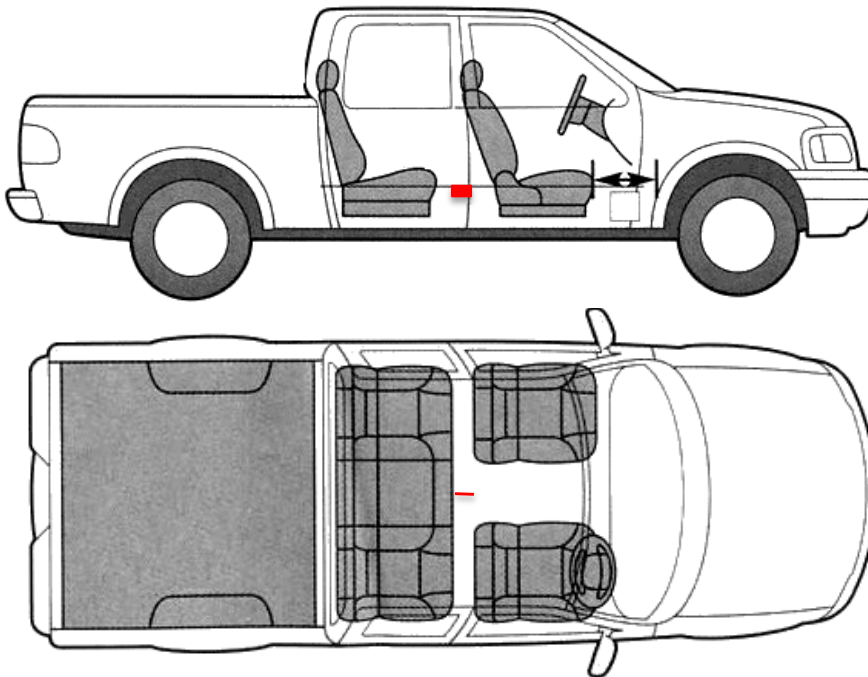
Vehicle Instrumentation and Experimentation

Alonzo Kelly

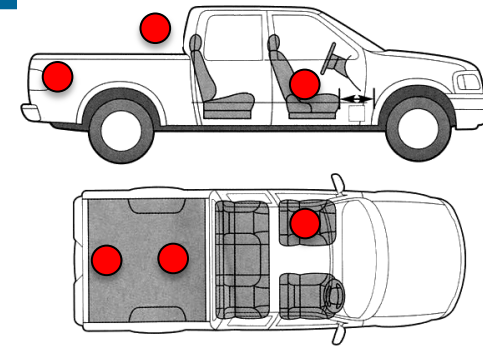


4 tests

- 4 different c.g. locations
- 3 different payloads



Approximate extent of c.g. motion due to payload variations shown in red.



Payload locations

Experiment #	Driver (kg)	Rear Payload (kg)	Forward Payload (kg)
1	100.0	0	0
2	100.0	0	222.6
3	100.0	222.6	0
4	100.0	110.8	0

Experiments³⁴



Parameter	Value
Max. Speed	22.4 mph
Max. Forward Acceleration	0.30 g
Max. lateral acceleration	0.48 g
Max. Pitch Angle	0.43 deg
Max. Roll Angle	3.28 deg

- **Leave one-out validation (more realistic than alternatives).**
 - Use 3 experiments to calibrate stiffness etc. models.
We presented methods previously to avoid this if you have OEM data about the vehicle suspension and performance.
 - Test using 4th.
- **Results presented here use batch solver**
 - We presented methods previously to perform equivalent calculations using Kalman filtering.
 - Both methods can be used online.

Experiment - Video³⁵

DARPA M3

Directional & Attitude Stability Kit

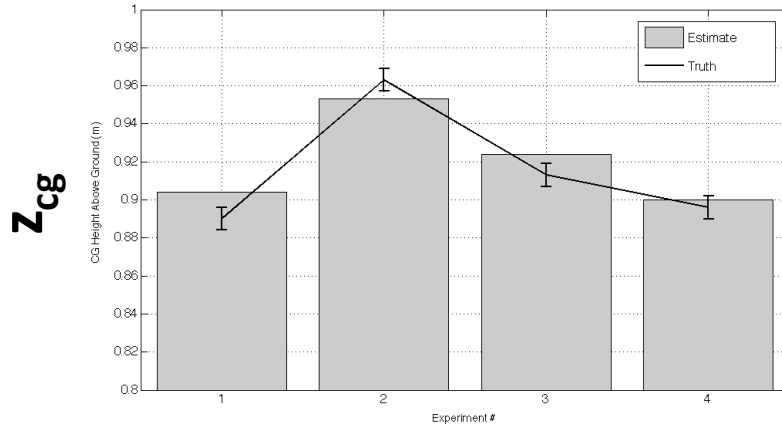
Vehicle Instrumentation and Experimentation

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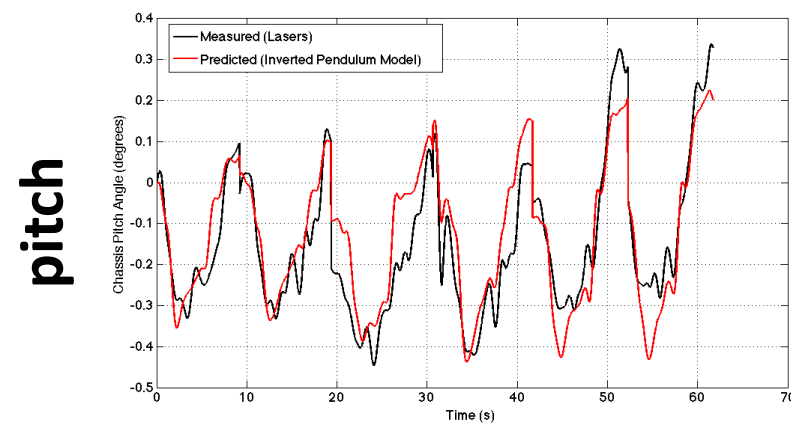
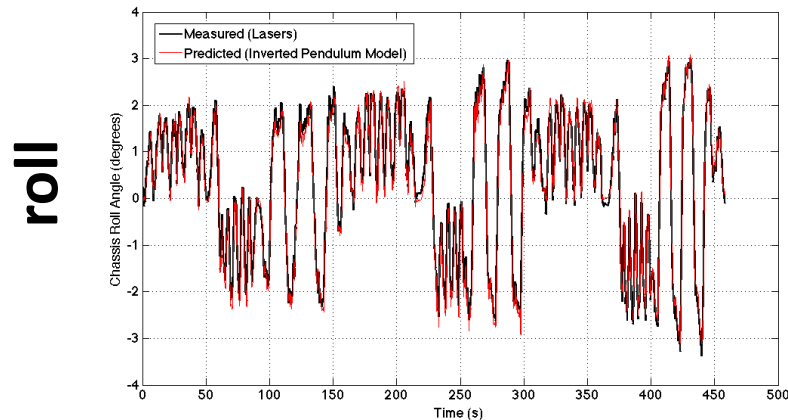


Results – Center of Gravity³⁶

Lateral and longitudinal cg estimation was not possible given the experimental limitations (Achievable payload and accelerations).

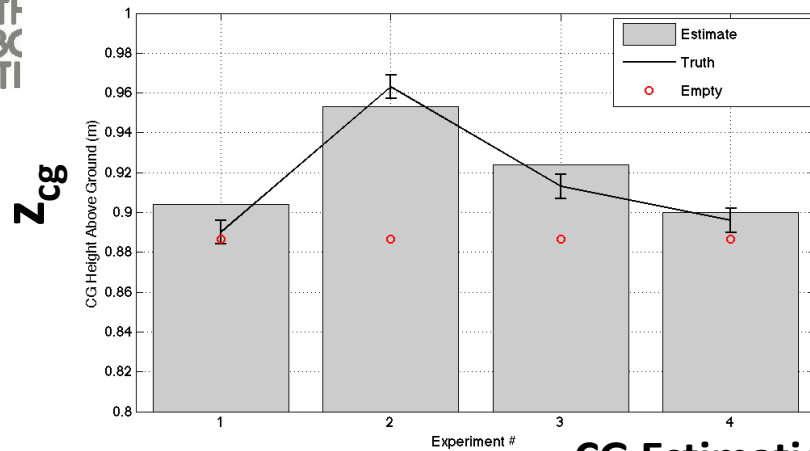


Experiment #	CG Error (cm)	CG Error (%)
1	1.4	1.57
2	-1.0	1.04
3	1.1	1.20
4	0.4	0.45



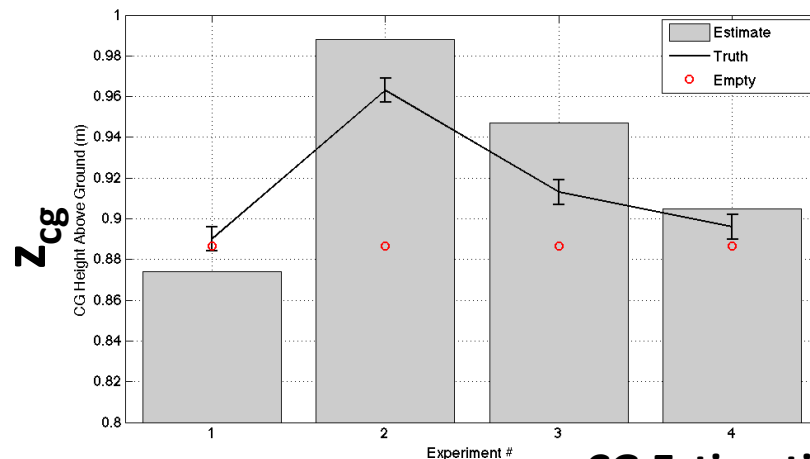
**Vertical cg accurate to 1 cm. 50 cm variance is possible on MRAP.
Horizontal too small to see (or matter)**

Results – Center of Gravity³⁷



CG Estimation From Lasers

Experiment #	CG Error (m)	CG Error (%)
1	1.4	1.57
2	-1.0	1.04
3	1.1	1.20
4	0.4	0.45



CG Estimation From IMU

Experiment #	CG Error (m)	CG Error (%)
1	-1.6	1.80
2	2.5	2.60
3	3.4	3.72
4	0.9	1.00

IMU+roll dynamics can be used to estimate cg very accurately.

Results - Mass³⁸

Mass estimates **rely on fuel flow measurements** from the engine.

- Rolling resistance, aerodynamic drag, rotational inertial and engine efficiency are accounted for.
- Does not account for powertrain delays.

Experiment #	Mass Error (kg)	Mass Error (%)
1	343	9.2
2	175	4.4
3	-325	8.3
4	-69	1.8

Mass can resolved to the weight of 2 persons+gear using a particle model.

MRAP mass may vary by 14,000 lbs (relative to 40,000 curb weight) – 36%.

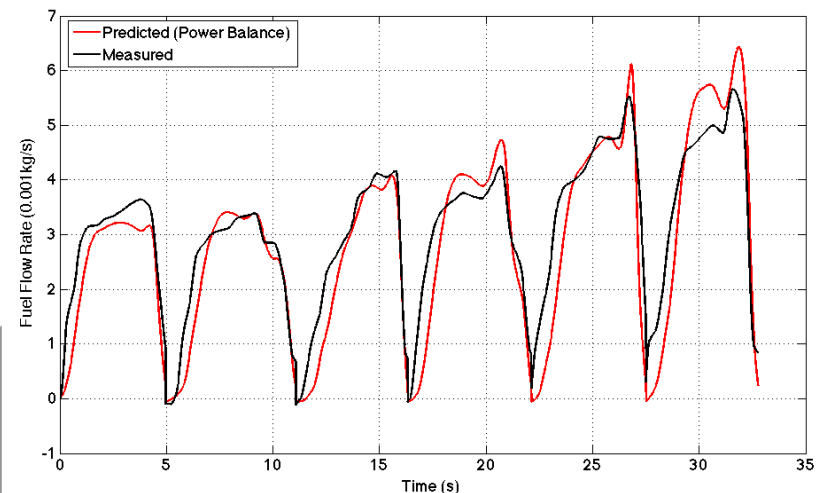


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Lessons Learned⁴⁰

- **Safely testing vehicle dynamics is hard.**
- **Commercial vehicles are designed to have very limited variability in the cg**
- **Engine data is crucial but the quality and availability varies widely between models and manufacturers.**

Conclusions⁴¹

- Adaptive online calibration of rollover stability control **works**.
 - On a commercial passenger vehicle ...
 - Using an **IMU + structural dynamics to measure mass*cg**
 - Using **longitudinal dynamics + throttle to measure mass**.
- This may improve performance and enhance safety in military applications.
 - Real impact will depend on human factors design issues.
- The exact accuracy and feasibility of add-on kits depends heavily on vehicle and application.
 - SAE J1939 engine interfaces or MILSPEC equivalent are needed.
 - Suspension instrumentation helps a lot (especially off-road).

Outlook / Next Steps⁴²

- **Some (more) gates to Deployment**
 - Drive mass error down.
 - Test on a real MRAP.
 - Test off-road.
 - Test with terrain perception?
 - Implement at least a governor.
 - Human factors testing.
- **Cost reduction**
 - 4 lasers = \$6K
 - IMU = \$10K

- **As of May 1, 2014**
 - \$400K awarded
 - \$400K spent

Acknowledgements⁴⁴

- The following people have contributed in significant ways to the project.
 - Jason Ziglar, Robotics Engineer
 - Forrest Rogers-Marcovitz, Robotics Engineer
 - Neal Seegmiller, Robotics PhD Student
 - Nicholas Chan, Robotics Engineer
 - Michel Laverne, Robotics Engineer
 - Dane Bennington, Robotics Engineer
 - Michael George, Robotics Engineer
 - Greg Miller, Robotics Engineer
 - Herman Herman, NREC Faculty
 - Dimitrious Apostopoulous, RI Systems Scientist