ARL-SR-0387 ● DEC 2017

US Army Research Laboratory

2017 ARL Summer Student Program, Volume I: Symposium Presentations

Compiled by Rose Pesce-Rodriguez

NOTICES

Disclaimers

ARL-SR-0387 ● DEC 2017

US Army Research Laboratory

2017 ARL Summer Student Program, Volume I: Symposium Presentations

Compiled by Rose Pesce-Rodriguez

REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**						
1. REPORT DATE *(DD-MM-YYYY)* December 2017	**2. REPORT TYPE** Special Report					**3. DATES COVERED (From - To)** April–August 2017
4. TITLE AND SUBTITLE 2017 ARL Summer Student Program, Volume I: Symposium Presentations						**5a. CONTRACT NUMBER**
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. COMPILER(S) Rose Pesce-Rodriguez						**5d. PROJECT NUMBER**
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1138						**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-SR-0387
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)						**10. SPONSOR/MONITOR'S ACRONYM(S)**
						11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The US Army Research Laboratory (ARL) Summer Student Symposium is an ARL Director's Award Program for all the students participating in various summer scholarship and contract activities across ARL. The goal of the program is to recognize and publicize exceptional achievements made by students and their mentors in support of Army science. All undergraduate and graduate interns are encouraged to submit an abstract summarizing their accomplishments and to participate in the symposium. Presentations given by all directorate finalists are published in Volume I of the proceedings ("Symposium Presentations"; ARL-SR-0387), while abstracts are collected in Volume II ("Compendium of Abstracts"; ARL-SR-0388).						
15. SUBJECT TERMS ARL Summer Student Research, SEAP						
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**		**19a. NAME OF RESPONSIBLE PERSON** Rose Pesce-Rodriguez
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	170		**19b. TELEPHONE NUMBER (Include area code)** (410) 306-1877

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

INTENTIONALLY LEFT BLANK.

Director's Foreword

The US Army Research Laboratory (ARL) mission is to "provide innovative science, technology, and analyses to enable full spectrum operations." As the Army's corporate laboratory, we provide the technological underpinnings critical to providing capabilities required by our current and future Soldiers.

Our nation is projected to experience a shortage of scientists and engineers. ARL recognizes the criticality of intellectual capital in generating capabilities for the Army. As the Army's corporate laboratory, addressing the projected shortfall is a key responsibility for us. We have, therefore, identified the nation's next generation of scientists and engineers as a key community of interest and have generated a robust educational outreach program to strengthen and support them. We have achieved many successes with this community. We believe that the breadth and depth of our outreach programs will have a significant positive effect on the participants, facilitating their journey toward becoming this Nation's next generation of scientists and engineers.

A fundamental component of our outreach program is to provide students with summer research experiences. During the summer of 2017, ARL hosted more than 170 undergraduate and graduate students. Many of these students chose to participate in directorate-level competitions with the goal of being selected as a directorate finalist and competing at the ARL-wide Summer Student Symposium; others participated in the symposium by presenting posters. I applaud symposium participants and all summer interns who contributed to the ARL mission.

We are very pleased to have hosted this outstanding group of students for the summer. It is our hope that they will continue their pursuit of technical degrees and will someday assist us in providing critical technologies for our Soldiers.

Philip Perconti
Director

INTENTIONALLY LEFT BLANK.

Introduction

The ARL Summer Student Research Symposium is an ARL Director's Award Program for students participating in various summer internship opportunities across ARL. The goal of the program is to recognize and publicize exceptional achievements made by the students and their mentors in the support of Army science.

All undergraduate and graduate interns are eligible to compete for a finalist position and give an oral presentation at the symposium. All students, including high schoolers in the Science and Engineering Apprentice Program (SEAP), are encouraged to present posters at the symposium and submit abstracts summarizing their accomplishments.

Oral presentations at the symposium are given by finalists selected based on directorate-level competitions. Each directorate can send one graduate student and one undergraduate finalist to the symposium. The Sensors and Electron Devices Directorate and Weapons and Materials Research Directorate have relatively large numbers of interns and can each send 2 undergrad finalists.

This year's symposium was held at the Mallette Center at Aberdeen Proving Ground, Maryland, on Thursday, 10 August 2017. Oral presentations were judged by a panel of senior ARL scientists (including ARL Fellows and Chief Scientists). Students with the top 3 presentations ("Corporate Medalists") were awarded the ARL Summer Student Research Gold ($500), Silver ($300), and Bronze ($200) awards in the undergraduate and graduate student levels.

This volume of the Summer Student Symposium Proceedings contains presentations given by all directorate finalists at the symposium. Volume II (ARL-SR-0388) is a compendium of student abstracts.

INTENTIONALLY LEFT BLANK.

2017 ARL Summer Student Symposium Agenda

10 August 2017
Mallette Training Center Auditorium (B6008)
Aberdeen Proving Ground, MD

0700	Bus departs ALC	
0820	Bus arrives from ALC	
0830-0840	Welcome	Dr. Rose Pesce-Rodriguez
0840-1130	**Undergraduate Presentations (Auditorium)**	
	Robust Adaptive Control of Unmanned Aerial Systems (UAS)	Blake Anderson (VTD)
	Dynamic Occlusion Culling in VR	Ben Kolarik (SLAD)
	Fabrication & Characterization of Silicon Nanoparticles for Energetic Applications	Sarah Adams (SEDD)
	Ultra-Low-Power Sensing & Processing	Peter Deaville (SEDD)
	A Comparison Study of Carbon Polymer Electrodes for Electroencephalography (EEG) Recording	Christina Nguyen (HRED)
	Collision Avoidance Robot Using Neuromorphic Hardware	Clarence Wong (CISD)
	High-Strain Rate Hardness of Tungsten Carbides	Luke Hanner (WMRD)
	Effect of B:B2O3 on Reactive Hot-Pressing of Boron Suboxide"	Howard Payne (WMRD)
1130-1215	Lunch + poster session (Room 10B) Deliberations (Undergrad category) by Review Panel	All
1215-1420	**Graduate Presentations (Auditorium)**	
	A physical Manifestation of Dynamic Scaling Laws	Daniel Blackman (VTD)
	Limits of Subpixel Motion Detection with a Video Camera	Minas Benyamin (SEDD)
	The Effect of Imperceptible Noise Stimulation on the Spinal Reflex	Maxwell Alander (HRED)
	Solving Vertex Cover Via Using Spin Model On Neuromorphic Processor	Kevin Corder (CISD)
	Modeling RDX Decomposition Products with Mesoscale Particles	James (Matt) Mansell (WMRD)
	Visualization of Human Vulnerability in VR	Tiffany Raber SLAD
1420-1455	Refreshments + poster session (Room 10B) Deliberations (Graduate category) by Review Panel	All
1450-1515	Awards Ceremony	
1530	Bus departs for ALC	
1645	Bus arrives at ALC	

INTENTIONALLY LEFT BLANK.

Undergraduate category winners

Gold Medalist:
Sarah Adams, Sensors and Electron Devices Directorate
Fabrication & Characterization of Silicon Nanoparticles for Energetic Applications

Silver Medalist:
Peter Deaville, Sensors and Electron Devices Directorate,
Ultra-Low-Power Sensing & Processing

Bronze Medalist:
Luke Hanner, Weapons & Materials Research Directorate,
High-Strain Rate Hardness of Tungsten Carbides

Graduate category winners

Gold Medalist:
James (Matt) Mansell, Weapons & Materials Research Directorate
Modeling RDX Decomposition Products with Mesoscale Particles

Silver Medalist:
Minas Benyamin, Sensors and Electron Devices Directorate
Limits of Subpixel Motion Detection with a Video Camera

Bronze Medalist:
Maxwell Alander, Human Research & Engineering Directorate
The Effect of Imperceptible Noise Stimulation on the Spinal Reflex

Special awards were presented to 2 of the top student presentations from ARL West.

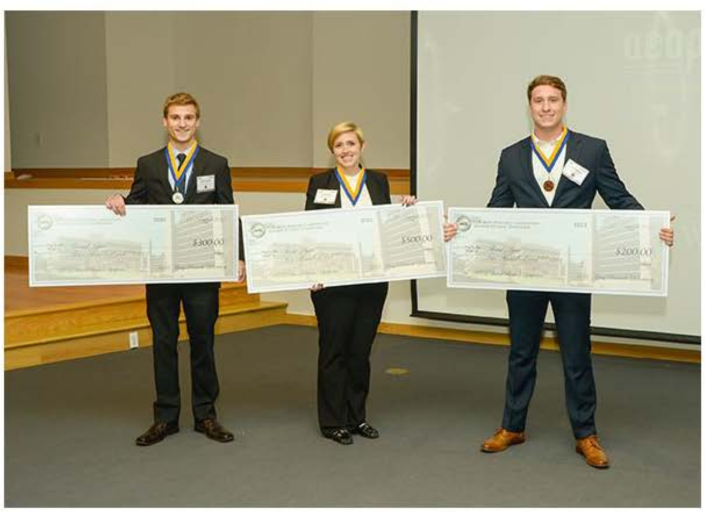
ARL West top honors for 2017 presentations:

Undergraduate category: Elnaz Ahmadi, University of California, Santa Barbara

Graduate category: Tiffany Raber, University of Illinois at Chicago

Undergraduate and graduate Directorate Finalists who participated in the U.S. Army Research Laboratory's 2017 Summer Student Symposium held August 10 at Aberdeen Proving Ground, Maryland. (U.S. Army photo by Conrad Johnson, RDECOM).

https://arlinside.arl.army.mil/inside/news/articles/view.cfm?id=2051



The undergraduate Gold Medalist, Sarah Adams; Silver Medalist, Peter Deaville and Bronze Medalist, Luke Hanner display their winnings from the U.S. Army Research Laboratory's 2017 Summer Student Symposium held August 10 at Aberdeen Proving Ground, Maryland. (U.S. Army photo by Conrad Johnson)

https://arlinside.arl.army.mil/inside/news/articles/view.cfm?id=2051

The graduate Gold Medalist, James (Matt) Mansell; Silver Medalist, Minas Benyamin and Bronze Medalist, Maxwell Alander display their winnings from the U.S. Army Research Laboratory's 2017 Summer Student Symposium held August 10 at Aberdeen Proving Ground, Maryland. (U.S. Army photo by Conrad Johnson, U.S. RDECOM)

https://arlinside.arl.army.mil/inside/news/articles/view.cfm?id=2051

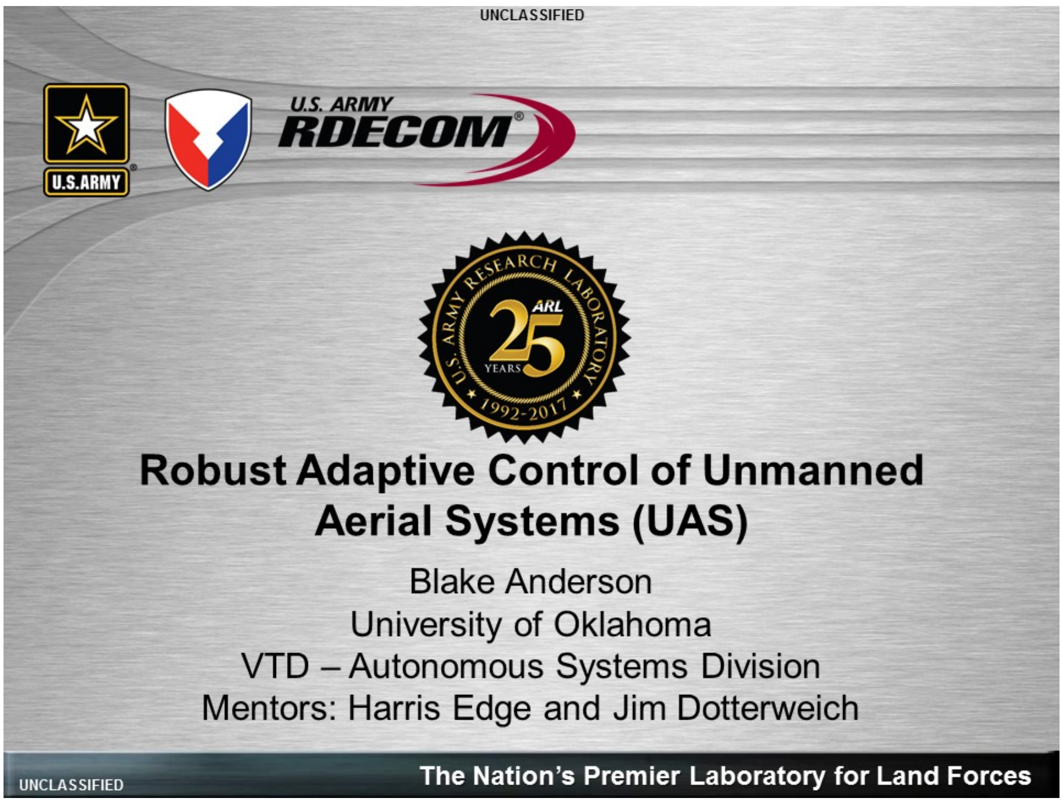
INTENTIONALLY LEFT BLANK.

Undergraduate Presentations

INTENTIONALLY LEFT BLANK

Blake Anderson

I am currently a senior attending the University of Oklahoma (OU). My major is engineering physics with a design sequence focusing on aerospace engineering; more specifically, I am focusing on the controls side of aerospace. I began doing research at the Advanced Control Systems Lab (ASCL) at OU in May of 2016. At ASCL, we have been focusing on creating easy-to-use interfaces for control testing and accurate virtual simulators, as well as designing autopilots with nonlinear controls for multirotor vehicles. My current advisor, Dr Andrea L'Afflitto, runs ASCL, and after graduating this December, I plan on pursuing my master's degree in aerospace engineering under his guidance.



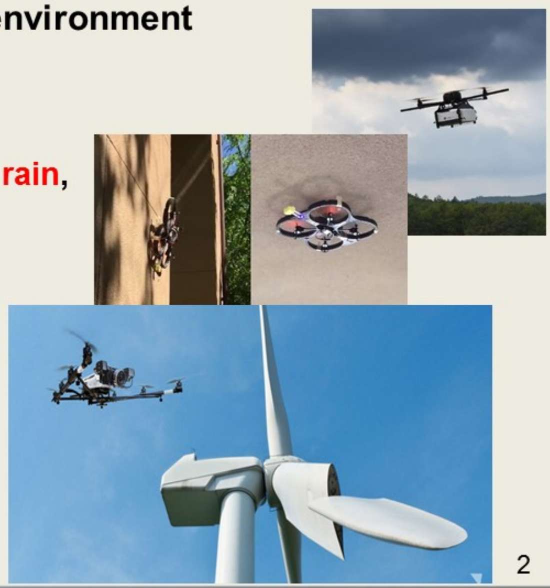
UNCLASSIFIED

U.S. ARMY RDECOM

Problem Statement

ARL

Controls research focusing on allowing drones to do work in an unstructured environment



- Environmental Interaction
  - Perching
  - External factors (wind, rain, etc.)
  - Payload Manipulation (swinging payloads)
- New problems
  - Changing mass
  - Dynamic payloads
  - Surface interaction

2

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

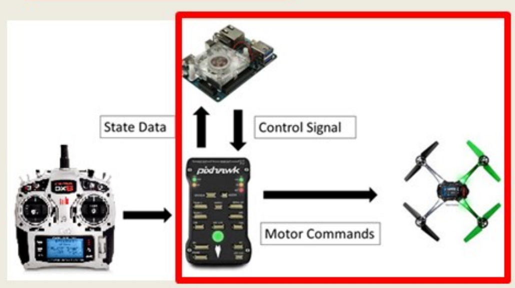
Technical Approach

ARL

- Design and implement a robust adaptive controller for a quadrotor vehicle
- Created a new methodology:
  - Created reliable virtual simulator for testing & performance prediction
  - Odroid single board computer connected to a Pixhawk autopilot running the open source PX4 flight stack.

MK-82 JDAM

- Gen I: flown 1999, 2003
- Gen II: 2002 – 2006
  - ✓ flight test 4th Q 2005
- Gen III: 2006



3

UNCLASSIFIED

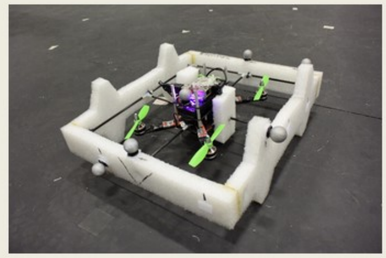
The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

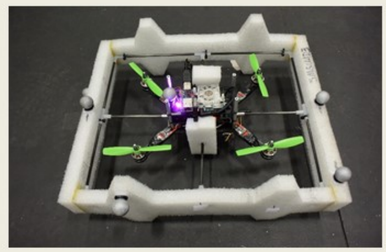
Impact

ARL

- **Advanced control techniques** that guarantee **robustness** to strong external **disturbances**, **failures** of the propulsion system, & high **safety margins**.



- **Rapid development** of new **control algorithms** by streamlining the transition between control design, simulation, & experiments.



4

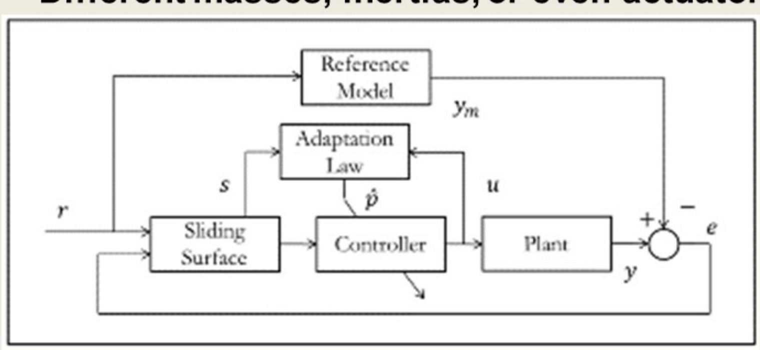
U.S. ARMY RDECOM

Control Approach

ARL

Adaptive Sliding Mode

- Gains are now **functions of time**
  - Classic PID gains are fixed
- Corrects for **uncertainties** the system
  - Different masses, inertias, or even actuator faults

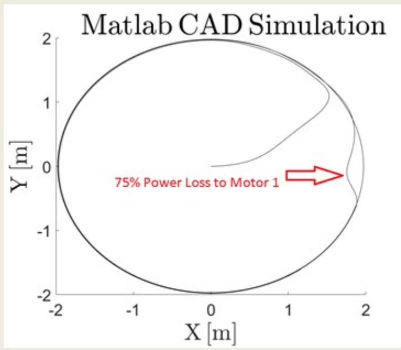


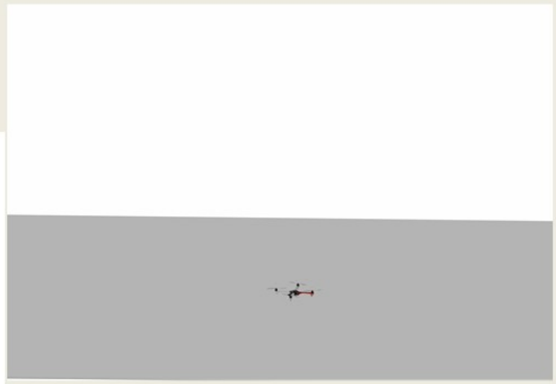
5

Results I

MATLAB CAD Simulation

- Trajectory can still be followed after **a loss of 75%** in the thrust of one of the motors.



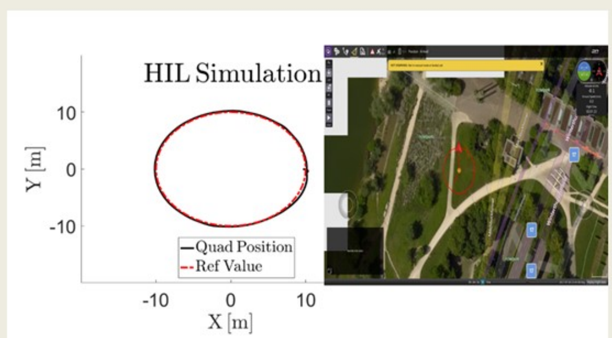


6

Results II

Hardware in the Loop Simulation

- HIL simulation executes the exact **same code structure** that runs in real flight.
- **Reduced risks** & better use flight test time
- Uses QGroundControl



Chosen simulator: jMAVSim

7

Approved for public release; distribution is unlimited.

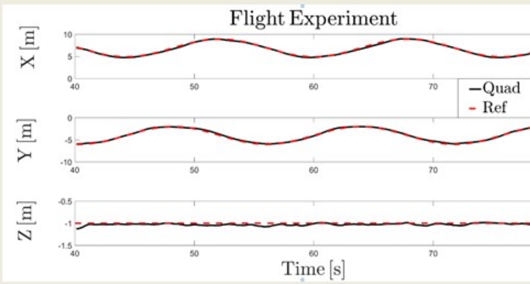
UNCLASSIFIED

U.S. ARMY RDECOM

Results III

ARL

Waypoint and Trajectory Following



Flight test results showing the quad following circle of 2 m radius at constant altitude

Avg error in x-y < 9 cm **Avg error in z < 3 cm**

8

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

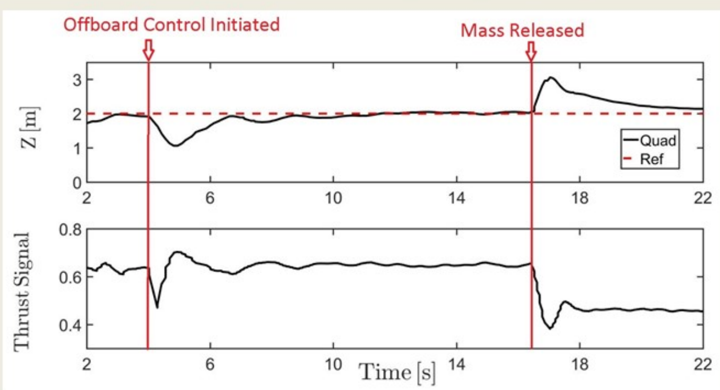
UNCLASSIFIED

U.S. ARMY RDECOM

Results IV

ARL

Changing Payload



Mass of the vehicle is changed approximately 40%

- **Correction occurs in under 3 s**
- **Controller tuned for and assumes mass of .91 kg, actual mass = 1.4 kg**

9

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Results V

PID | **Adaptive Sliding Mode**

Much slower response to disturbance

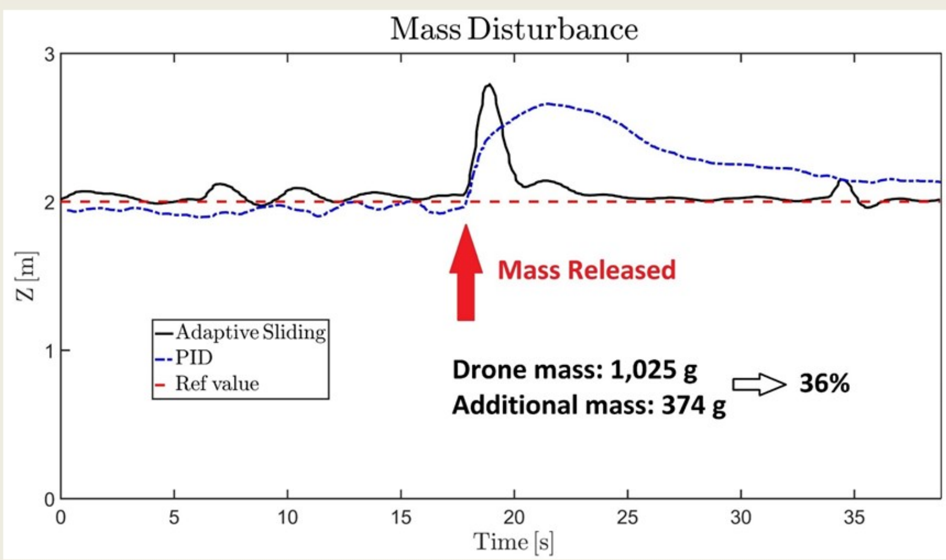
Returns to desired height in under 3 s

10

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Results VI



11

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

Discussion

- ✓ Successful **virtual, hardware-in-the-loop, and indoor tests** for proposed control algorithm.
- ✓ Shown **higher performance** with respect to classical PID-based autopilots.
- ✓ Successfully demonstrated **disturbance rejection** with changing mass.

Near Future Work

- More **indoor and outdoor tests**.
- Matching simulation and test results.
- Carrying **dynamic payload**.

12

UNCLASSIFIED

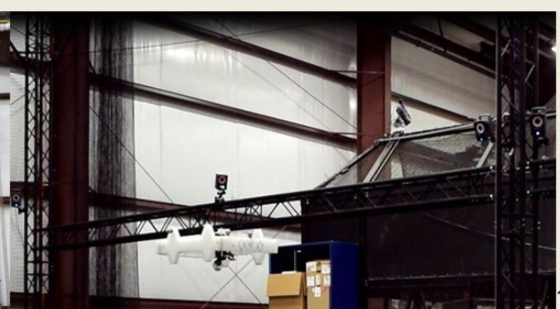
Future Work

ARL Collaboration with University of Oklahoma

- **Open Campus** -- Discussions with ASD
- Signed a **CRADA** -- Joined **ARL South**
- Taking the **same vehicle** to test in a similar **Vicon system**

OU

ARL



13

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Acknowledgements

ARL

Special thanks to:

- Mentors Harris Edge and Jim Dotterweich
- VTD and the Autonomous Systems Division
- Advisor Dr. Andrea L'Afflitto

Advanced Control Systems Lab

ARL

UNCLASSIFIED

U.S. ARMY RDECOM ARL

Questions?

References

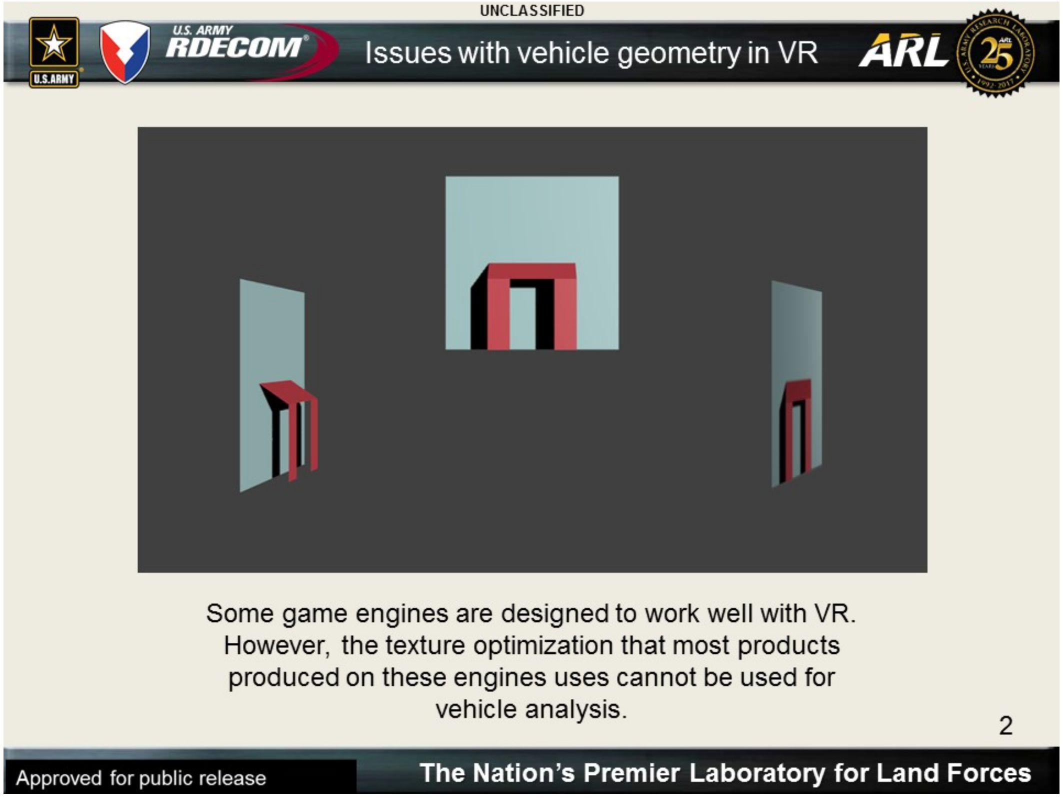
1. **Wang, Lifeng, Chongkui He, and Pei Zhu. "Adaptive sliding mode control for quadrotor aerial robot with I type configuration." International Journal of Automation and Control Engineering (2014).**

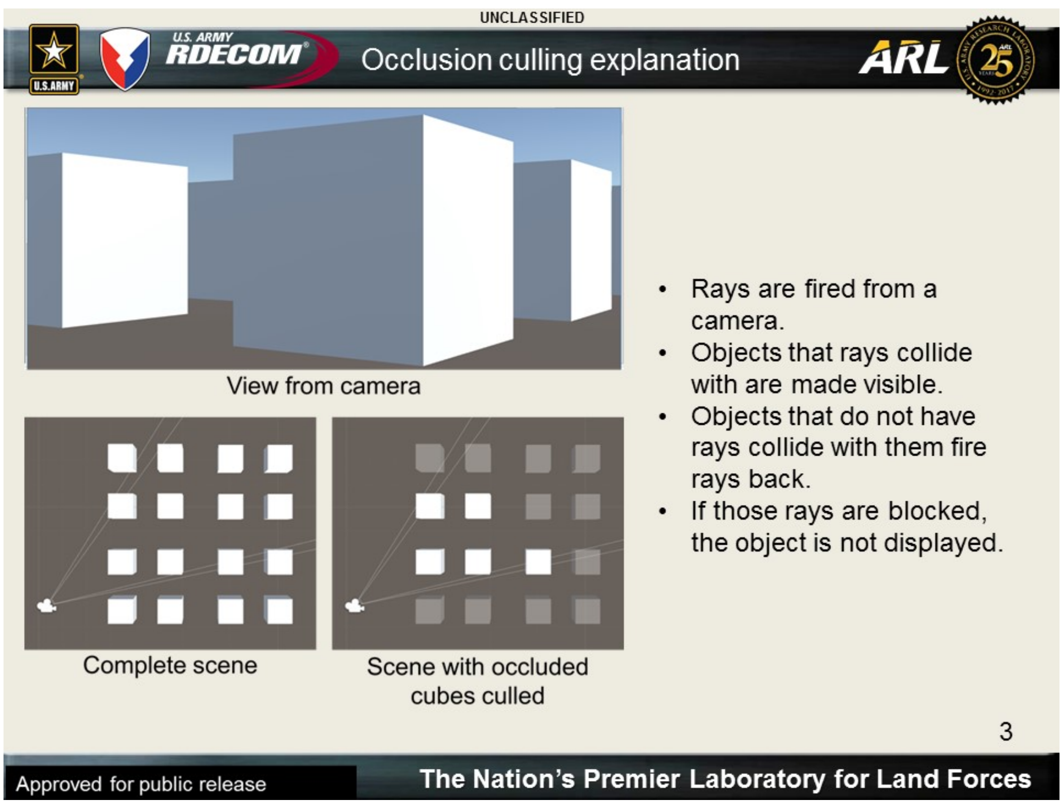
2. **Gregory, Irene. "Fundamentals of Adaptive Control: Flight Control Perspective," NESC GNC Webcast, 28 November 2012.**

Benjamin Kolarik

I am a senior undergraduate student in computer science at the University of Maryland, Baltimore County in Catonsville, MD. This is my first summer in the ARL internship program. After graduating I hope to work in the field of computer graphics, either with ARL or in the private sector.

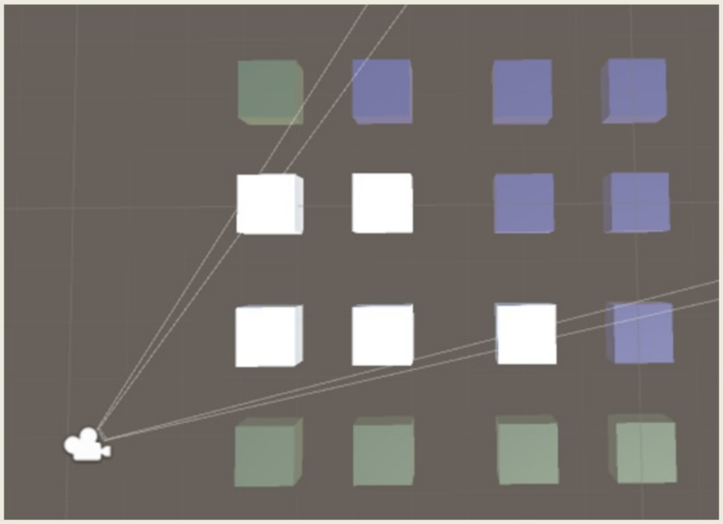
I would like to thank my mentors for their assistance in this work, as it would not have been possible without them. This summer has improved my knowledge in the field of computer graphics as well as given me workplace experience.


UNCLASSIFIED
U.S. ARMY
RDECOM
Issues with vehicle geometry in VR
ARL
Some game engines are designed to work well with VR.
However, the texture optimization that most products
produced on these engines uses cannot be used for
vehicle analysis.
2
Approved for public release
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Occlusion culling explanation
ARL
View from camera
Complete scene
Scene with occluded
cubes culled
• Rays are fired from a camera.
• Objects that rays collide with are made visible.
• Objects that do not have rays collide with them fire rays back.
• If those rays are blocked, the object is not displayed.
3
Approved for public release
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Occlusion culling explanation cont.



Blue cubes aren't rendered because they are blocked, or occluded by other cubes.

Green cubes aren't rendered because they are outside of the viewing frustum.

White cubes are rendered.

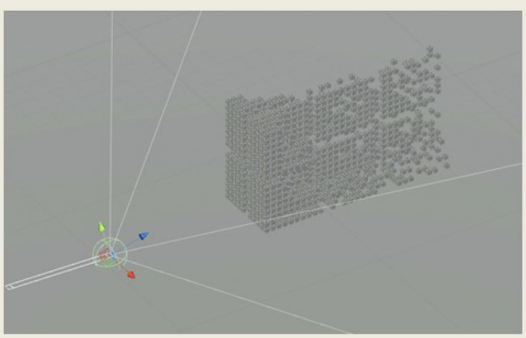
4

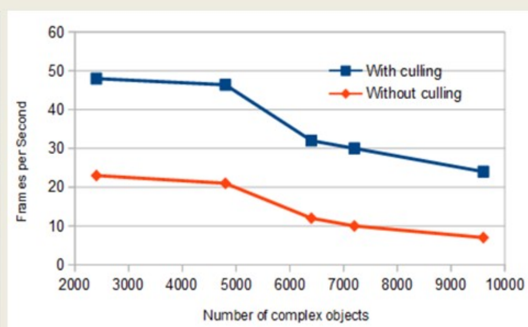
Approved for public release

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Occlusion culling doubles performance





This test case we developed simulates complex geometry using over 4000 Menger sponges, which is an appropriate approximation of the geometry ARL uses.

When occlusion culling is used, performance increases due to the decreased number of objects that need to be shown.

5

Approved for public release

The Nation's Premier Laboratory for Land Forces

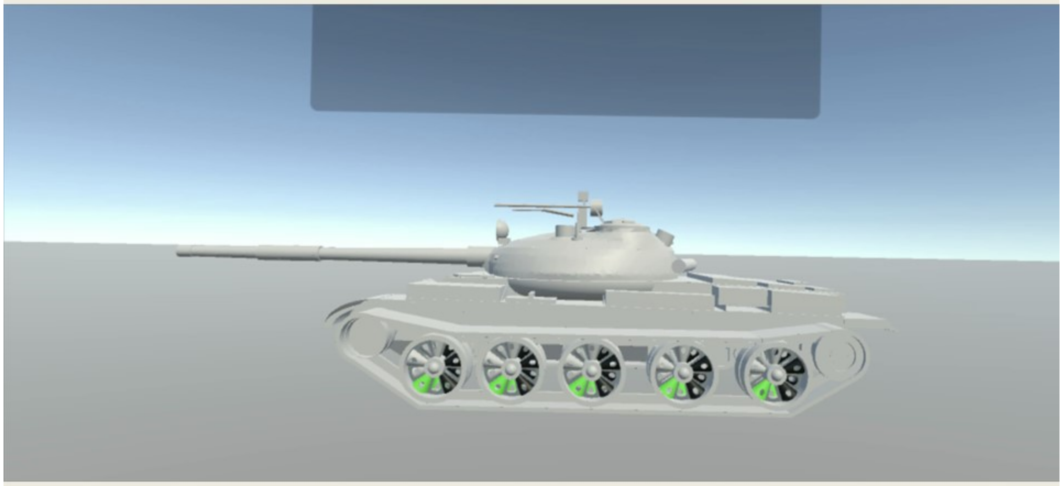
Approved for public release; distribution is unlimited.

UNCLASSIFIED

U.S. ARMY RDECOM®

Menu for visibility

ARL



Analysts often need to see parts of geometry that are inside the vehicle.
This menu allows them to view that geometry.

6

Approved for public release

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM®

Future additions

ARL

- Introduction of a cutting plane, to improve ease of analysis
- Refinement of menu system, needs more ways to select visible objects
- Informing user of the name of the viewed part, so that analysts understand what items they are looking at

7

Approved for public release

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Questions

???

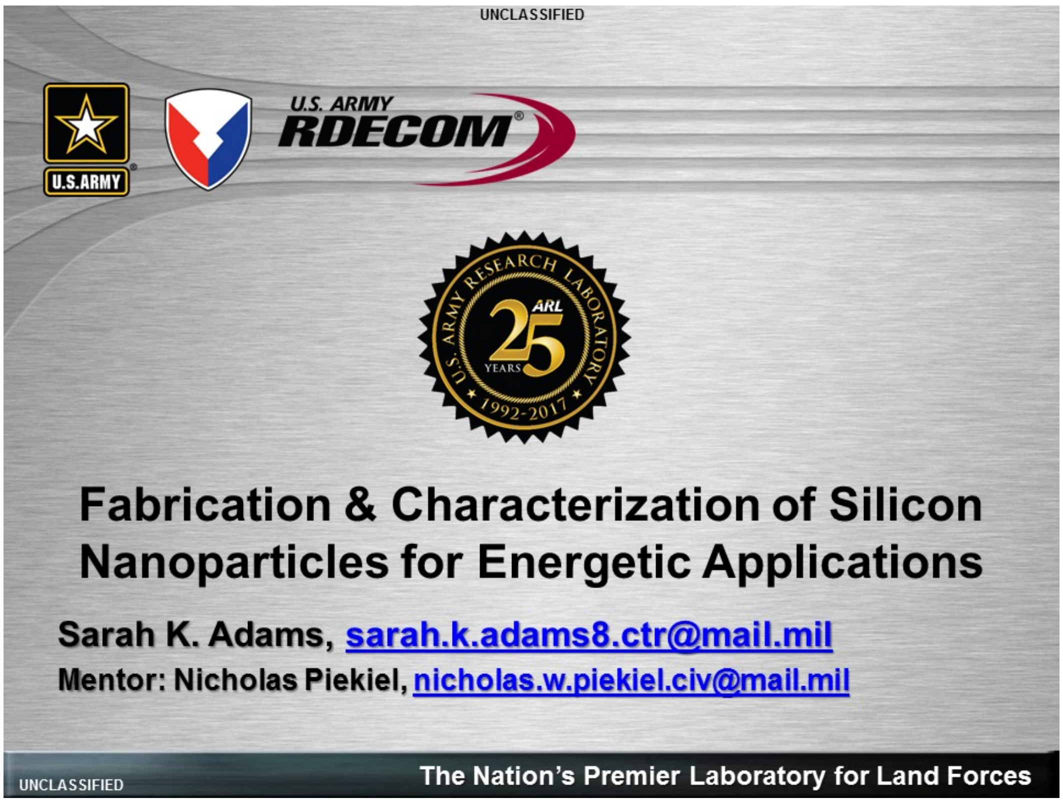
8

Approved for public release

The Nation's Premier Laboratory for Land Forces

Sarah Adams

Sarah Adams is a senior majoring in materials science and engineering at the University of Maryland. This summer her research covered the fabrication and combustion of silicon nanoparticles made from porous silicon films. Sarah previously worked in the Center for Nanophysics & Advanced Materials at the University of Maryland, studying the effects of lanthanide superconductor doping and the application of the Kondo insulator SmB_6 as a driver for self-oscillating circuits. She will graduate in December of this year, at which point she plans to enter the workforce prior to returning to school to complete a master's degree.



U.S. ARMY RDECOM

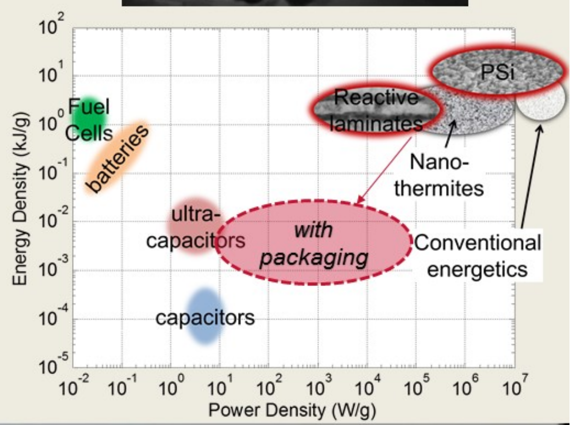
Background

ARL

On-chip Energetics
Advanced electronics/MEMS capabilities

Army Applications:
- Microthrusters
- Thermal battery actuation (FY17-19 ManTech)
- Fuzing

Desired Properties:
- ✓ High energy density
- ✓ High power density
- ✓ Inexpensive

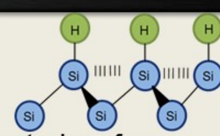


UNCLASSIFIED

U.S. ARMY RDECOM

Porous Silicon

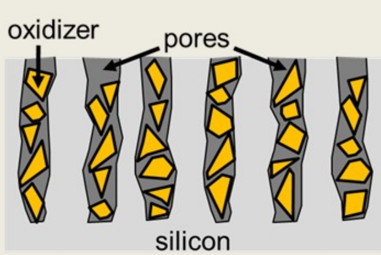
ARL



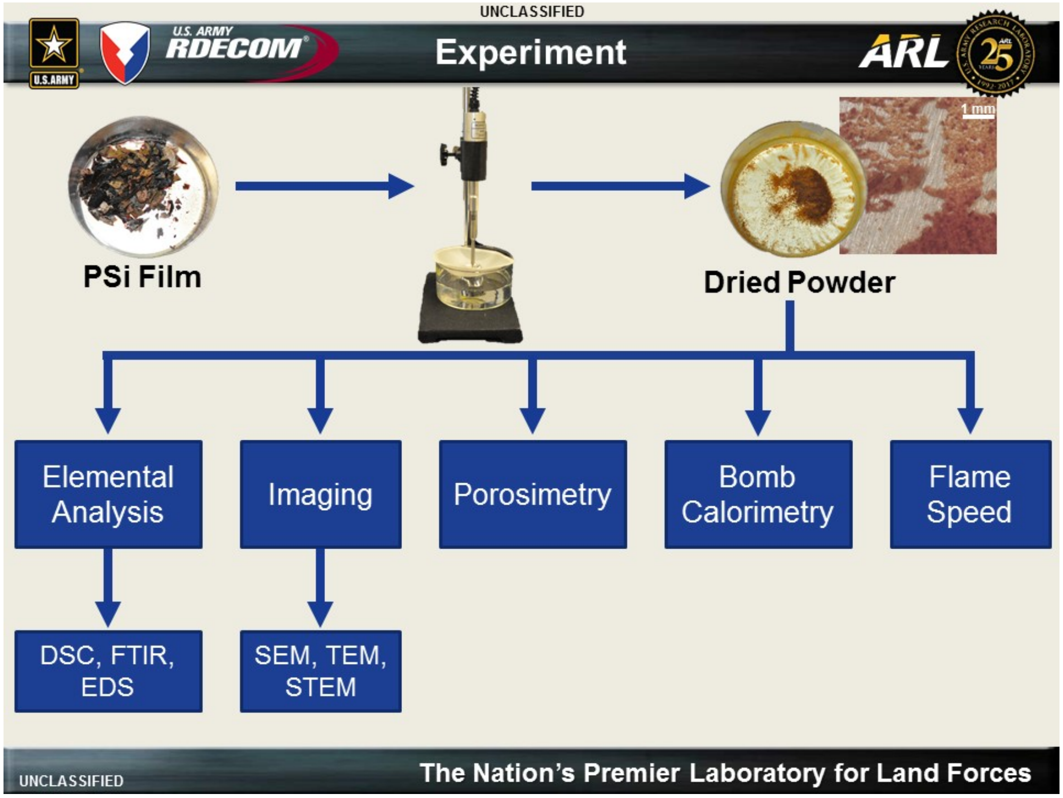
- PSi films well-studied for energetic properties
  - Tunable flame speeds: 1 m/s to 3000 m/s
  - High surface area (>800 m^2/g), hydrogen-terminated surface
- Reacts well with $NaClO_4$

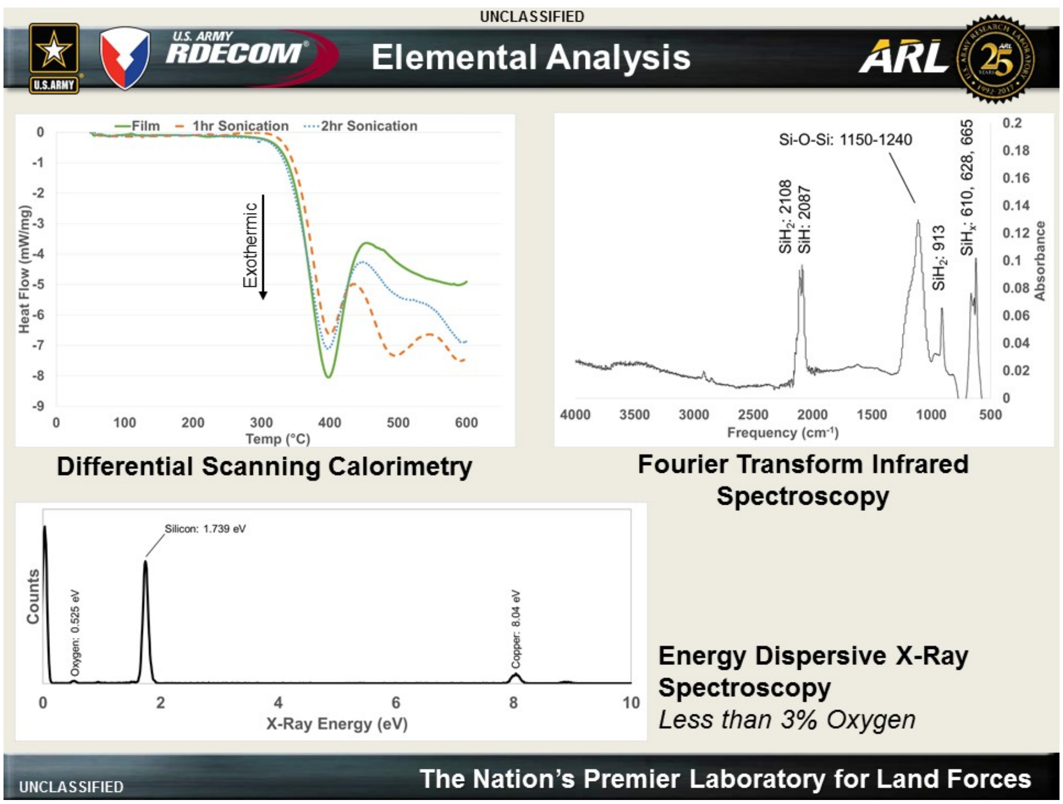
$$(1-n)\mathrm{Si} + n\mathrm{SiH_2} + \frac{2+n}{4}\mathrm{NaClO_4} \rightarrow \mathrm{SiO_2} + \mathrm{NaCl} + n\mathrm{H_2O}$$

- Formed by electrochemical etch in HF → **Limited applications**



Goals
- Reduce requirements for PSi applications
- Create avenues for new applications:
  - Additive manufacturing
  - Fuel additives
  - Apply to chips without HF etch
  - Applicable to any substrate



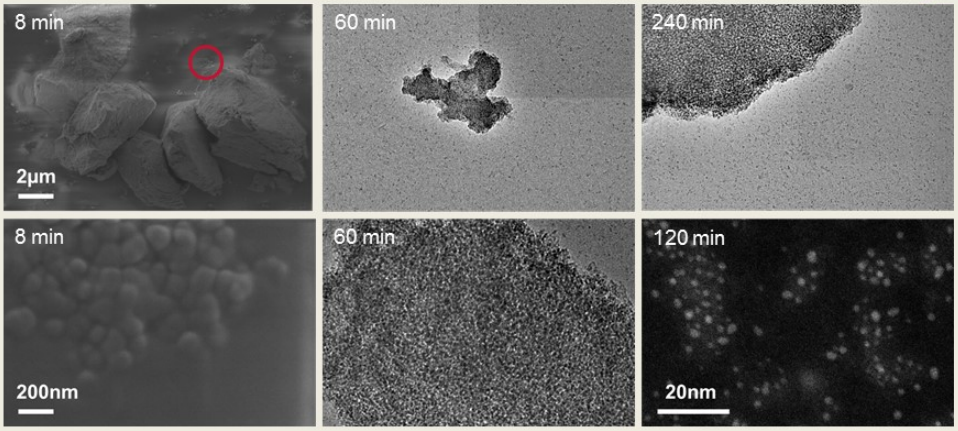


Approved for public release; distribution is unlimited.

U.S. ARMY RDECOM

Imaging

ARL



SEM
Small clusters of particles seen

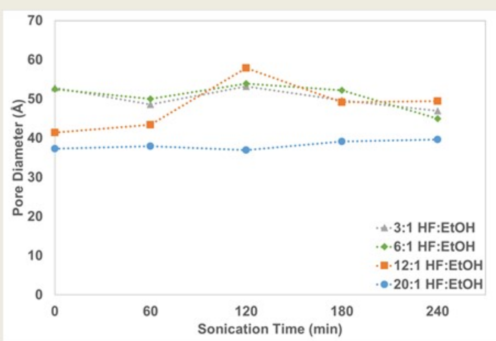
TEM/STEM
~5 nm diameter particles

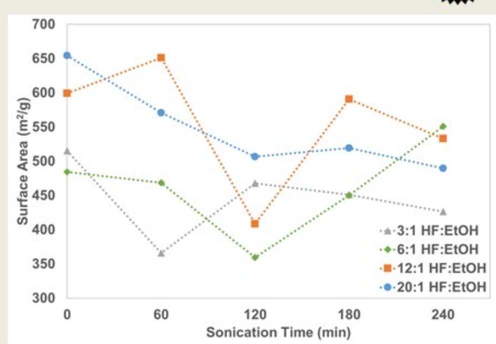
UNCLASSIFIED

U.S. ARMY RDECOM

Porosimetry

ARL

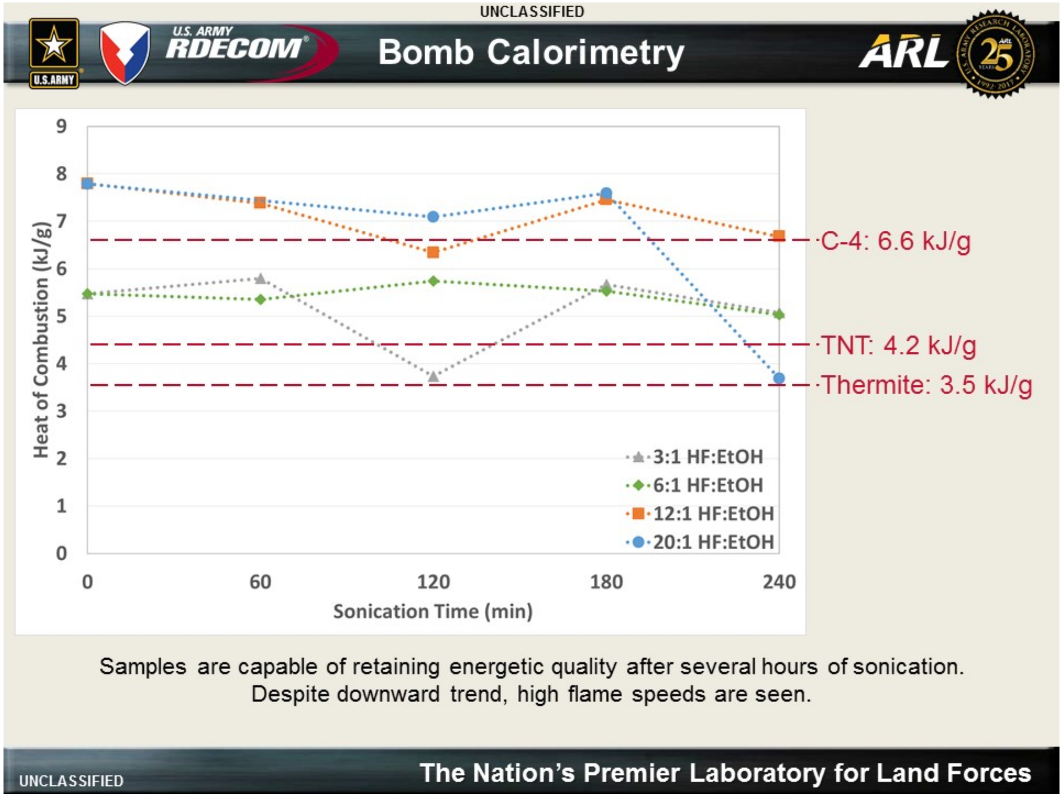


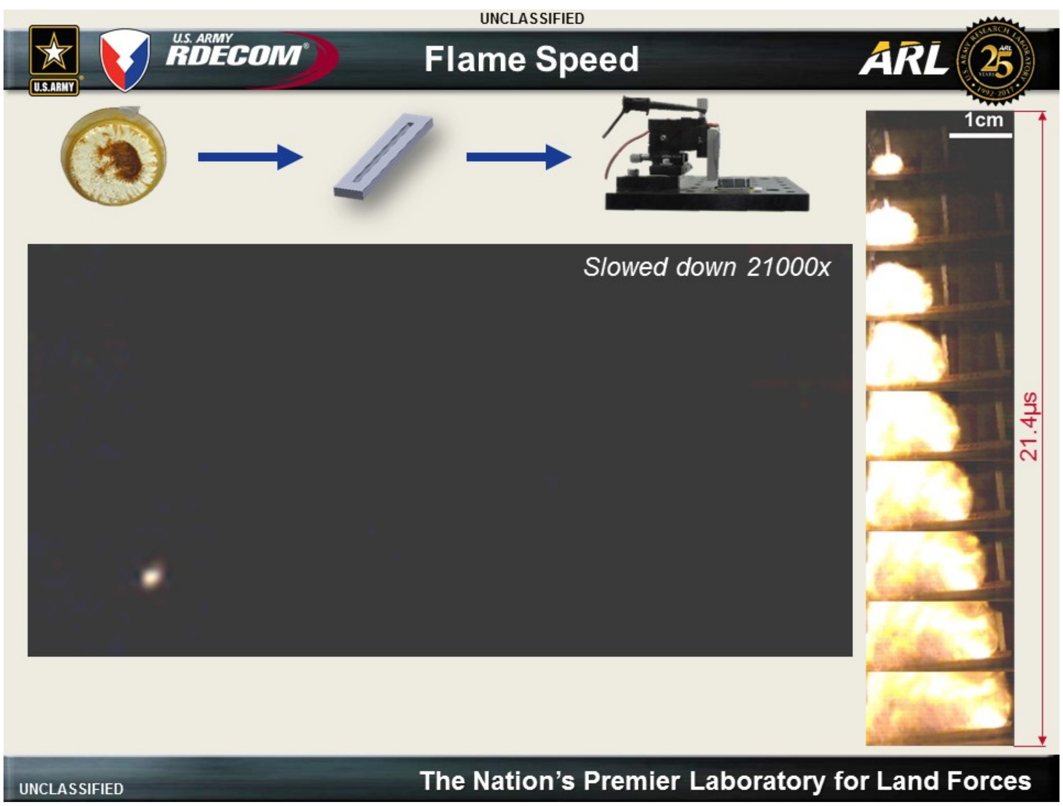


Pore sizes remain small
Surface area shows downward trend
Sonication affects films differently:

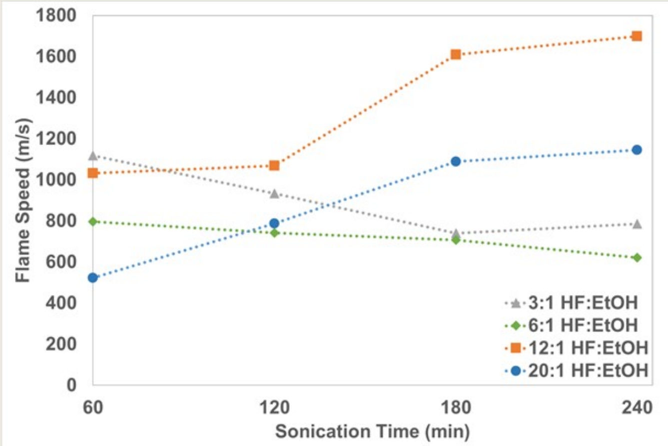
- Film thickness, pore size, etc.
- Little relation seen between porosimetry results and flame speeds

UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Bomb Calorimetry
ARL
Heat of Combustion (kJ/g)
Sonication Time (min)
0
60
120
180
240
C-4: 6.6 kJ/g
TNT: 4.2 kJ/g
Thermite: 3.5 kJ/g
3:1 HF:EtOH
6:1 HF:EtOH
12:1 HF:EtOH
20:1 HF:EtOH
Samples are capable of retaining energetic quality after several hours of sonication.
Despite downward trend, high flame speeds are seen.
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Flame Speed
ARL
Slowed down 21000x
1cm
21.4μs
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

Flame Speed



Best Performing Powder:
2550 m/s
12:1 HF:EtOH Ratio
4 hr sonication
5 nm pore size
530 m^2/g
70% porosity

	Max Reported Flame Speed (m/s)
Churaman, 2010	1590
Becker, 2011	3050
Piekiel, 2013	3660
Piekiel, 2015	1950
This Work	**2550**

Min Speed: ~400 m/s
Max Speed: ~2500 m/s

Flame speeds competitive with PSi films!

Future Work

Explore sonication parameters
→ Will higher amplitude or longer time create more consistent particle sizes?

Quantify polydispersity
→ How does the distribution of particle sizes change with sonication time?
→ How does distribution of particle sizes affect flame speeds?

Explore new methods for PSi application:
→ Inkjet printing/additive manufacturing
→ Evaporation-driven assembly

UNCLASSIFIED

U.S. ARMY RDECOM

Summary

ARL

1. Particles retain **hydrogen-terminated surface** after sonication in liquid medium – important for inkjet printing applications
2. Synthesis method produces **particles <5 nm in diameter**
3. Particles retain similar **surface area & combustion properties** to original film
4. Particle **flame speeds competitive** with fastest reported for film

[redacted]

UNCLASSIFIED

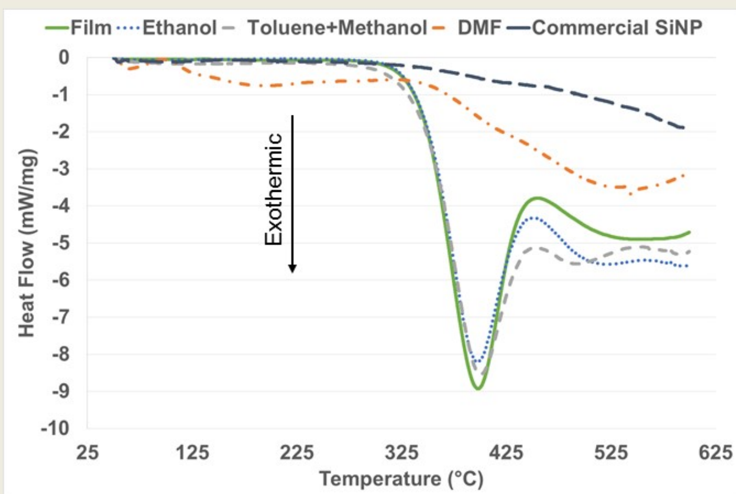
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

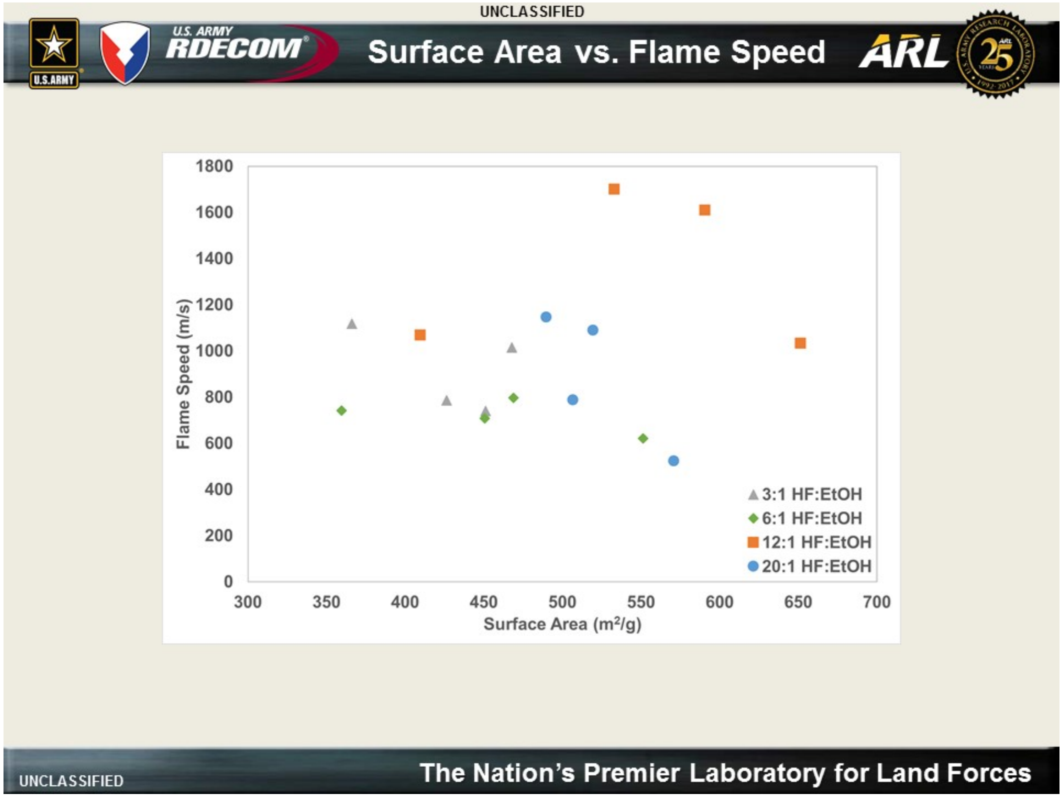
Sonication Media

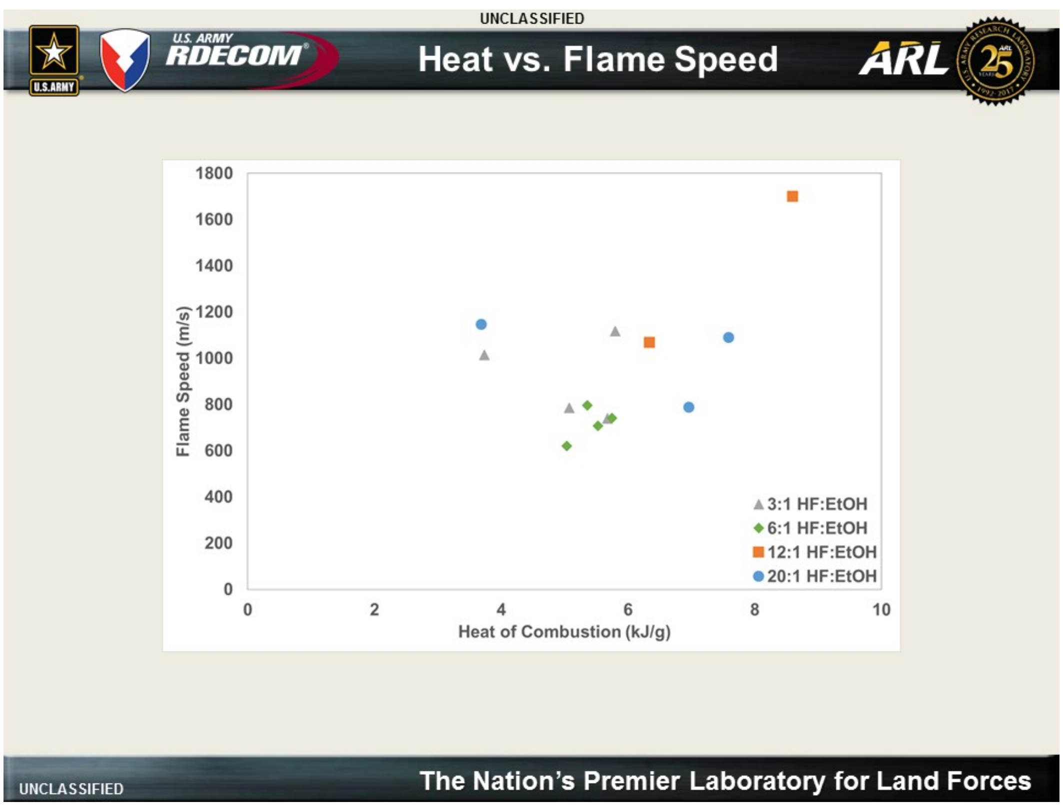
ARL



UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

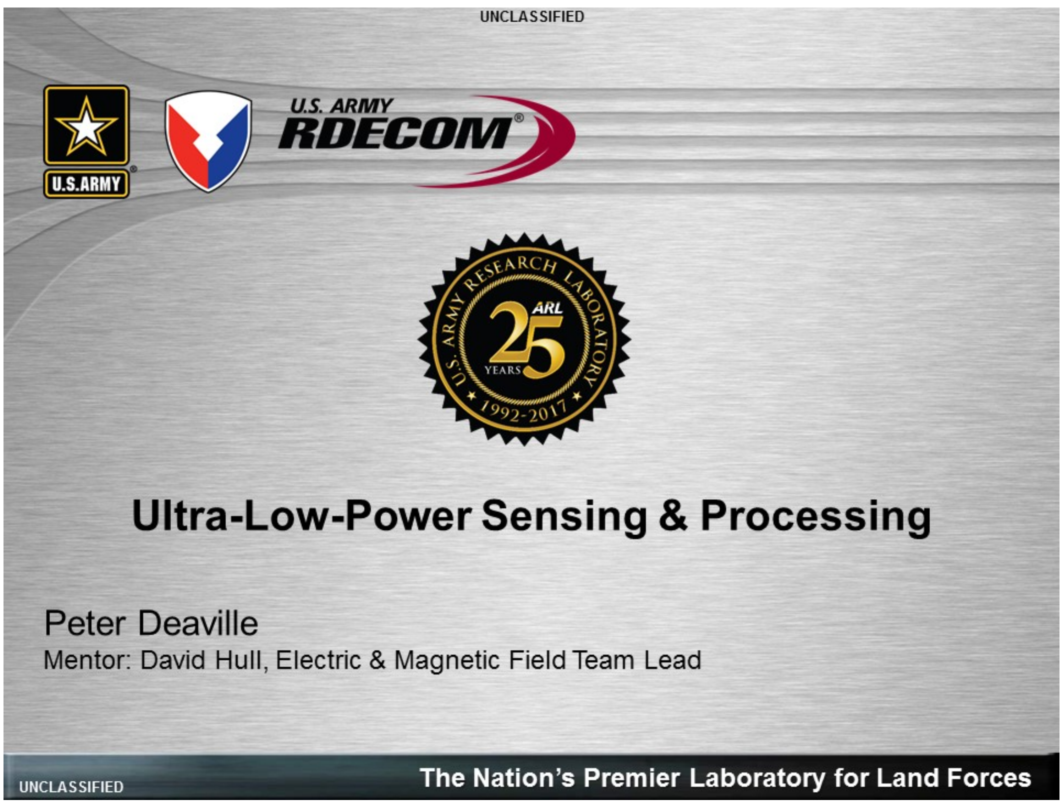

UNCLASSIFIED
U.S. ARMY
RDECOM
U.S. ARMY
Surface Area vs. Flame Speed
ARL
25
Flame Speed (m/s)
1800
1600
1400
1200
1000
800
600
400
200
0
300
350
400
450
500
550
600
650
700
Surface Area (m²/g)
3:1 HF:EtOH
6:1 HF:EtOH
12:1 HF:EtOH
20:1 HF:EtOH
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
U.S. ARMY
Heat vs. Flame Speed
ARL
25
Flame Speed (m/s)
1800
1600
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
Heat of Combustion (kJ/g)
3:1 HF:EtOH
6:1 HF:EtOH
12:1 HF:EtOH
20:1 HF:EtOH
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

Peter Deaville

I am a rising senior electrical engineering student at the University of Maryland, College Park. This is my first research experience and my first internship at the US Army Research Laboratory (ARL). Previously I completed a co-op in avionics integration at Bell Helicopter. My interests are in microelectronics (particularly low-power, embedded systems) and in signal processing. In the future, I hope to attend graduate school with the goal of working in research in either the public or private sector.

I would like to acknowledge the mentorship of David Hull, and the assistance of Sean Heintzelman. I had a very positive experience at ARL, and gained an invaluable amount of experience this summer.



UNCLASSIFIED

U.S. ARMY RDECOM

Importance of Power

ARL

ARTEMIS-Mobile Power Consumption: ~2 W

Regular operation:
3 BB-2590 batteries would last 2 weeks

Using a 2-mW wake-up system to detect events:

A small solar panel could power the system continuously

(or a single BB-2590 for a year)

2

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Project Overview and Methods

ARL

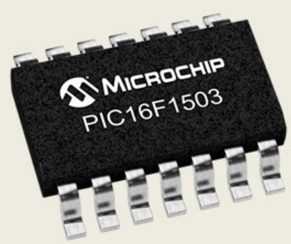
- **Goal: compare sensing and processing methods for low-power phasor extraction**
  - **Explore low-power E/H sensor options**
  - **Compare analog signal processing with low-power digital microcontrollers (MCUs)**
  - **Target <1 mW continuous operation**

Aspinity RAMP Analog/Mixed Signal Processor

20 uW*

TI MSP430 digital microcontroller

200 uW/MHz**



Microchip PIC digital Microcontroller

900 uW/MHz

3

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

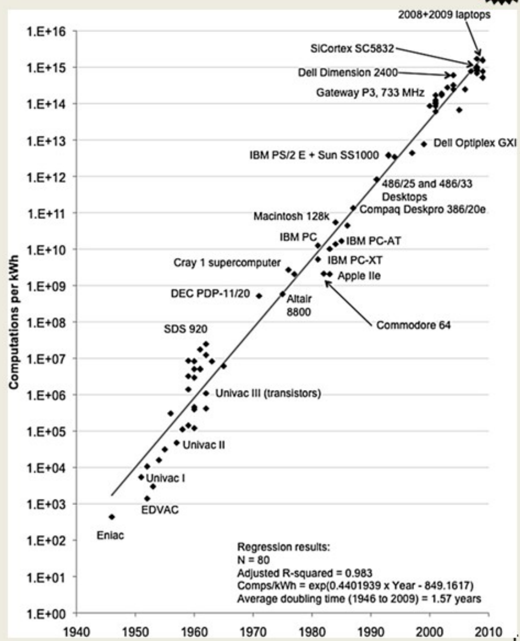
UNCLASSIFIED

U.S. ARMY RDECOM

Digital Low-Power Potential

ARL

- Koomey's Law: similar to Moore's law
- Power-efficiency of digital electronics doubles every 18 months



UNCLASSIFIED

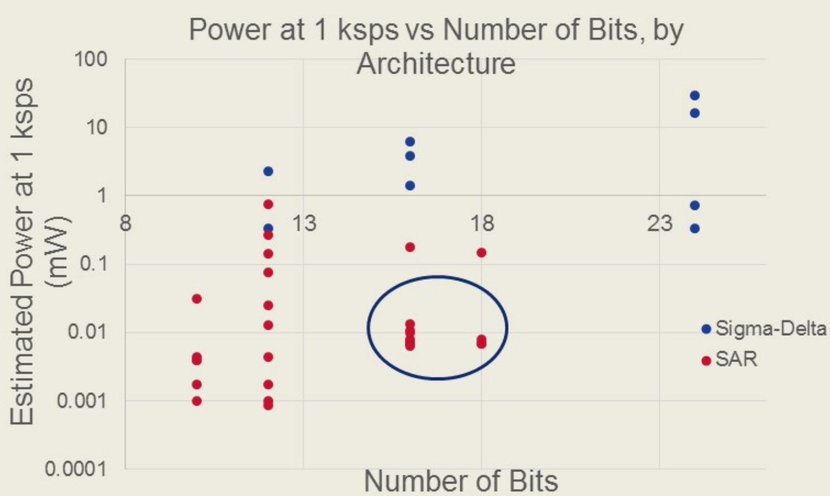
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Low-Power ADCs

ARL



- SAR ADCs provide best power consumption (10 uW), with 16 bits
- Can get 10-12 bit ADCs at 1 uW

Based on a study of 38 Analog Devices, Microchip and Texas Instruments ADC's, using datasheet information

5

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

Approved for public release; distribution is unlimited.

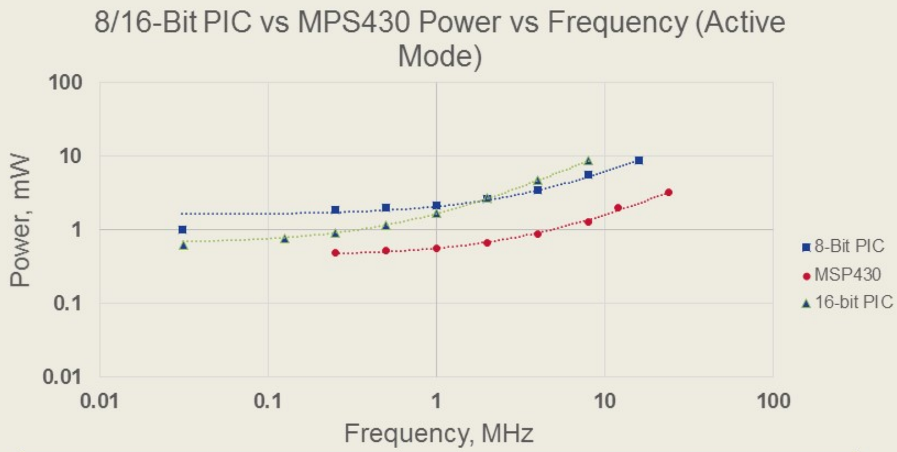
UNCLASSIFIED

U.S. ARMY RDECOM

Benchmarking Digital Options

ARL

MSP430 vs PIC Active Mode Baseline Power Consumption



Only the MSP430 achieves sub-mW performance at 1 MHz

6

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

MSP430 vs PIC (2)

ARL

	TI MSP430	Microchip PIC
Active Mode Power (Baseline, 1 MHz)	570 uW	2200 uW
Idle Power	121 uW	5 – 50 uW

The Microchip PIC series will have lower power only for applications with duty cycle < 4%

Therefore PIC is less useful for an always-on low-power sensor

7

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

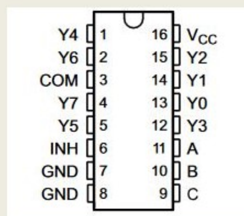
Digital Prototype: Components

TI ADS8866 ADC

- 16-bit SAR architecture
- Typically adds about **10 uW**

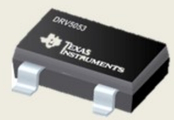
TI SN74LV4051 8-Channel Multiplexer

- **60 microwatts** or less power consumption

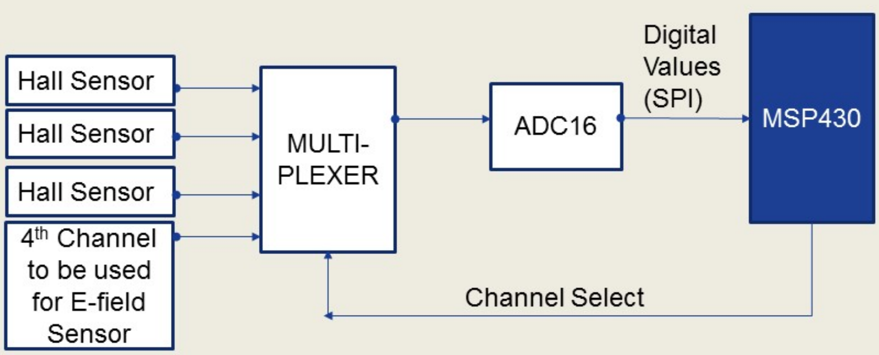


TI DRV5053 Hall-Effect Magnetic Sensor

- **0.288 mW** with 4.3% duty cycle



16-Bit Digital Prototype



900 uW + 60 uW + 10 uW + 1100 uW* = 2.1 mW

Options to reduce power:

- Use 1 or 2 Hall-effect sensors (but can't do phasor calibration)
- Use new TMR magnetic sensor (100 uW/channel, but unproven/expensive)
- Use multiple MCUs (at lower clock rates) and/or co-processor

U.S. ARMY RDECOM

Digital Prototype Cycle Breakdown

ARL

	Sampling Phase	FFT Calculation Phase	Total Sampling/FFT Cycle Power
Power (mW)	2.96	1.42	**2.18 mW**
Duration (s)	0.53	0.54	

- **Equivalent to 2.32 mJ/cycle, where a cycle is 512 samples & FFT**
- **Processor and Hall-effect sensors consume the bulk of the power**

ARTEMIS System: ~2 W

1000x Power Improvement

Low-power system with MSP430: ~2 mW

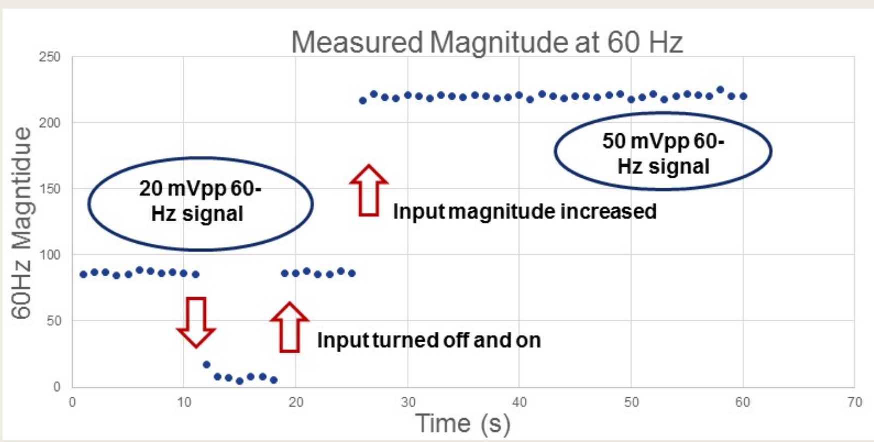
10

U.S. ARMY RDECOM

Fast-Fourier Transform Result

ARL

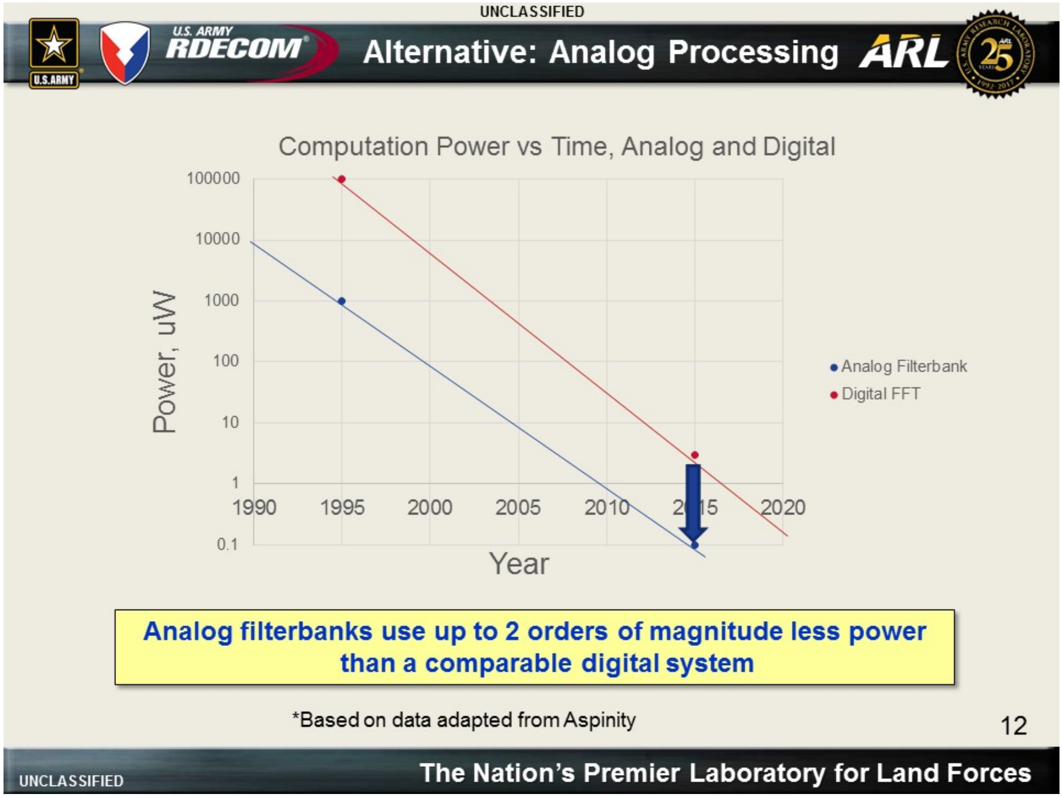
- Real-world events were simulated using a 60-Hz input to one of the sensor channels (without using the sensors themselves)

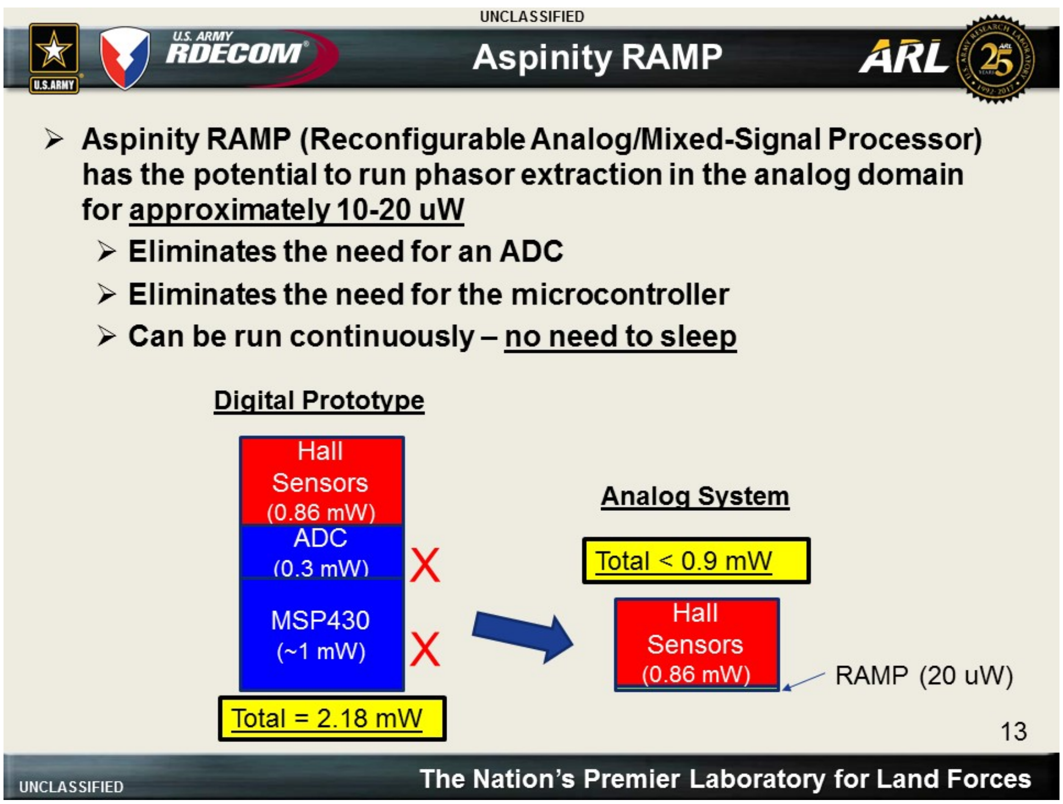


This test could last for 166 days using two AA batteries

11

Approved for public release; distribution is unlimited.


UNCLASSIFIED
U.S. ARMY
RDECOM
Alternative: Analog Processing
ARL
Computation Power vs Time, Analog and Digital
Power, uW
Year
100000
10000
1000
100
10
1
0.1
1990
1995
2000
2005
2010
2015
2020
Analog Filterbank
Digital FFT
Analog filterbanks use up to 2 orders of magnitude less power than a comparable digital system
*Based on data adapted from Aspinity
12
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Aspinity RAMP
ARL
Aspinity RAMP (Reconfigurable Analog/Mixed-Signal Processor) has the potential to run phasor extraction in the analog domain for approximately 10-20 uW
Eliminates the need for an ADC
Eliminates the need for the microcontroller
Can be run continuously – no need to sleep
Digital Prototype
Hall Sensors (0.86 mW)
ADC (0.3 mW)
MSP430 (~1 mW)
Total = 2.18 mW
Analog System
Total < 0.9 mW
Hall Sensors (0.86 mW)
RAMP (20 uW)
13
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

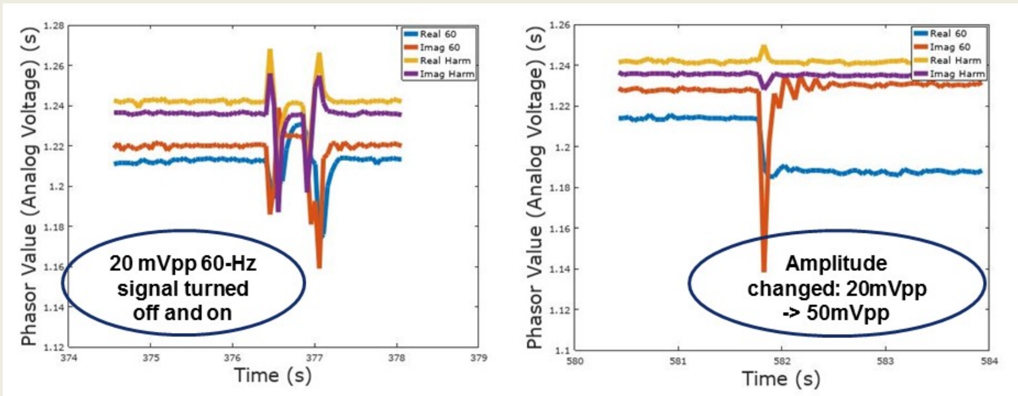
UNCLASSIFIED

U.S. ARMY RDECOM

Analog Phasor Extraction Results

ARL

- Similar to the digital system test, a waveform generator simulated events on the sensor input channel



<u>This test could last for >10 years on the capacity of two AA batteries</u>

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Advantages/Challenges in Analog

ARL

Challenges	Advantages
Does not eliminate the high power consumption of the Hall Sensors 	Operates continuously for tens of microwatts
Not as easy to store and recall detailed data from <u>before</u> the detected event	Potential for adding sensors directly on-chip
Limited to approximately 60 dB of dynamic range (range of detectable amplitudes). With digital system, can achieve 80-100 dB.	Fewer components involved – can be used as an analog front-end as well
Unproven for use as a calibrated measurement in a standalone system	

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

Approved for public release; distribution is unlimited.

UNCLASSIFIED

U.S. ARMY RDECOM

Summary

ARL

Digital Processing:

- **1000x Power Improvement over ARL Mobile Power Meter**

Analog Processing:

- **2000x Power Improvement over ARL Mobile Power Meter**

Both:

- **Demonstrated event detection**
- **Battery life improvement from weeks to years**
- **Potential for future power efficiency increases**

I would like to acknowledge the mentorship of David Hull, as well as the valuable assistance provided by Sean Heintzelman and Brandon Parks on the E/H Field Sensing Team.

16

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Future Work

ARL

- **Replace FFTs with custom phasor processing (may have similar power)**
- **Use multiple MCU's to split up tasks (i.e., one for sampling, one for processing)**
- **Add event classification to the low-power MCU, leveraging machine learning techniques**

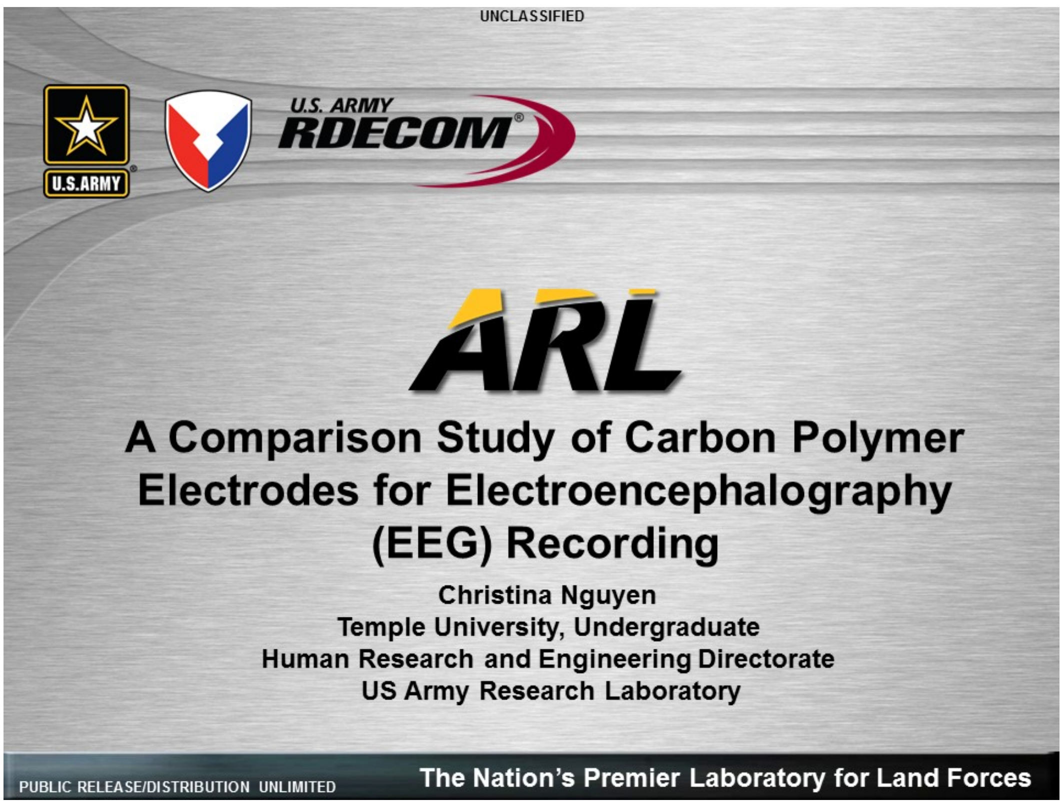
- **Explore options to reach next milestone: *1 microwatt***
  - **On the order of the leakage current of a small battery**

17

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

Christina Nguyen

Christina Nguyen is entering her senior year as an undergraduate student at Temple University, majoring in Neuroscience. She has previous research experience in the lab of Gregory Smutzer at Temple University determining thresholds for tasting different fatty acids. She also has previous experience in the lab of Chantelle Hart at the Center for Obesity Research and Education studying how adolescent sleep habits affect eating habits and weight. This summer she worked in the Mission Impact through Neurotechnology Design (MIND) lab within the Human Research and Engineering directorate under the direction of J Cortney Bradford and W David Hairston. Her work this summer focused on determining the efficacy of US Army Research Laboratory-developed carbon polymer electroencephalography (EEG) electrodes for measuring human brain signals. After graduation, she plans to attend medical school and pursue a career in both clinical work and research.



UNCLASSIFIED

U.S. ARMY RDECOM

Summer Goals

ARL

- My background:
  - Neuroscience major
  - Psychology and biology lab experience
- Hope to contribute:
  - Use neuroscience background
  - My experience with testing subjects and developing testing protocols
  - Results that lead to further research
- Hope to learn:
  - MATLAB skills
  - Details of a career in research

1

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Background: EEG

ARL

- Electroencephalography (*Vrocher et al. 2016*)
  - Measures microvolt-level electrical activity from underlying brain activity
  - Picked up by multiple electrodes on scalp
  - Recording can be visualized as a trace
- Army Usage
  - Monitor Soldier state, which can indicate Soldier performance

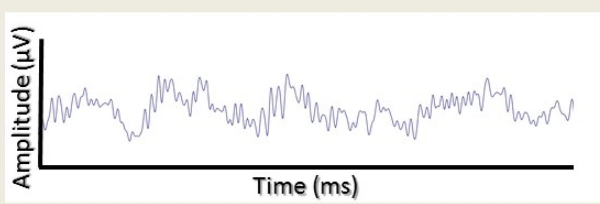


Figure 1. Example of a single raw EEG trace

2

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

Background: Electrodes

- Army applications
  - Safe and comfortable field electrode
  - Reliable data collection
- Wet vs Dry (*Mathewson et al. 2017*)

Wet	Dry
Preferred clinical method	Relatively new
Better data quality	Poorer data quality
Limited usage time	Limited usage time
Difficult application/removal	Easy application/removal

Figure 2. Example of a wet EEG system

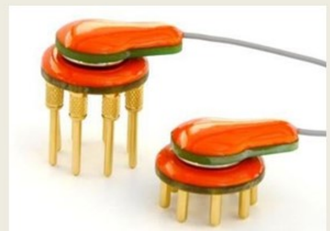


Figure 3. Example of a dry EEG system

Background: Electrodes

- Solution: Polymer electrode
  - Conductive carbon nanofiber-filled polydimethylsiloxane (*Slipher et al. 2016*) → ARL collaboration
- Functions as a dry electrode without the problems associated with wet and dry
- Viable option shown through bench testing before my internship
- Never been tested on human subjects
  - My role this summer from May 2017 to August 2017 (10 weeks)

Figure 4. Top view of polymer electrode

Figure 5. Side view of polymer electrode

UNCLASSIFIED

U.S. ARMY RDECOM

Electrode Types

ARL

- Three electrodes used:
  - g.SAHARA (dry)
  - Carbon polymer with silver epoxy coating
  - Hydrodot (wet)

Figure 6. Side view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

Figure 7. Top view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

5

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Electrode Types

ARL

- Three electrodes used:
  - **g.SAHARA (dry)**
  - Carbon polymer with silver epoxy coating
  - Hydrodot (wet)

Figure 6. Side view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

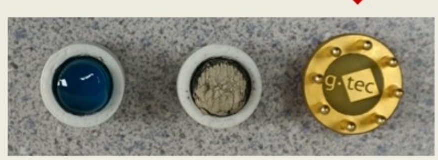


Figure 7. Top view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

5

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Electrode Types

ARL

- Three electrodes used:
  - g.SAHARA (dry)
  - **Carbon polymer with silver epoxy coating**
  - Hydrodot (wet)

Figure 6. Side view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

Figure 7. Top view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

5

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Electrode Types

ARL

- Three electrodes used:
  - g.SAHARA (dry)
  - Carbon polymer with silver epoxy coating
  - **Hydrodot (wet)**

Figure 6. Side view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

Figure 7. Top view of electrodes. From left to right: hydrodot, polymer, g.SAHARA

5

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM ARL

Objective

- **<u>Objective</u>**: Determine the efficacy of the polymer electrodes for human EEG in recording known brain responses during decision making tasks.

6

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM ARL

Experimental Tasks

- Four tasks given to test electrodes' ability to record known brain responses and its susceptibility to noise
- Focus was using a rapid serial visual presentation (RSVP) task (*Ries et al. 2013*)
  - Images flashed every 500 ms (target, distractor, background)
  - Button press in response to only target stimuli

Figure 8. Target – Button press

Figure 9. Distractors – No button press

Figure 10. Background – No button press

7

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

Experimental Tasks

- Four tasks given to test electrodes' ability to **record known brain responses** and its susceptibility to noise

- Focus was using a rapid serial visual presentation (RSVP) task (*Ries et al. 2013*)
  - Images flashed every 500 ms (target, distractor, background)
  - Button press in response to only target stimuli

Figure 8. Target – Button press

Figure 9. Distractors – No button press

Figure 10. Background – No button press

Event Related Potential (ERP)

- ERP: Measured brain response that is linked to a specific event
- What is P300?
  - Component of ERP
  - Decision making tasks provoke P300 response
- Why P300?
  - Well documented → High reproducibility
  - Differing amplitudes depending on stimuli (*Ries et al. 2013*)

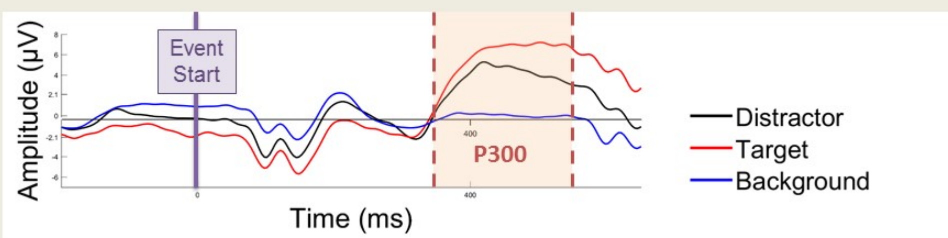


Figure 11. Example of an expected P300 response

Approved for public release; distribution is unlimited.

UNCLASSIFIED

Experimental P300

- Three different curves
  - Target: Largest amplitude
  - Distractor: Second largest amplitude
  - Background: Same amplitude as baseline

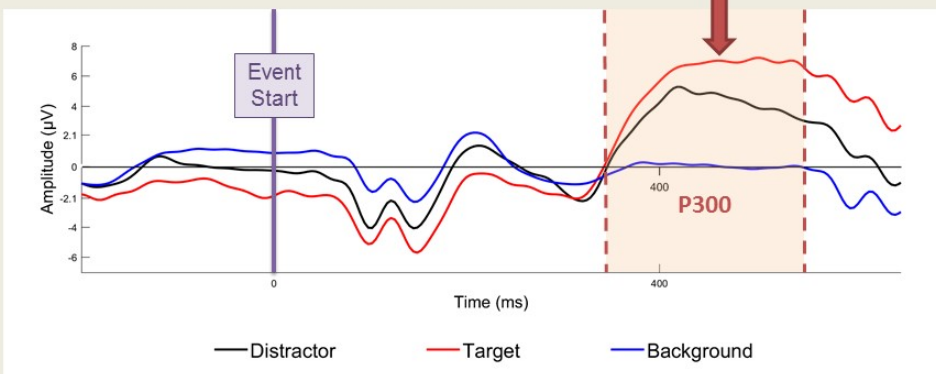


Figure 12. Example of expected curves for different stimuli

9

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Experimental P300

- Three different curves
  - Target: Largest amplitude
  - Distractor: Second largest amplitude
  - Background: Same amplitude as baseline

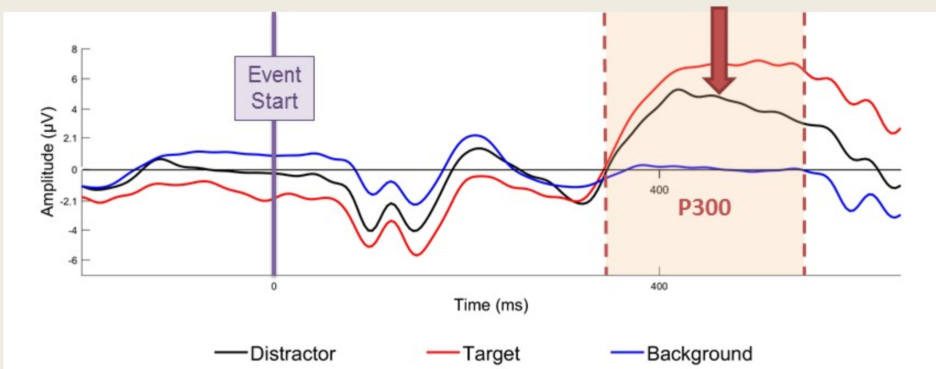


Figure 12. Example of expected curves for different stimuli

9

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Experimental P300

- Three different curves
  - Target: Largest amplitude
  - Distractor: Second largest amplitude
  - Background: Same amplitude as baseline

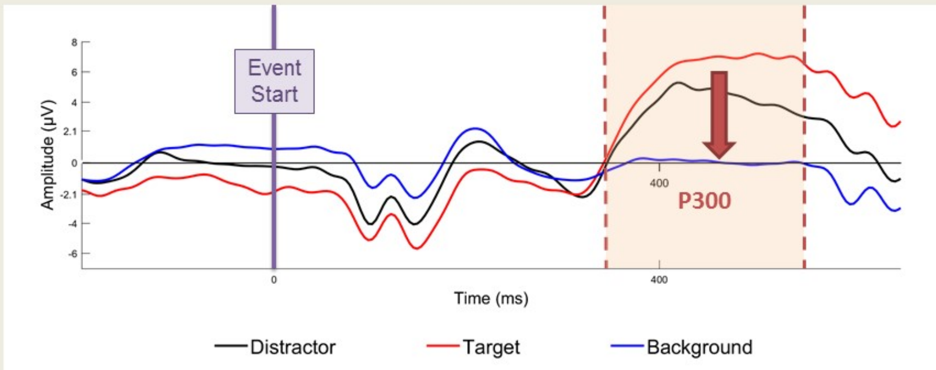


Figure 12. Example of expected curves for different stimuli

9

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Experimental P300

- **<u>Hypothesis</u>**: Our polymer electrodes will record a P300 response with the target having the highest amplitude, followed by the distractor and background.

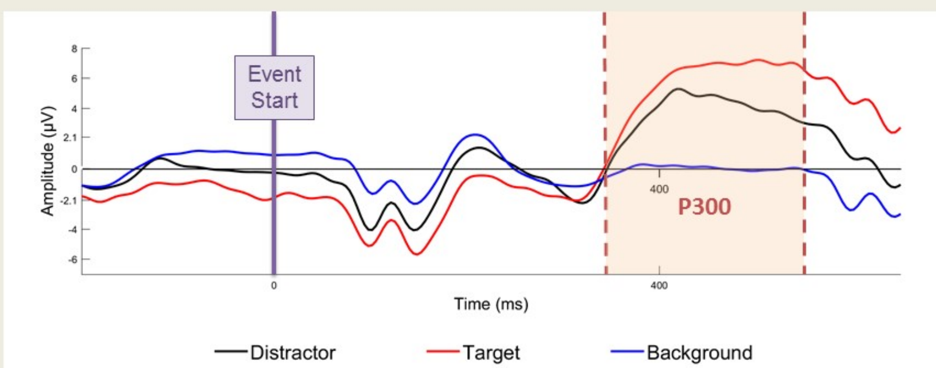


Figure 12. Example of expected curves for different stimuli

10

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Headset Development

ARL

- Custom headset design with designated 10 – 20 locations
  - Fpz, Cz, Pz, Oz (three electrodes per region)
  - Three electrooculogram (EOG) sites
  - Sixteen-channel g.SAHARA EEG system; 15 channels used

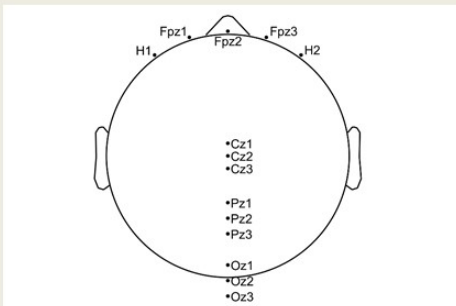


Figure 13. Channel locations based on 10-20 system

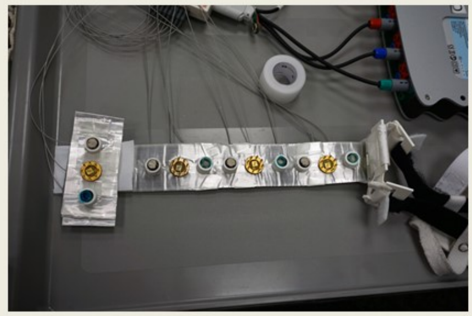


Figure 14. Top view of custom headset

11

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Headset Development

ARL

- Custom headset design with designated 10 – 20 locations
  - Fpz, Cz, Pz, Oz (three electrodes per region)
  - Three electrooculogram (EOG) sites
  - Sixteen-channel g.SAHARA EEG system; 15 channels used

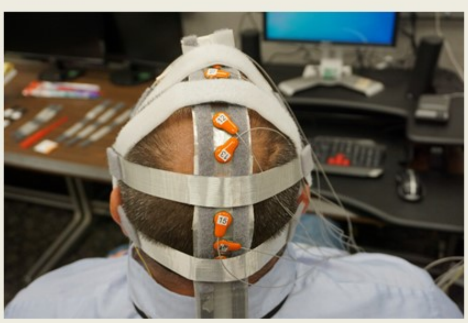


Figure 15. Posterior view of custom headset with electrodes snapped in

Figure 16. Side view of custom headset with electrodes snapped in

12

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

Raw Data Collection

- Sixteen subjects; only used 9 subjects
  - Each subject needed all 3 electrode types with sufficient data quality or else rejected
- Dry electrodes often were the issue
  - g.SAHARA and polymer electrodes were equally the cause of subject rejection

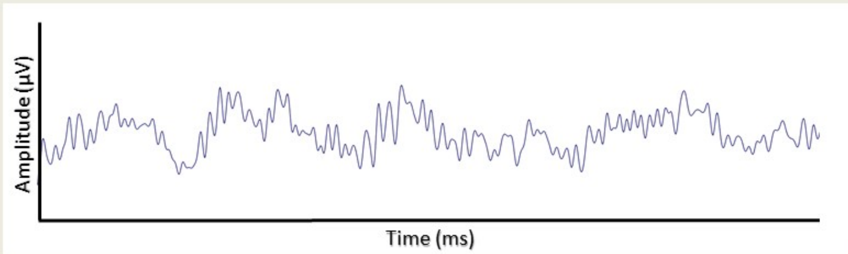


Figure 17. Example of a single EEG trace

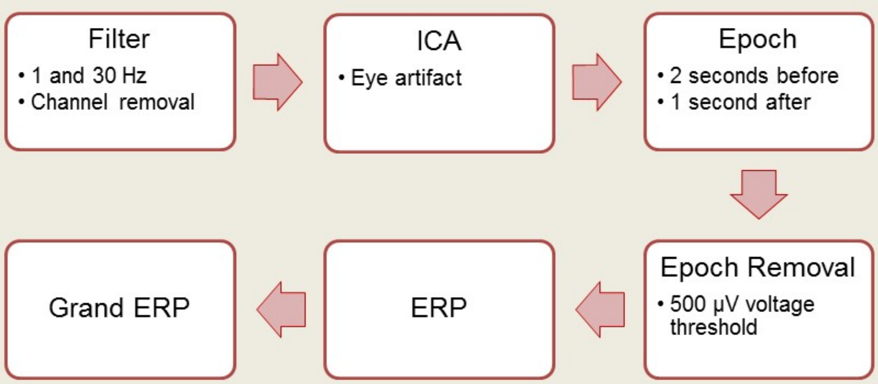
13

UNCLASSIFIED

Processing Pathway

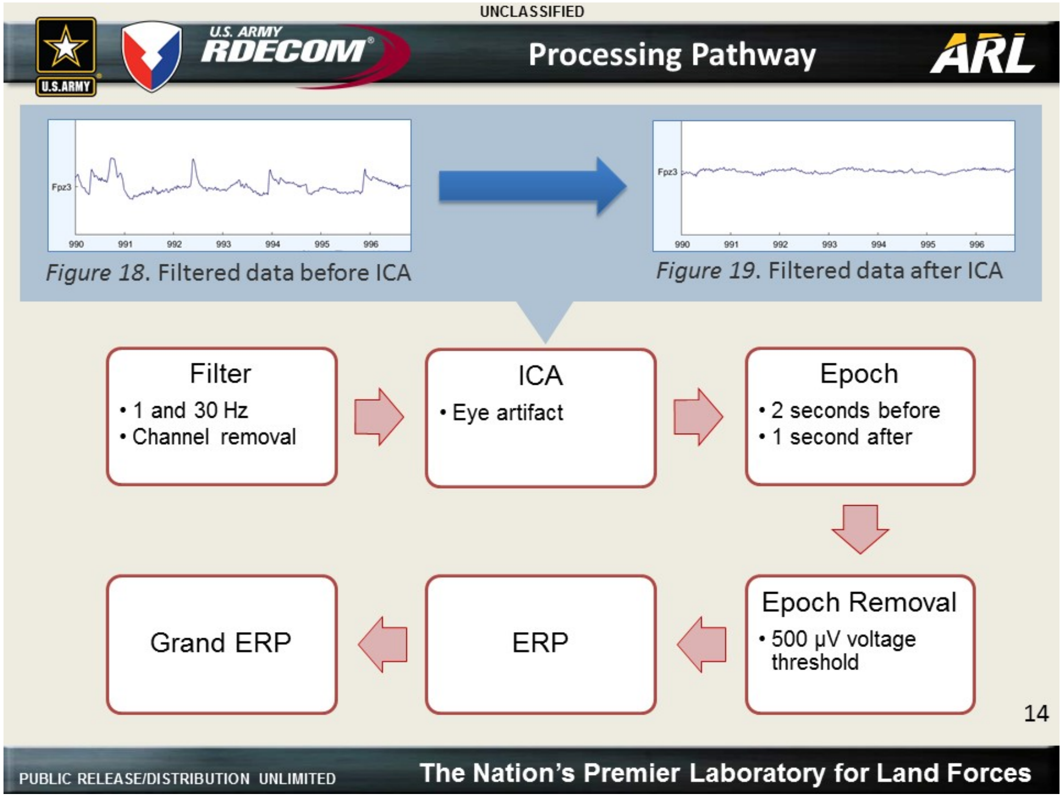
MATLAB

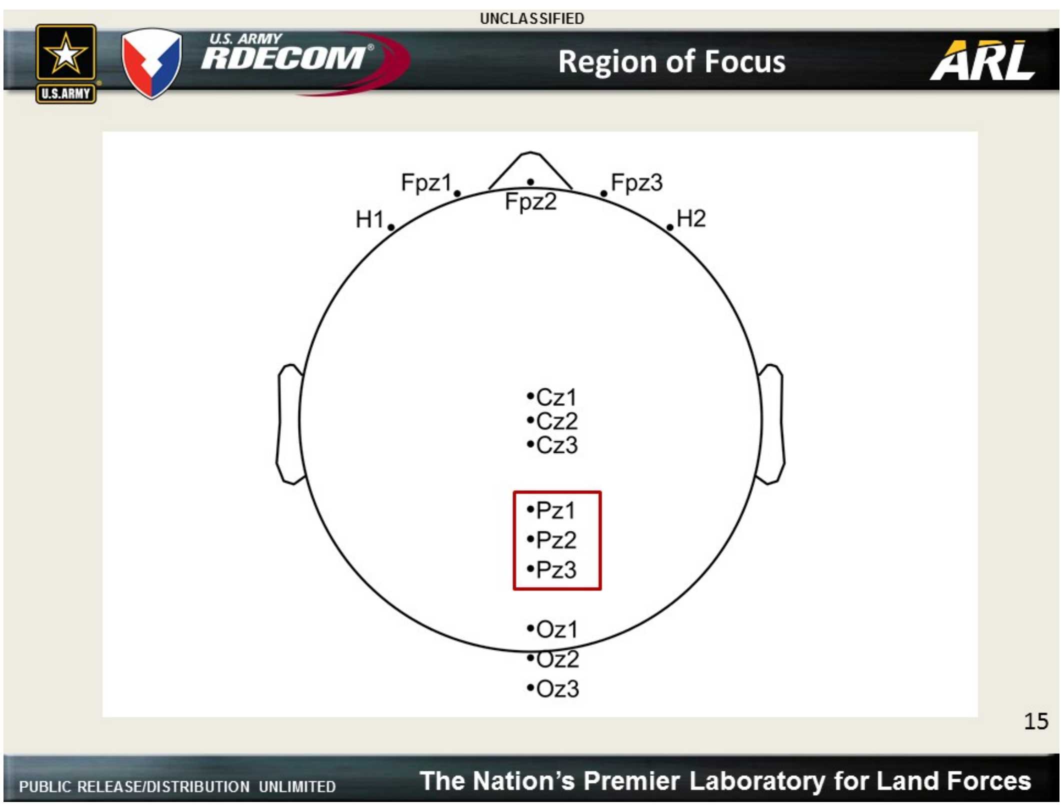
EEGLAB

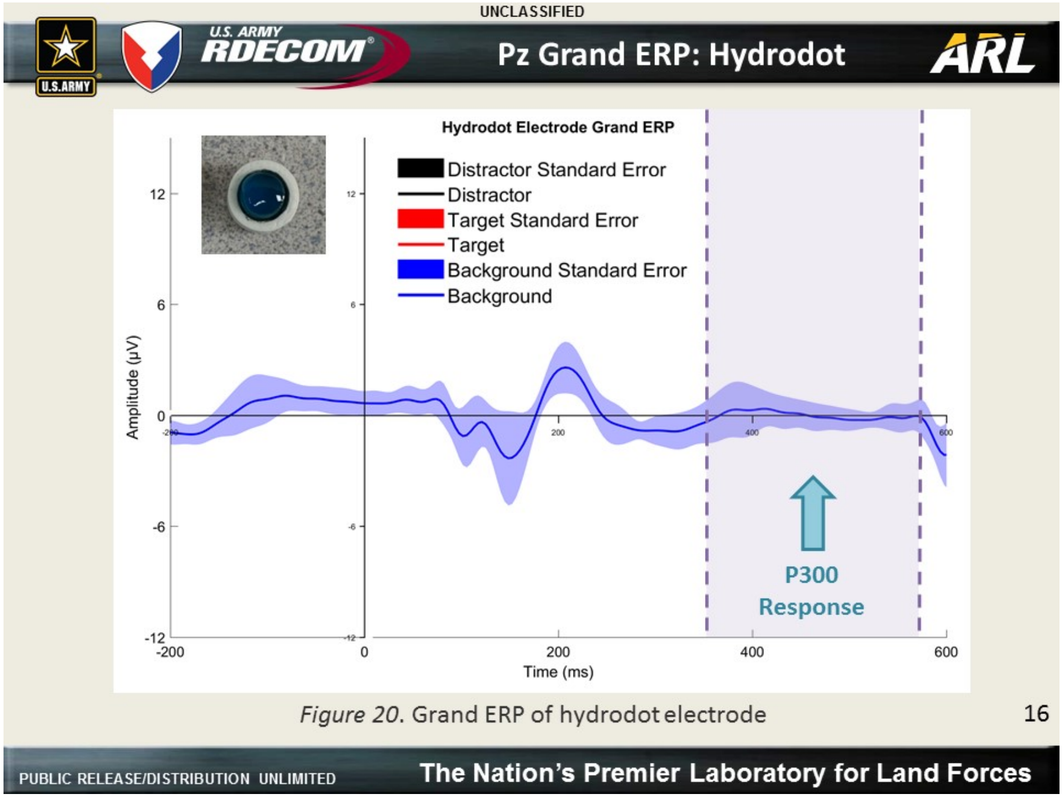


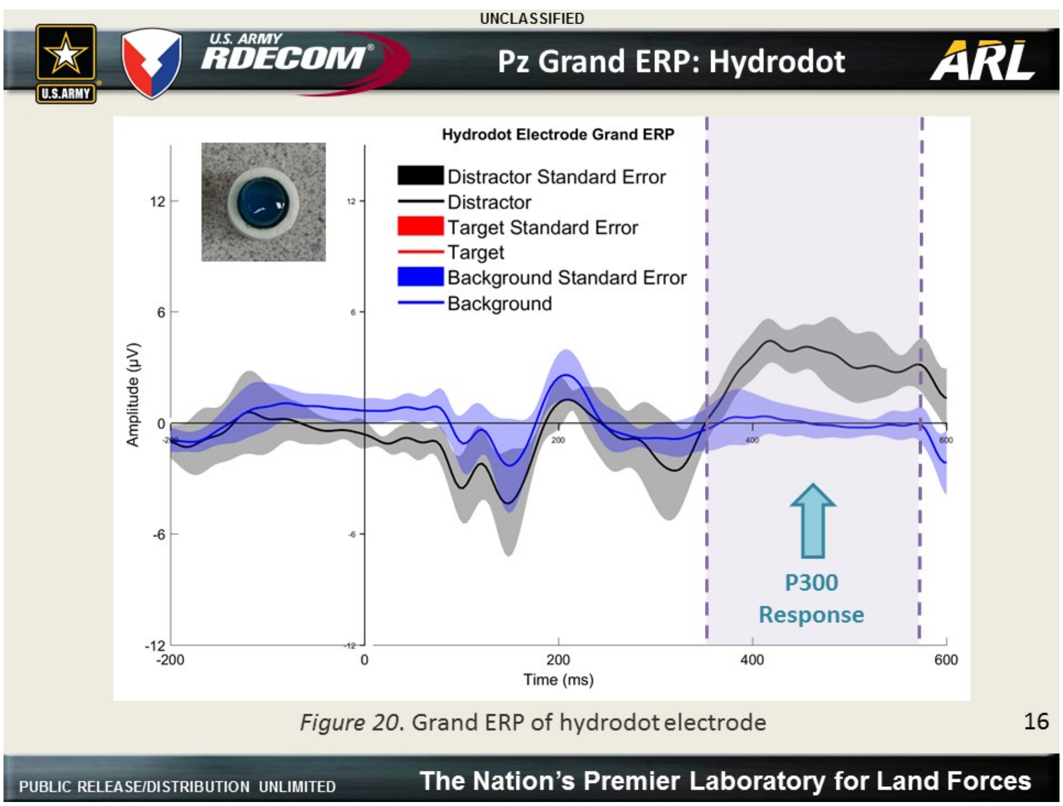
14

PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
U.S.ARMY
Processing Pathway
ARL
Fpz3
990
991
992
993
994
995
996
Figure 18. Filtered data before ICA
Figure 19. Filtered data after ICA
Filter
• 1 and 30 Hz
• Channel removal
ICA
• Eye artifact
Epoch
• 2 seconds before
• 1 second after
Epoch Removal
• 500 µV voltage threshold
ERP
Grand ERP
14
PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
U.S.ARMY
Region of Focus
ARL
Fpz1
Fpz2
Fpz3
H1
H2
•Cz1
•Cz2
•Cz3
•Pz1
•Pz2
•Pz3
•Oz1
•Oz2
•Oz3
15
PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
U.S. ARMY
Pz Grand ERP: Hydrodot
ARL
Hydrodot Electrode Grand ERP
Distractor Standard Error
Distractor
Target Standard Error
Target
Background Standard Error
Background
Amplitude (µV)
Time (ms)
P300
Response
Figure 20. Grand ERP of hydrodot electrode
16
PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
U.S. ARMY
Pz Grand ERP: Hydrodot
ARL
Hydrodot Electrode Grand ERP
Distractor Standard Error
Distractor
Target Standard Error
Target
Background Standard Error
Background
Amplitude (µV)
Time (ms)
P300
Response
Figure 20. Grand ERP of hydrodot electrode
16
PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces

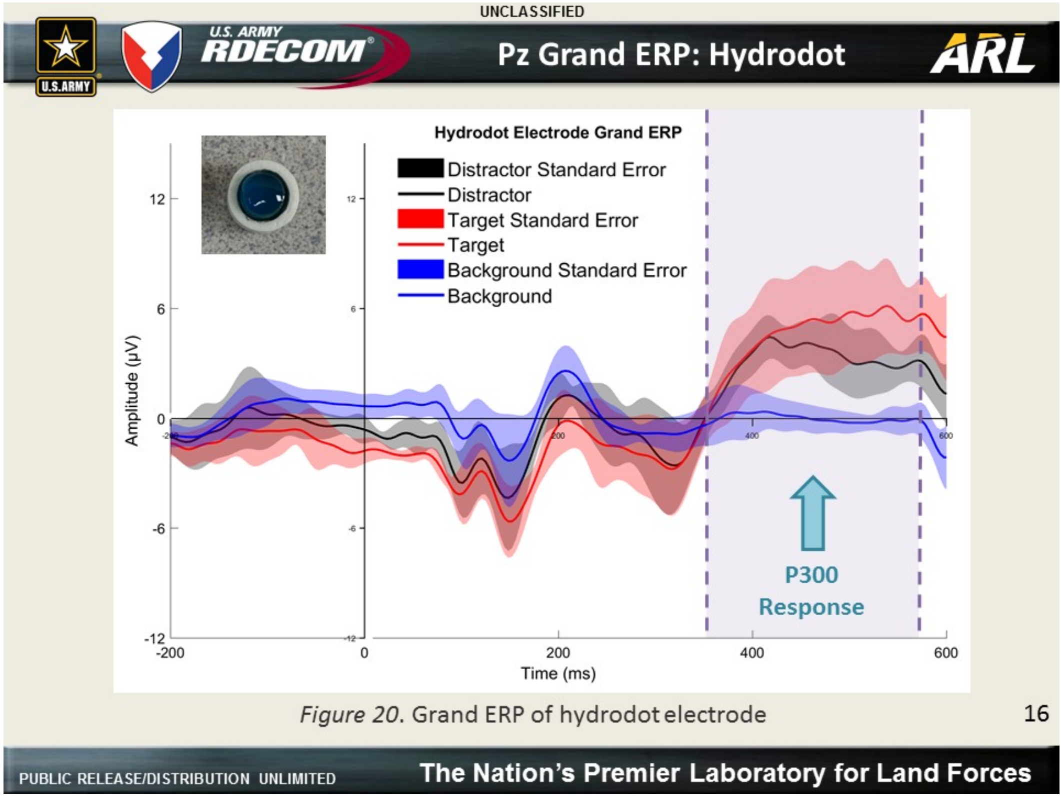


Figure 20. Grand ERP of hydrodot electrode

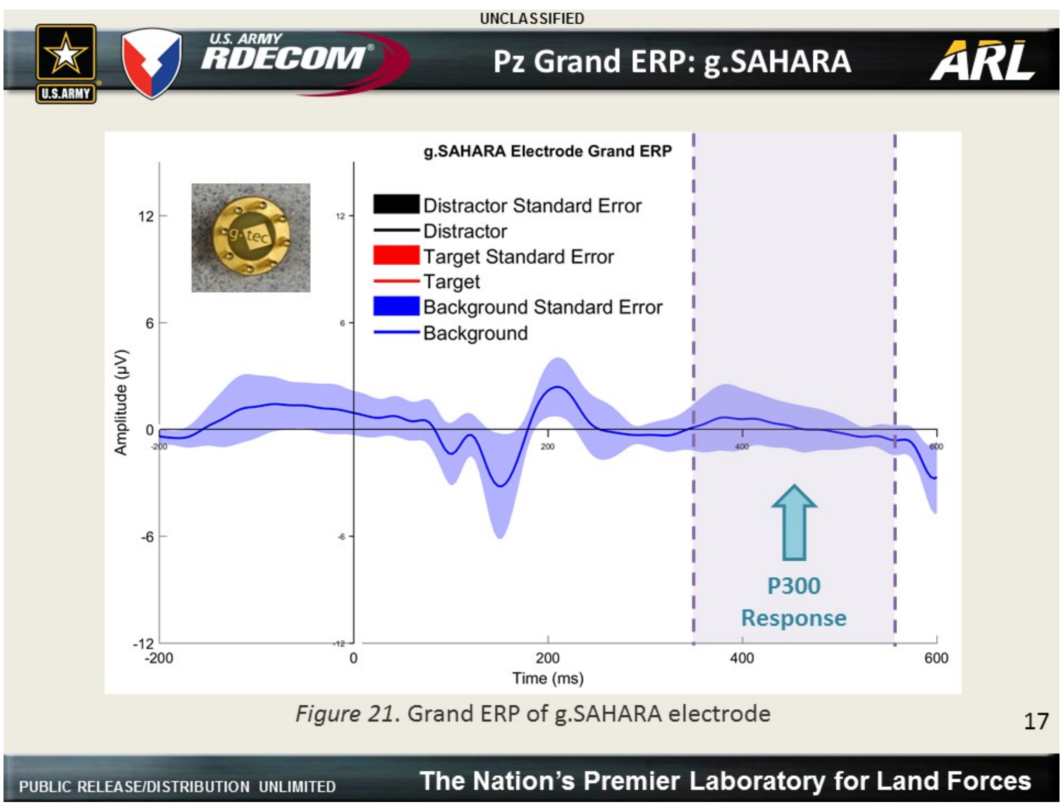
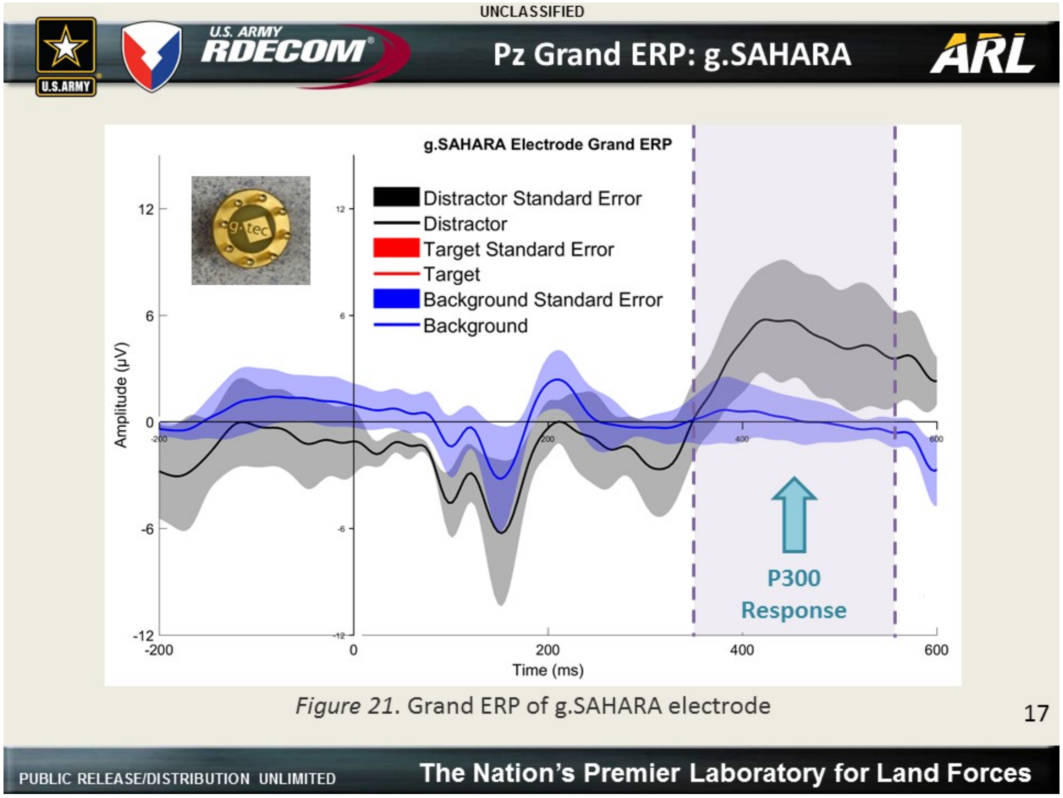
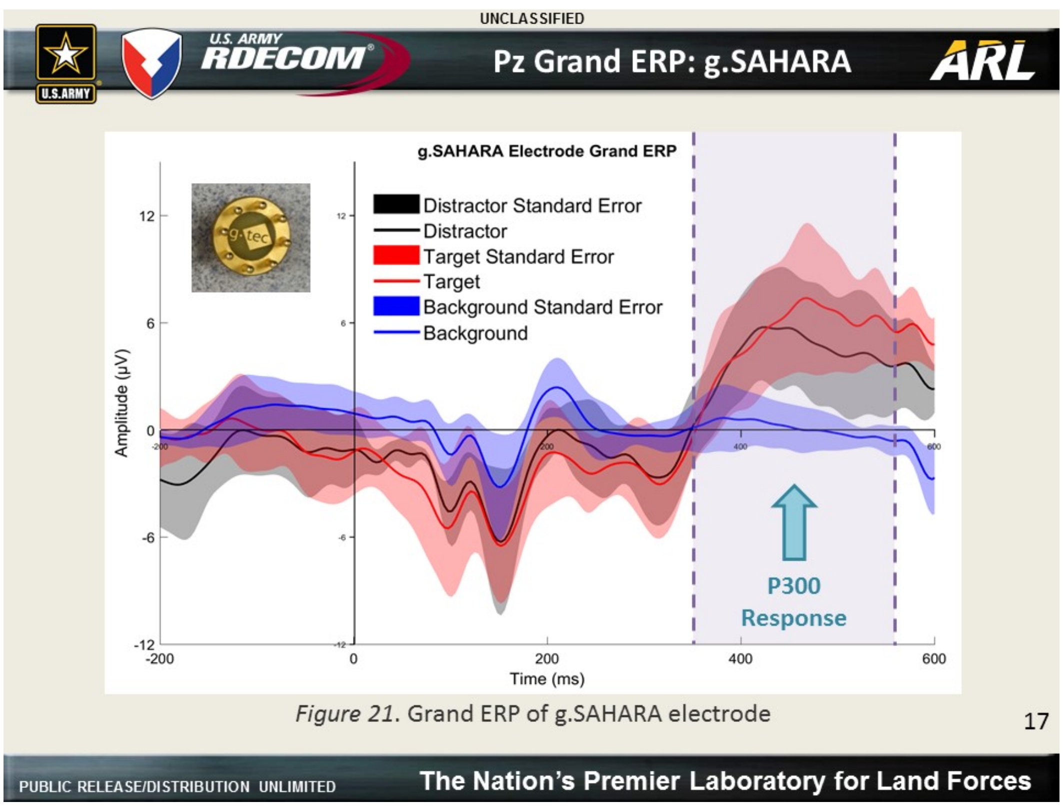


Figure 21. Grand ERP of g.SAHARA electrode


UNCLASSIFIED
U.S. ARMY
RDECOM
Pz Grand ERP: g.SAHARA
g.SAHARA Electrode Grand ERP
Distractor Standard Error
Distractor
Target Standard Error
Target
Background Standard Error
Background
Amplitude (μV)
12
6
0
-6
-12
-200
0
200
400
600
Time (ms)
P300
Response
Figure 21. Grand ERP of g.SAHARA electrode
17
PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Pz Grand ERP: g.SAHARA
g.SAHARA Electrode Grand ERP
Distractor Standard Error
Distractor
Target Standard Error
Target
Background Standard Error
Background
Amplitude (μV)
12
6
0
-6
-12
-200
0
200
400
600
Time (ms)
P300
Response
Figure 21. Grand ERP of g.SAHARA electrode
17
PUBLIC RELEASE/DISTRIBUTION UNLIMITED
The Nation's Premier Laboratory for Land Forces

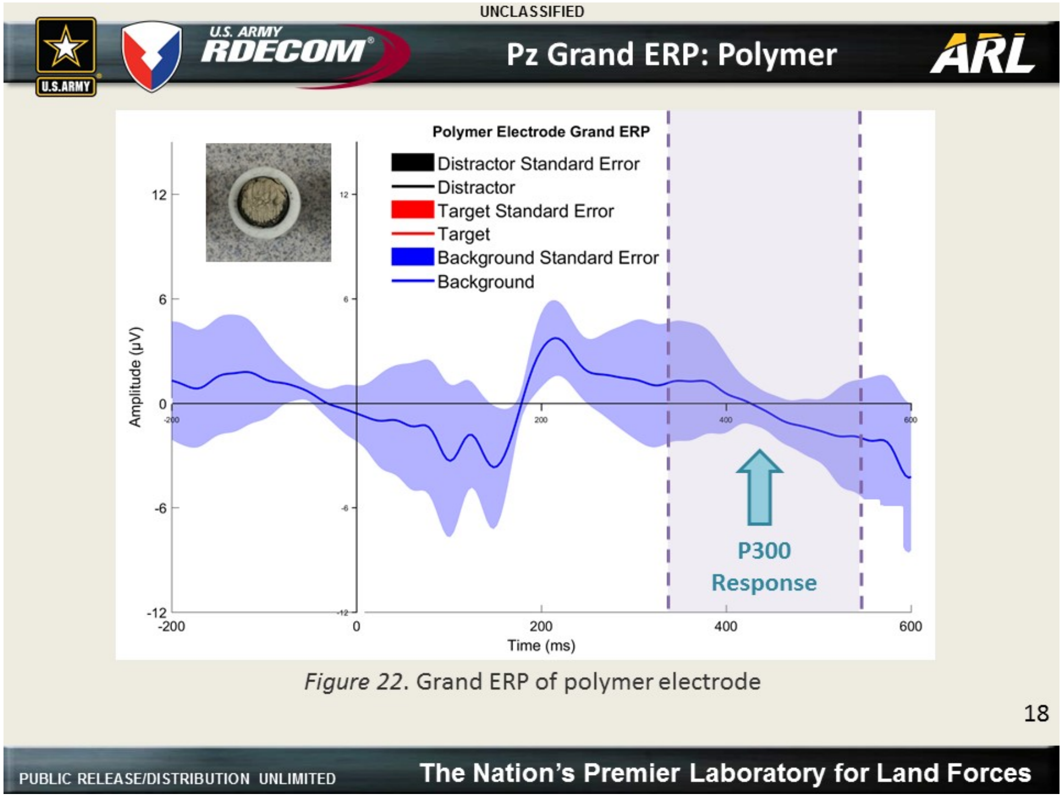


Figure 22. Grand ERP of polymer electrode

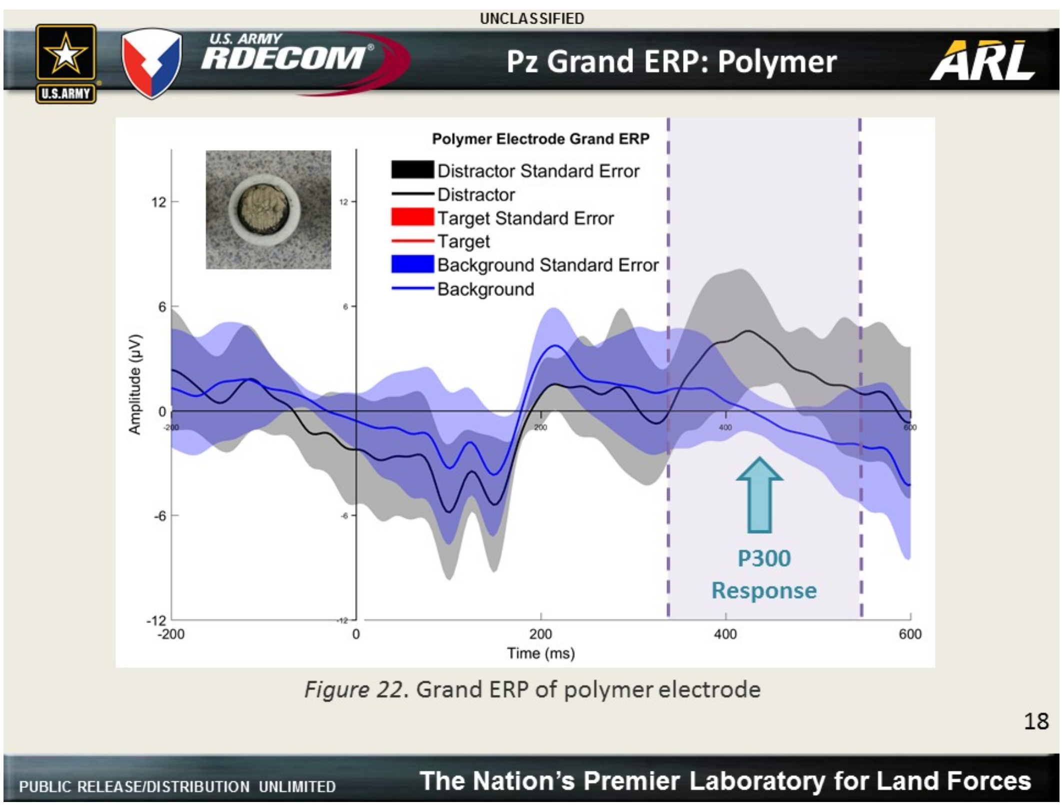


Figure 22. Grand ERP of polymer electrode

UNCLASSIFIED

U.S. ARMY RDECOM

Pz Grand ERP: Polymer

ARL

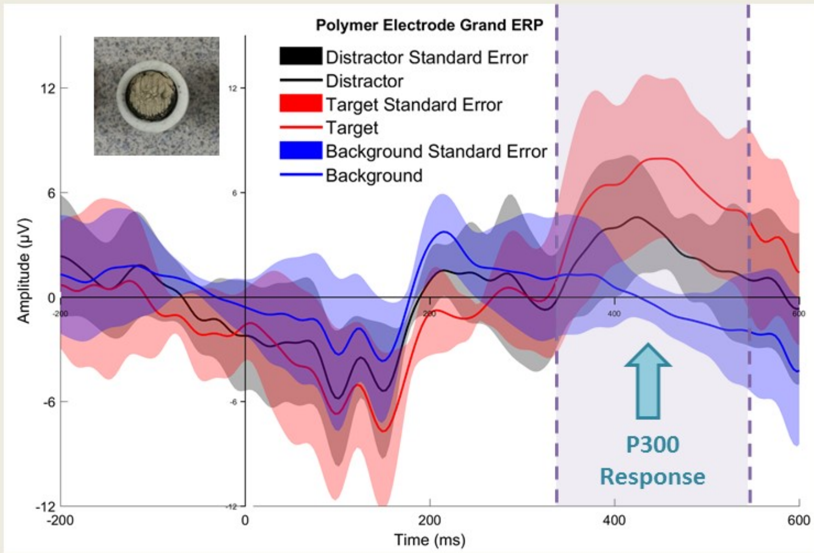


Figure 22. Grand ERP of polymer electrode

18

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

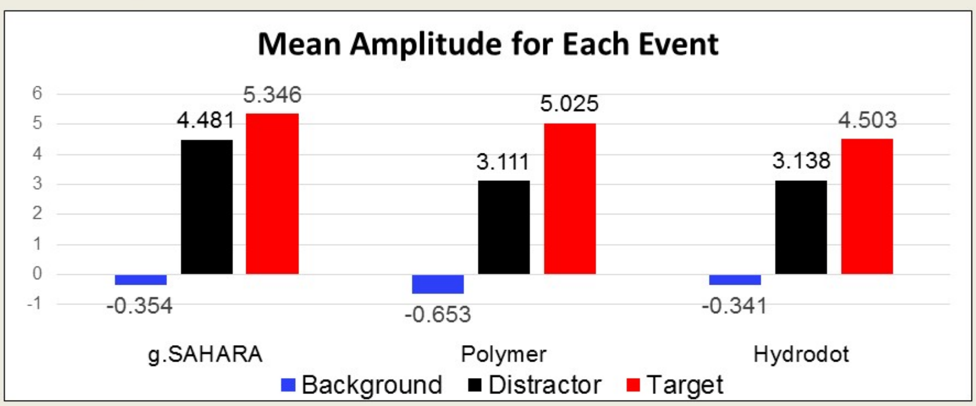
UNCLASSIFIED

U.S. ARMY RDECOM

Mean Amplitude

ARL

- What is mean amplitude?
  - Measurement tool for analysis (*Handy 2005*)
- Average taken from 350 ms to 600 ms



Graph 1. Average mean amplitude of each electrode for target, distractor, and background

19

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Mean Amplitude Paired t-Test

ARL

- Used a paired t-test with Bonferroni correction to determine whether differences between conditions were significant
- Preliminary results show significant differences for target/background and distractor/background

	g.SAHARA	**Polymer**	**Hydrodot**
Target/Distractor	p = 0.181 t = 1.466	p = 0.0532 t = 2.267	p = 0.0515 t = 2.287
Target/Background	p = 0.000145 t = 6.753	p = 0.000948 t = 5.084	p = 0.0000264 t = 8.574
Distractor/ Background	p = 0.0024 t = 4.365	p = 0.000670 t = 5.369	p = 0.0000860 t = 7.274

Table 1. Achieved p-values when comparing differing conditions across the three electrode types. Green is significant and red is not significant. Used $\alpha = 0.017$. Degrees of freedom = 2.

20

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Mean Amplitude Paired t-Test

ARL

- Used a paired t-test with Bonferroni correction to determine whether differences between conditions were significant
- Preliminary results show significant differences for target/background and distractor/background

	g.SAHARA	**Polymer**	**Hydrodot**
Target/Distractor	p = 0.181 t = 1.466	p = 0.0532 t = 2.267	p = 0.0515 t = 2.287
Target/Background	p = 0.000145 t = 6.753	p = 0.000948 t = 5.084	p = 0.0000264 t = 8.574
Distractor/ Background	p = 0.0024 t = 4.365	p = 0.000670 t = 5.369	p = 0.0000860 t = 7.274

Table 1. Achieved p-values when comparing differing conditions across the three electrode types. Green is significant and red is not significant. Used $\alpha = 0.017$. Degrees of freedom = 2.

20

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Mean Amplitude Paired t-Test

- Used a paired t-test with Bonferroni correction to determine whether differences between conditions were significant
- Preliminary results show significant differences for target/background and distractor/background

	g.SAHARA	Polymer	Hydrodot
Target/Distractor	p = 0.181 t = 1.466	p = 0.0532 t = 2.267	p = 0.0515 t = 2.287
Target/Background	p = 0.000145 t = 6.753	p = 0.000948 t = 5.084	p = 0.0000264 t = 8.574
Distractor/ Background	p = 0.0024 t = 4.365	p = 0.000670 t = 5.369	p = 0.0000860 t = 7.274

Table 1. Achieved p-values when comparing differing conditions across the three electrode types. Green is significant and red is not significant. Used $\alpha = 0.017$. Degrees of freedom = 2.

20

PUBLIC RELEASE/DISTRIBUTION UNLIMITED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Discussion

- All 3 electrodes were able to measure an ERP with the characteristic P300 signal and amplitude pattern.
- All electrodes could detect a significant difference between distractor/background and target/background.
- None of the electrodes could detect a significant difference between target/distractor.
- Power analysis suggests a sample size of n = 10.
  - Data collection is ongoing

21

PUBLIC RELEASE/DISTRIBUTION UNLIMITED The Nation's Premier Laboratory for Land Forces

Conclusion

- Objective reached, hypothesis supported
  - Polymer electrode was able to record the expected P300 response for the target, distractor, and background.
- Promising alternative for safe, comfortable electrodes for Army usage in the field
- Issues with current electrode geometry
  - Hard to get through hair with polymer electrode
- Analyze data from artifact-inducing tasks in experiment
  - We only looked at recording known brain responses.

22

UNCLASSIFIED

Summer Take Away

- Contributions:
  - Designed a novel headset for electrodes
  - Collected data on human subjects
  - Developed my own processing pipeline for EEG analysis
- Knowledge gained:
  - Hands-on experience with EEG
  - MATLAB skills
  - Experience in a research-oriented career
  - The military applications of neuroscience research

23

PUBLIC RELEASE/DISTRIBUTION UNLIMITED The Nation's Premier Laboratory for Land Forces

Acknowledgements

- Lab Mentors
  - Cortney Bradford
  - Dave Hairston
- Fellow CQL intern
  - Ben Burke – Poster with additional analyses on the floor

References

Handy, T. C. (2005). Event-Related Potentials: A Methods Handbook. Cambridge: Mass.

Mathewson, K. E., Harrison, T. J., & Kizuk, S. A. (2016). High and dry? Comparing active dry EEG electrodes to active and passive wet electrodes. Psychophysiology, 54(1), 74-82. doi:10.1111/psyp.12536

Ries, A. J., & Larkin, G. B. (2013). Stimulus and Response-Locked P3 Activity in a Dynamic Rapid Serial Visual Presentation (RSVP) Task. Army Research Laboratory. Retrieved from http://www.dtic.mil/get-tr-doc/pdf?AD=ADA579452

Slipher, G. A., Hairston, W. D., & Mrozek, R. A. (2016). Carbon nanofiber-filled conductive silicone elastomers as soft, dry bioelectronic interfaces. doi:1609.08565

Vrocher, D., III, & Lowel, M. J. (2016, April 5). Electroencephalography (EEG) (W. C . Shiel, Ed.). Retrieved from http://www.emedicinehealth.com/electroencephalography_eeg/article_em.htm

UNCLASSIFIED

U.S. ARMY RDECOM ARL

Supplementary Slides

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM ARL

Power Analysis

- t-Test is affected by sample size and effect size → small sample is not reliable
- Conducted power analysis to find preferable subject number based on effect size and power of previous studies (*Mathewson and al. 2017*)
  - Two-tailed t-test
  - α = 0.017
  - Power = 0.979
  - Effect size = 1.696
  - **10 subjects**

26

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Effect Size of Mean Amplitude

ARL

- Found effect size of statistically significant results with estimated standard error of effect size
- These differences had a large effect (desire > 0.5)

	g.SAHARA	Polymer	Hydrodot
Distractor/ Background	2.21 *(S.E.: 0.59)*	2.53 *(S.E.: 0.62)*	3.51 *(S.E.: 0.73)*
Target/ Background	2.97 *(S.E.: 0.67)*	2.93 *(S.E.: 0.66)*	3.06 *(S.E.: 0.68)*

Table 2. Effect size of statistically significant conditions in relation to desired effect size

27

PUBLIC RELEASE/DISTRIBUTION UNLIMITED

The Nation's Premier Laboratory for Land Forces

Clarence Wong

I am from Knoxville, Tennessee, and I graduated with a BS in electrical engineering in May 2017 from the University of Tennessee. As an undergraduate, I studied under Dr Garrett Rose and researched Neuromorphic VLSI Circuit Design and Neuromorphic Computing. In the fall, I will return to the University of Tennessee to start my master's program in electrical engineering. As a master's student under Dr Rose, I will be involved with designing neuromorphic applications and platforms for testing different neuromorphic architectures. After I complete graduate school, I intend to work in industry as a project manager.

U.S. ARMY RDECOM

About Me

ARL

- From: Knoxville, Tennessee
- School: University of Tennessee
- Degree: BS in electrical engineering
- Starting Masters in electrical engineering in the Fall
- Undergraduate Research: Neuromorphic Circuit Design and Applications
- Been with ARL for 12 weeks
- cwong11@vols.utk.edu

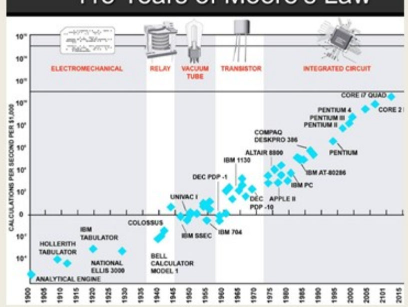
U.S. ARMY RDECOM

Moore's Law

ARL

- The number of transistors on a chip doubles about every 2 years, thus improving computing performance.
- The computing performance associated with Moore's Law has begun to plateau due to the sizing transistors below 10 nm and quantum tunneling.
- Using Neuromorphic Computing to go overcome Moore's Law.

115 Years of Moore's Law

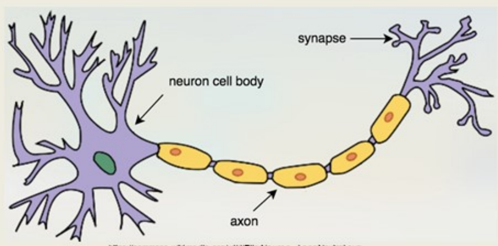


https://weeklyglobalresearch.wordpress.com/2017/02/19/exploring-opportunities-in-artificial-intelligence/

UNCLASSIFIED

Neuromorphic Computing

- Neuromorphic Computing: mimicking biology and the brain using integrated circuits
- Advantages: size, weight, and power (SWP)
- Programmable Neuromorphic Hardware e.g. IBM TrueNorth
- Synapses – determine the amount of action potential (charge/weight) to send to a neuron
- Axon – connection between neurons and synapses
- Neurons – collect action potential and spikes when a threshold is met



https://commons.wikimedia.org/wiki/File:Neuron_LangNeutral.svg

4

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Project Description

- The idea of merging Neuromorphic Computing and robotics. As well, merging theory and simulation with real world applications.
- Overall Goal - Design a platform for testing:
    - Different neuromorphic hardware (e.g., TrueNorth, FPGA)
    - Architectures (e.g., TrueNorth, MrDANNA, DANNA)
    - Training methods (e.g., supervised, unsupervised, online, offline)
    - Connecting hardware (e.g., sonar, camera, motor, LIDAR, phones)
- Short term goal
    - Design a Collision Avoidance Robot that drives autonomously using Neuromorphic Hardware.
- Work based off of University of California, Irvine's Jeff Krichmar and research group. Project differs by hardware, learning algorithms, and application used.

5

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

Collision Avoidance Robot

- Purpose: Autonomously avoid colliding into objects using IBM TrueNorth and Convolutional Neural Networks (CNN) to determine the output motor response.
- Three sonar sensors placed on the left, center, and right side of the car are used to detect objects.
- Four predefined motor control commands: Forward, 90 degree left turn, 90° right turn, and reverse
- Two main components to the project: Robotics/Electronics and Neuromorphic Process

http://www.dagurobot.com/goods.php?id=154

6

U.S. ARMY RDECOM ARL

Electronics

- Three sonar sensors – measures the amount of time the sound wave bounces back to the object and produces an analog output
- Arduino Mega – programmable microcontroller written in Arduino's version of C/C++
- Motor controller – intermediary between the Arduino and DC motors to control speed and direction of the motor
- Serial Bluetooth module
- Six DC motors – tank control method (turning controlled by stopping or reducing the speed of the left or right motor)
- IBM TrueNorth – programmable neuromorphic chip

https://www.maxbotix.com/Ultrasonic_Sensors/MB1002.htm

http://www.electroschematics.com/7963/arduino-mega-2560-pinout/

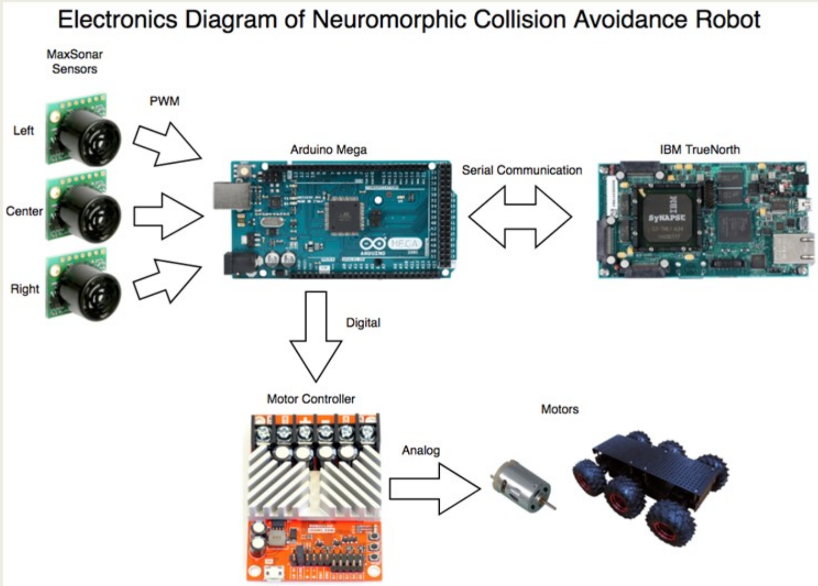
http://www.robotshop.com/en/roboclaw-2x45a-6-34vdc-regenerative-motor-controller.html

http://blog.ibmjstart.net/2015/09/10/truenorth-next-generation-cognitive-computing/

7

U.S. ARMY RDECOM ARL

Electronics Diagram

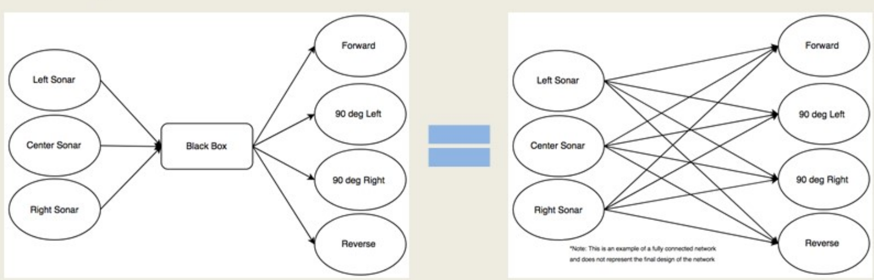


8

U.S. ARMY RDECOM ARL

Neuromorphic Process

- **Neural Networks are essentially Black Boxes.**
- **In this case, Black Box equals a Fully Connected Forward Pass CNN.**
- **Incorporating TrueNorth with Robotics:**
  - **Step 1: Learn about TrueNorth Architecture and Corelet Programming**
  - **Step 2: Create a TrueNorth Control Corelet based off of a truth table approach**
  - **Step 3: Create communication between Arduino and TrueNorth**
  - **Step 4: Collect Training Data**
  - **Step 5: Create Trained CNNs**



9

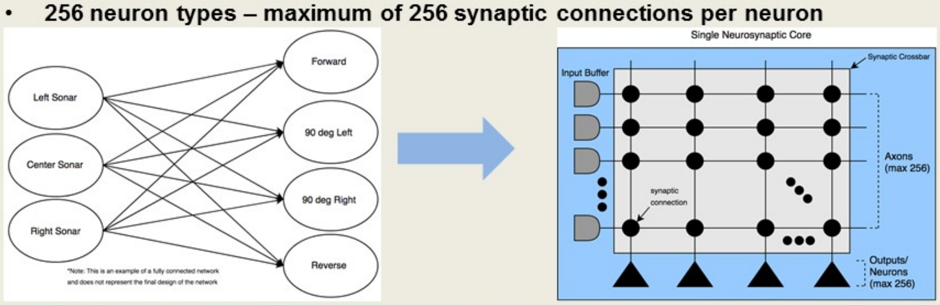
UNCLASSIFIED

U.S. ARMY RDECOM

TrueNorth and Corelets

ARL

- IBM TrueNorth – programmable neuromorphic chip
- Corelet programing – process of converting neural networks into the TrueNorth framework (Matlab functions provided by IBM)
- Corelet Process: set up input and output pins, Neurosynaptic Cores, Synaptic Crossbar, and Neuron parameters (e.g. weight, threshold) which produces model and connection files that can be imported to TrueNorth
- TrueNorth Constraints - 4,096 Neurosynaptic Cores, maximum of 256 Neurons and Axons per core, maximum of 65,536 Synapses per core
- Four axon types – maximum of 4x256 different weights
- 256 neuron types – maximum of 256 synaptic connections per neuron



10

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Control Corelet

ARL

- Translating a truth table into a fully connected Corelet
- No learning – determined the neuron parameters and framework by hand
- Focus: learn how to correctly utilize the IBM provided Matlab functions used to set up the input and output connections, crossbar, and neuron parameters
- Truth Table:
  - 1 represents the sonar value is below a user defined value/ object is close
  - 0 represents the sonar value is above a user defined value

Example When Threshold = 25in			
Sonar Range (Inches)			Corresponding Motor Direction
Left	Center	Right	
41	24	22	Left
15	23	30	Right
35	78	29	Forward

1 represents when a sonar sensor receives a reading below a specified range.
0 represents when a sonar sensor does not receive a reading below a specified range.
F = Forward
L = Left
R = Right
Rev = Reverse
Order of Priority: F --> L --> R

Left	Center	Right	Output
0	0	0	F
0	0	1	F/L
0	1	0	L/R
0	1	1	L
1	0	0	F/R
1	0	1	F
1	1	0	R
1	1	1	Rev

11

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

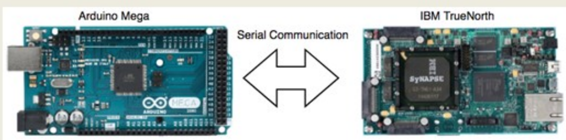
Approved for public release; distribution is unlimited.

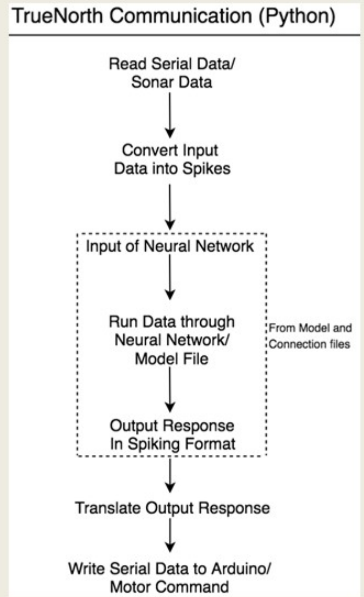
U.S. ARMY RDECOM

Communication Between Arduino and TrueNorth

ARL

- Physically connected using USB
- TrueNorth has Ubuntu on it
- Import model and connection files created by the Corelet onto TrueNorth
- Python script runs the model and connection files on TrueNorth, and reads and writes serial data between the Arduino and TrueNorth
- Python script utilizes multiprocessing by splitting up the processes of reading data, running the Corelet, and writing the data





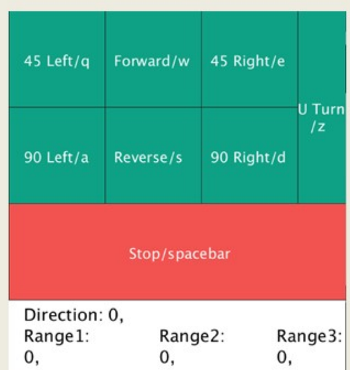
12

U.S. ARMY RDECOM

Collecting Training Data

ARL

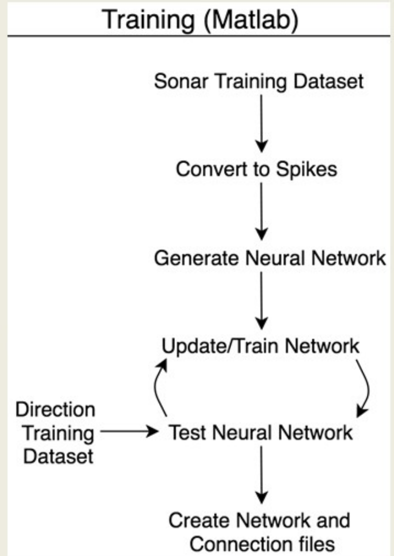
- Supervised Learning - mapping 3 sonar values to motor control commands
- Process: Capturing and writing direction and sonar values to a text file while manually driving the robot around an obstacle course
- Script and GUI written in Processing, which controls the robot, captures, and shows the direction and sonar values in real time
- Processing and Robot connected though Bluetooth Communication
- Amount of data points dependent on sonar sampling rate
- Limitation: only as good as the driver and consistency



13

Creating Trained CNNs

- Input: Sonar and Direction training datasets
- Output: Network and Connection files
- Process of updating/training the neuron parameters and structure of the neural network using techniques, such as Backpropagation or EEDN learning (Energy Efficient Deep Neuromorphic Networks)
- The created network and connection files are imported onto TrueNorth and tested using the TrueNorth Communication Python script



What Went Wrong

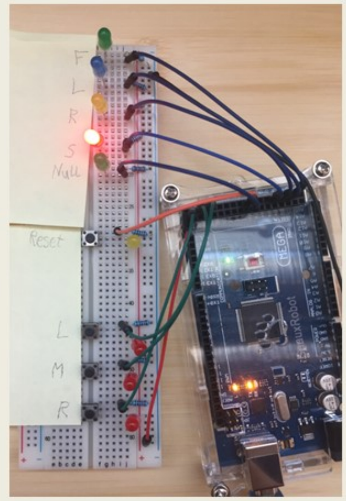
- Original idea: Design a robot that drives autonomously around an obstacle course using Neuromorphic Hardware and LIDAR unit stripped from a Neato XV-11 vacuum cleaner
- LIDAR unit's photodiode broke which caused a set back to sonar
- Limitations with serial data transfer and corruption bits
- IBM TrueNorth issues with open MPI and libraries
- Timing issues with TrueNorth and Arduino

https://en.wikipedia.org/wiki/Neato_Robotics#/media/File:Neato_XV-11.jpg

https://www.seeedstudio.com/RPLIDAR-360-degree-Laser-Scanner-Development-Kit-p-1823.html

Current Progress

- Completed
  - ✓ Training robot and Real Data collection
  - ✓ Hardware and electronics aspects finished
  - ✓ Control Corelet
  - ✓ Communication TrueNorth Python script
  - ✓ Control Corelet Test with Buttons, LEDs, and TrueNorth – truth table Corelet created and successfully implemented on TrueNorth



Needs Work

- Close to being completed
  - Intermediate steps between TrueNorth Python and startup scripts
  - Demo of Collision Avoidance Robot with Control Corelet
- Needs Work/Passing off to teammate Elizabeth
  - Training networks
  - Testing and verification

UNCLASSIFIED

Tests and Results

- Due to what went wrong, no data has been collected.
- Tests for data and results:
  - Performance Metrics:
    - Accuracy of the trained neural network
    - Power consumed by the TrueNorth (wattage and energy)
    - Speed of the neural network (how long it takes to obtain output response)
    - Temperature of the chip
  - How Performance Metrics are affected by:
    - Preprocessing input data
    - Using different spiking formats
    - Complexity of the network
    - Training
  - Compare against similar applications

18

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

What's Next? and Future Applications

- What's next for my project?
  - Expand to different or mix of hardware (e.g., phones, cameras, sensors, LIDAR, touch screen)
  - Apply different learning methods (e.g., supervised, unsupervised, online, offline, reinforcement, genetic algorithms)
  - Apply different architectures (e.g., TrueNorth, MrDANNA, DANNA)
- Future/Different Neuromorphic Applications
  - Autonomously driving - trail navigation, object avoidance, following robot
  - Image recognition – classifiers, phone application for determining objects, facial detection
  - Stability – balancing objects, helicopter, quadcopter, and camera stabilization

https://www.seeedstudio.com/RPLIDAR-A2-The-Thinest-LIDAR-p-2687.html

https://commons.wikimedia.org/wiki/File:WMCH_Drone.jpg

19

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Frequently Asked Questions

- **Why use TrueNorth or Neuromorphic Computing Architectures instead of a small computer (e.g., Raspberry Pi)?**
  - Neuromorphic Computing is NOT a replacement but an alternative to tradition computing
  - SWP – Size, Weight, and Power
  - Raspberry Pi 3 consumes ~1 Watt idle, TrueNorth consumes ~100mW or less depending on the network
  - Prospective solution Memristor and CMOS application specific chips consuming ~1 mW or less depending on the network
  - Application specific chips – chips dedicated to do one job/process (e.g., autonomous driving, stability, image recognition)

- **This already exists. What makes this different?**
  - University of California, Irvine's Jeff Krichmar and research group has developed this type of application.
  - Differences: hardware, learning algorithms, and application

20

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Conclusion

- **Neuromorphic computing is one way of going beyond Moore's Law.**
- **Main Idea of Project: Merging Neuromorphic Computing and robotics. As well, merging theory and simulation with real world applications.**
- **Overall Goal: Design a platform for testing Neuromorphic hardware and concepts.**
- **Short Term Goal: Design Collision Avoidance Robot using Neuromorphic Hardware.**

21

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

Bibliography

Dawson, Bryan, Jamie Infantolino, Manuel M. Vindiola, and John V. Monaco. “Tightly Integrated Deep Learning and Symbolic Programming on a Single Neuromorphic Chip.” 2017. Print

Hwu, Tiffany, Jacob Isbell, Nicolas Oros, and Jeffrey Krichmar. "A Self-Driving Robot Using Deep Convolutional Neural Networks on Neuromorphic Hardware." *A Self-Driving Robot Using Deep Convolutional Neural Networks on Neuromorphic Hardware*. N.p., 04 Nov. 2016. Web. 07 Aug. 2017.

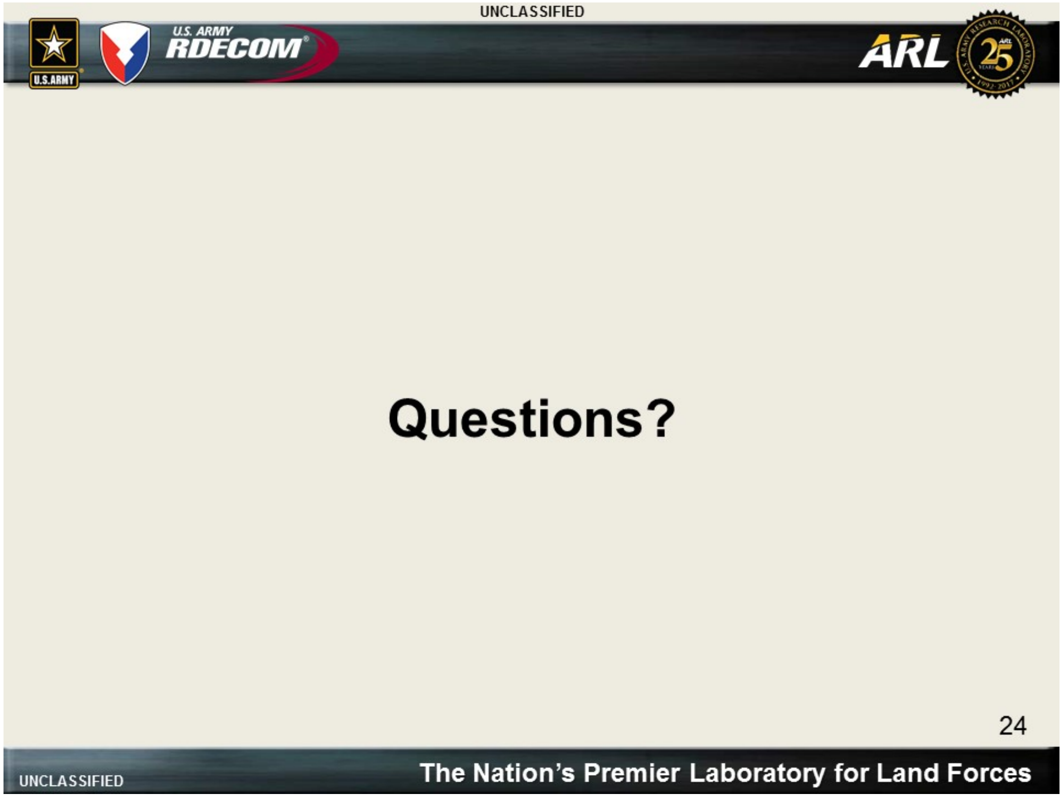
Mazur. "A Step by Step Backpropagation Example." *Matt Mazur*. N.p., 23 July 2017. Web. 07 Aug. 2017.

Nielsen, Michael A. "Neural Networks and Deep Learning." *Neural networks and deep learning*. Determination Press, 01 Jan. 1970. Web. 09 Aug. 2017.

UNCLASSIFIED

Acknowledgements

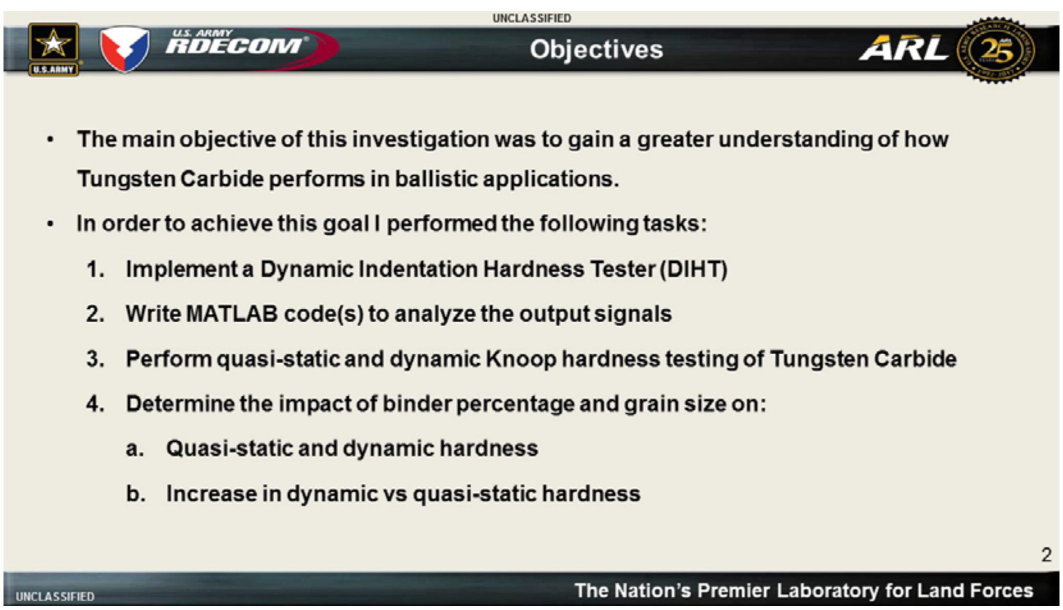
- I wish to acknowledge Manny Vindiola for being my mentor.
- Bryan Dawson, Jamie Infantolino, and Kevin Corder for helping with TrueNorth and various issues.
- Michael Barton, Ginny To, and ORISE for setting me up with this opportunity with ARL at APG.
- Kevin Wright and Andy Durkee for technical support.
- Elizabeth Klier helping design the neuromorphic aspects of the project.



Approved for public release; distribution is unlimited.

Luke A Hanner

I am a rising pre-junior at Drexel University in Philadelphia, Pennsylvania, where I am studying materials science and engineering. Last summer I participated in Drexel's Students Tackling Advanced Research (STAR) program, where I researched MAX Phase ternary carbides for 10 weeks. This is my first co-op experience and I began work on this project in May. In the future I hope to earn my master's degree and, possibly, a doctorate in materials science.



What is Tungsten Carbide?

- Tungsten Carbide (WC) is a cemented ceramic material composed of a hard WC main phase and a softer, more ductile metal binder phase.
  - The conventional binder is cobalt.
- WC is used in the M993 and M995 armor-piercing rounds (amongst others).
- WC is also used in industrial machining tools and applications.

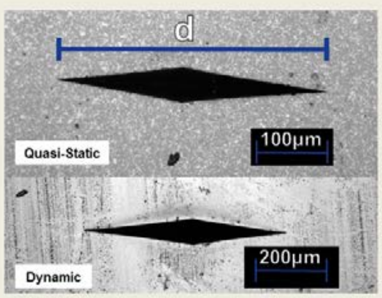
M993 7.62mm Armor-piercing cartridge

Globalsecurity.org

3

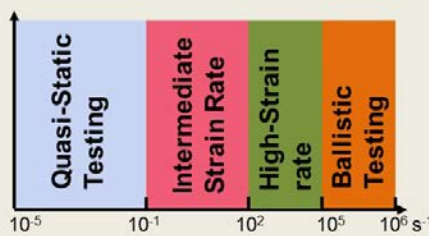
Indentation Hardness Testing

Indentation hardness is the measure of a material's resistance to plastic deformation.



Quasi-Static Knoop Hardness (HK):
- 2kgf, 5kgf, and 10kgf loads
- 10^{-5} s^{-1} strain rates

Dynamic Knoop Hardness (DHK):
- 30kgf - 110kgf load range
- 10^{3} s^{-1} strain rates



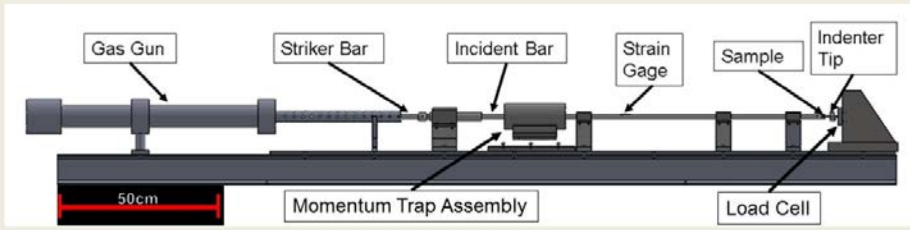
4

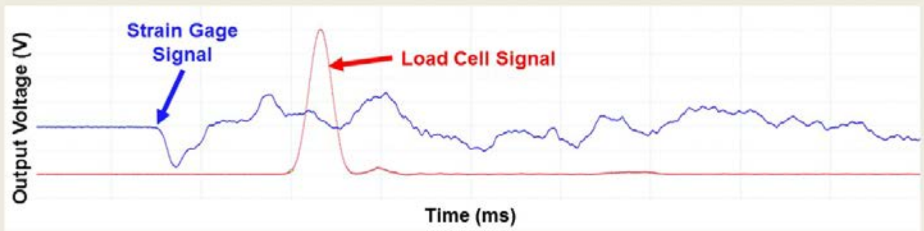
UNCLASSIFIED

U.S. ARMY RDECOM

Dynamic Indentation Hardness Tester

ARL





5

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

MATLAB Code

ARL

Analyzes raw strain gage and load cell signals to extract load and strain rate:

$$\varepsilon_i(t) = \frac{Bridge\ Factor \times Strain\ Gage\ Signal}{Excitation\ Voltage \times Gage\ Factor \times Amplifier\ Gain} \quad \text{(Eq. 1)}$$

$$\dot{\varepsilon}(t) = \frac{V}{d} = \frac{-C_0}{d}\varepsilon_i(t) \quad \text{(Eq. 2)}$$

$$P = Load\ Cell\ Signal \times Charge\ Amplifier \quad \text{(Eq. 3)}$$

$$HK = 0.014229 \times \frac{P}{d^2} \quad \text{(Eq. 4)}$$

ε = Strain
$\dot{\varepsilon}$ = Strain Rate (s^{-1})
d = Indent Diagonal (mm)
V = Indenter Velocity (m/s)
C_0 = Wave Speed in Bar (m/s)
P = Load (N)

6

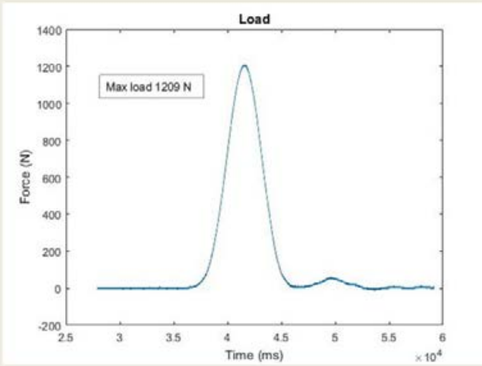
UNCLASSIFIED

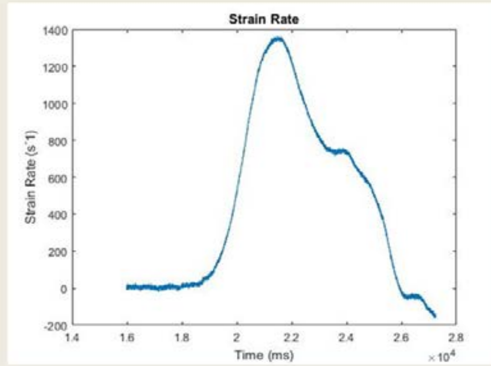
The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Analyzing Signals

ARL





7

The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

WC Compositions Tested

ARL

- Seven different compositions tested
- Variations:
  - Binder material
  - Binder percentage
  - Grain size
- Commercial compositions used as benchmarks for future investigations of ARL systems

Material	Binder	Wt% Binder	Grain Size (µm)
Cercom* WC Binderless	N/A	≈0%	0.4
Kennametal S105	Co	10%	0.6
MPI† 15	Co	15%	1.7
MPI† 20	Co	20%	1.1
MPI† 25	Co	25%	1.5
Kennametal KFY	$CrNi_3$	10%	0.6
Kennametal BFY	$CrNi_3$	10%	0.9

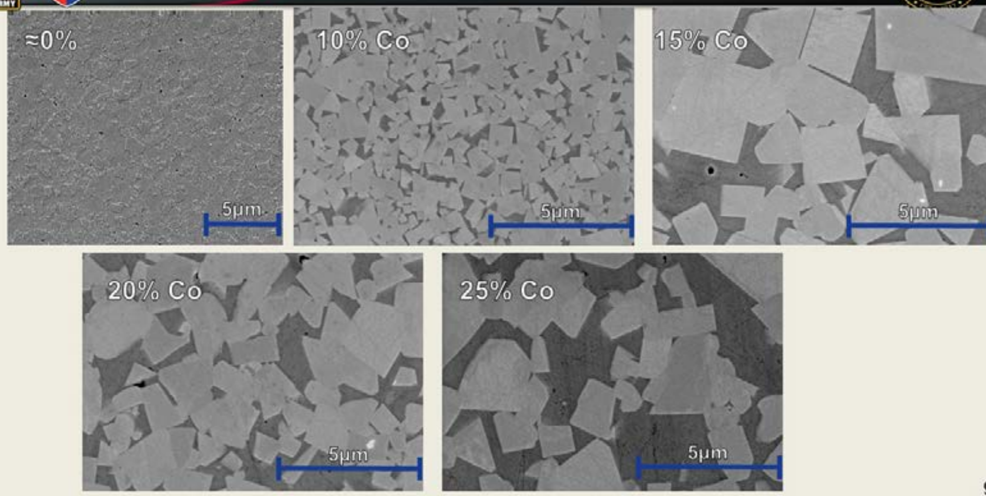
*Now part of CoorsTek, Golden, CO; †Materials Processing Inc.

8

The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM — ARL

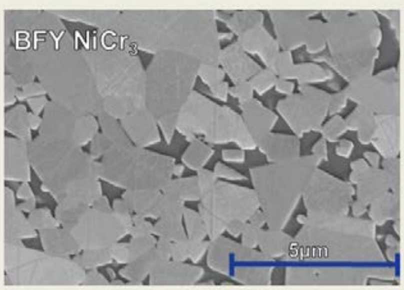
WC-Cobalt Microstructures

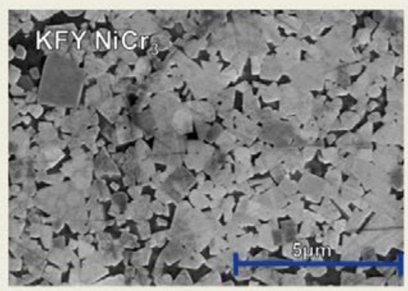


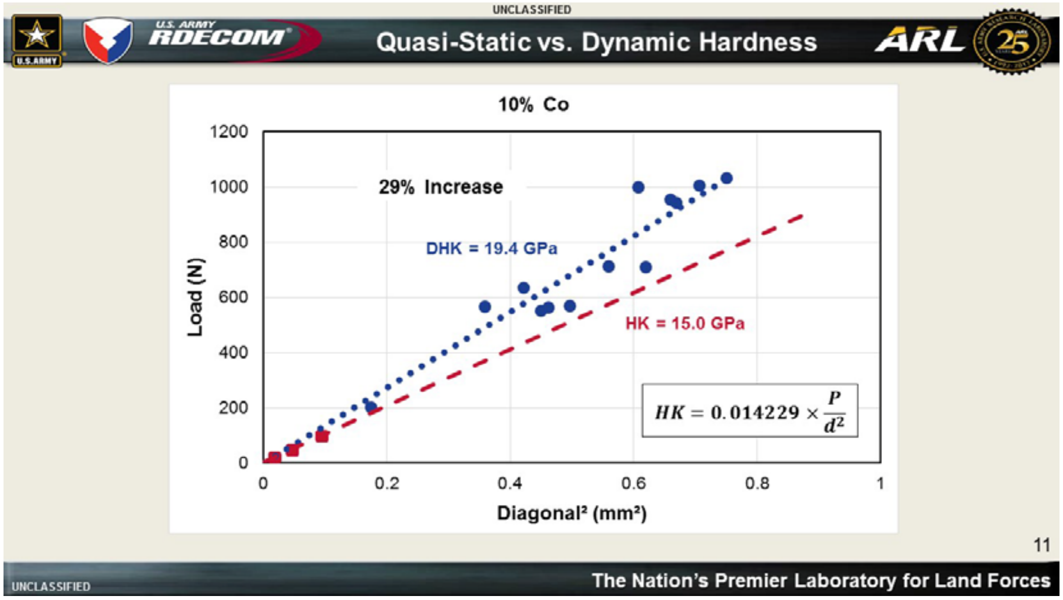
U.S. ARMY RDECOM — ARL

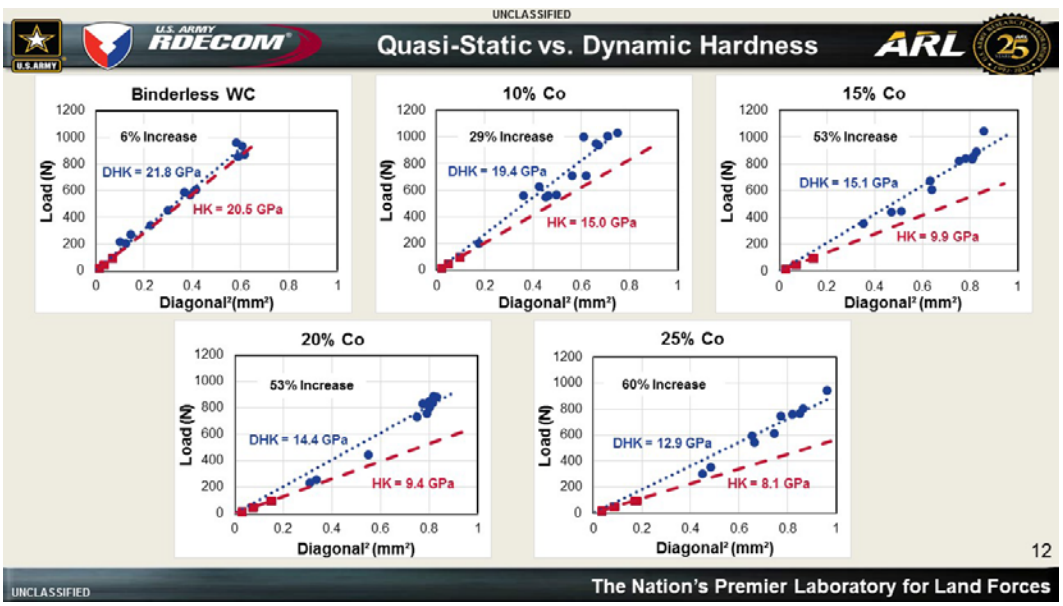
Cobalt-Free WC Microstructures

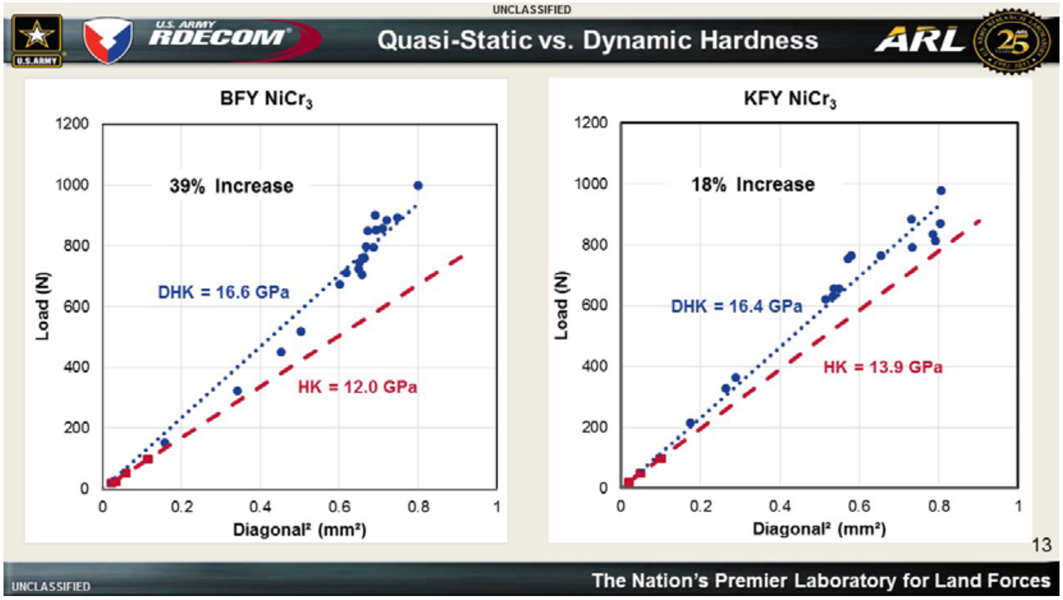
- **$CrNi_3$ binders forgo the traditional Co, which is being phased out due to health problems and economic viability.**
- **Other Ni and Fe based binders are also being researched as alternatives.**






UNCLASSIFIED
U.S. ARMY RDECOM
Quasi-Static vs. Dynamic Hardness
ARL
10% Co
29% Increase
DHK = 19.4 GPa
HK = 15.0 GPa
$HK = 0.014229 \times \frac{P}{d^2}$
Load (N)
Diagonal² (mm²)
11
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY RDECOM
Quasi-Static vs. Dynamic Hardness
ARL
Binderless WC
6% Increase
DHK = 21.8 GPa
HK = 20.5 GPa
10% Co
29% Increase
DHK = 19.4 GPa
HK = 15.0 GPa
15% Co
53% Increase
DHK = 15.1 GPa
HK = 9.9 GPa
20% Co
53% Increase
DHK = 14.4 GPa
HK = 9.4 GPa
25% Co
60% Increase
DHK = 12.9 GPa
HK = 8.1 GPa
Load (N)
Diagonal² (mm²)
12
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces



UNCLASSIFIED

U.S. ARMY RDECOM

Results from Indentation Testing

ARL

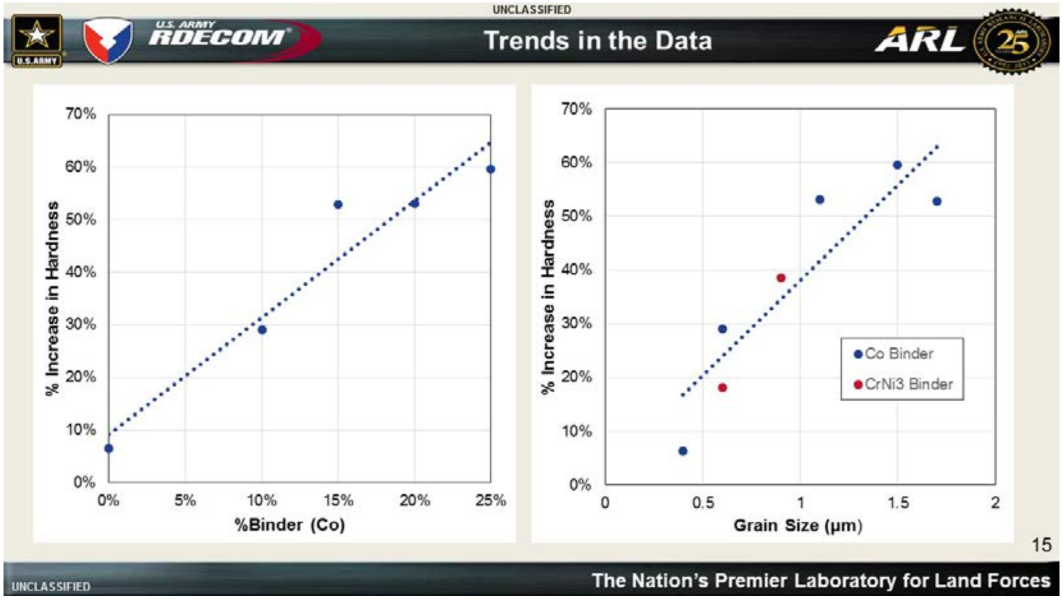
NAME	Binder	Wt% Binder	Grain Size (μm)	Average HK (GPa)	Average DHK (GPa)	% Increase
Cercom* WC Binderless	N/A	≈0%	0.4	20.5	21.8	6%
Kennametal S105	Co	10%	0.6	15.0	19.4	29%
MPI† 15	Co	15%	1.7	9.9	15.1	53%
MPI† 20	Co	20%	1.1	9.4	14.4	53%
MPI† 25	Co	25%	1.5	8.1	12.9	60%
Kennametal KFY	$CrNi_3$	10%	0.6	13.9	16.4	18%
Kennametal BFY	$CrNi_3$	10%	0.9	12.0	16.6	39%

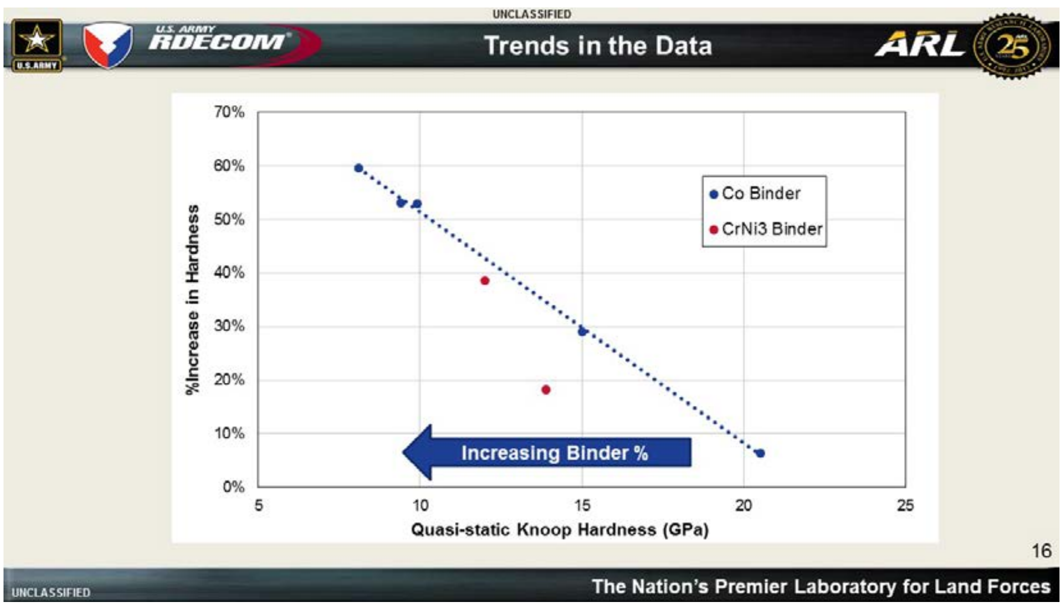
*Now part of CoorsTek, Golden, CO; †Materials Processing Inc

14

UNCLASSIFIED

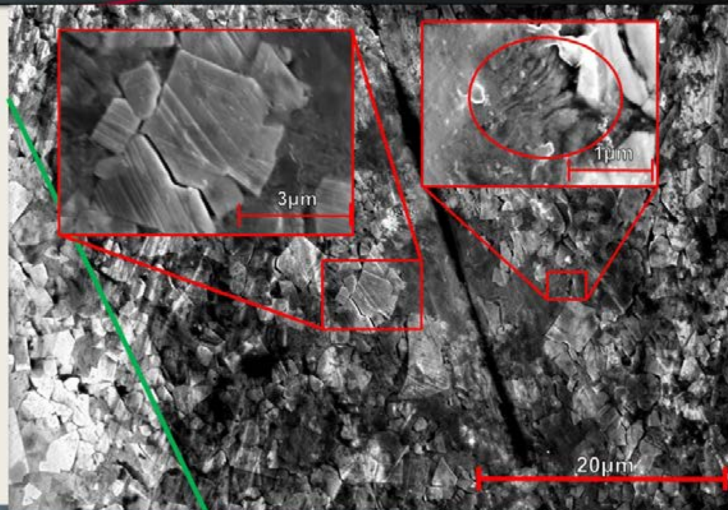
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Trends in the Data
ARL
% Increase in Hardness
%Binder (Co)
0%
5%
10%
15%
20%
25%
70%
60%
50%
40%
30%
20%
10%
Grain Size (µm)
0
0.5
1
1.5
2
Co Binder
CrNi3 Binder
15
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Trends in the Data
ARL
%Increase in Hardness
70%
60%
50%
40%
30%
20%
10%
0%
Co Binder
CrNi3 Binder
Increasing Binder %
5
10
15
20
25
Quasi-static Knoop Hardness (GPa)
16
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Deformation Mechanisms



17

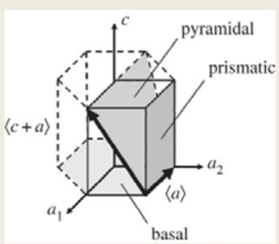
UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

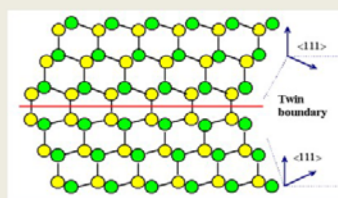
UNCLASSIFIED

Twinning in Cobalt Binder

- **Cobalt has an HCP crystal structure with a low stacking-fault energy (SFE) and a limited number of slip systems.**
- **HCP structures with low SFE are highly susceptible to forming twins at high-strain rates.**
- **Twin boundaries act as barriers to dislocation motion, increasing hardness.**



Hazell, P. J., et al.



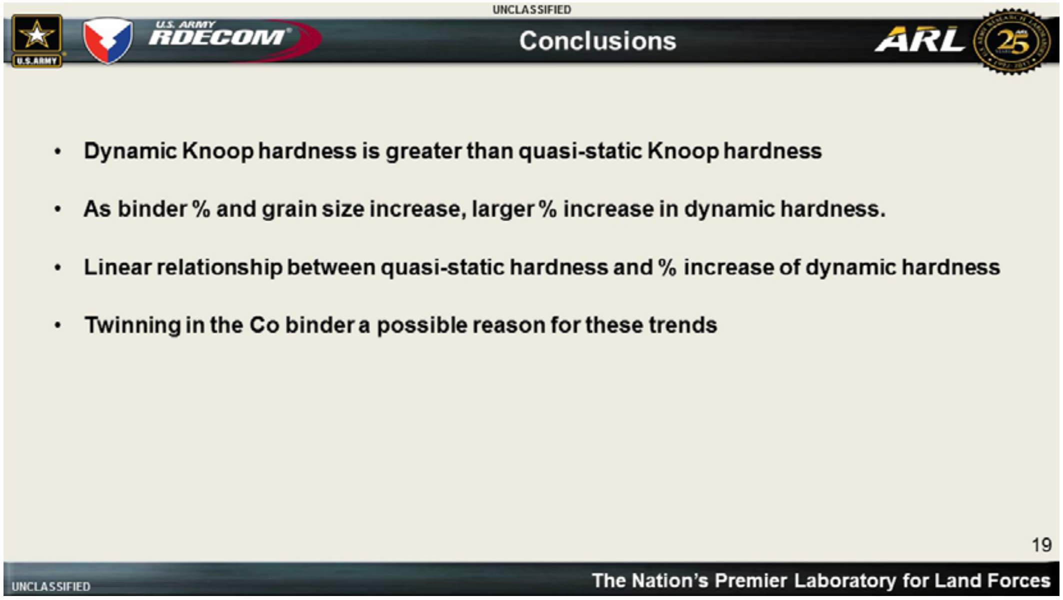
https://www.tf.uni-kiel.de/matwis/amat/def_en/kap_7/backbone/r7_1_1.html

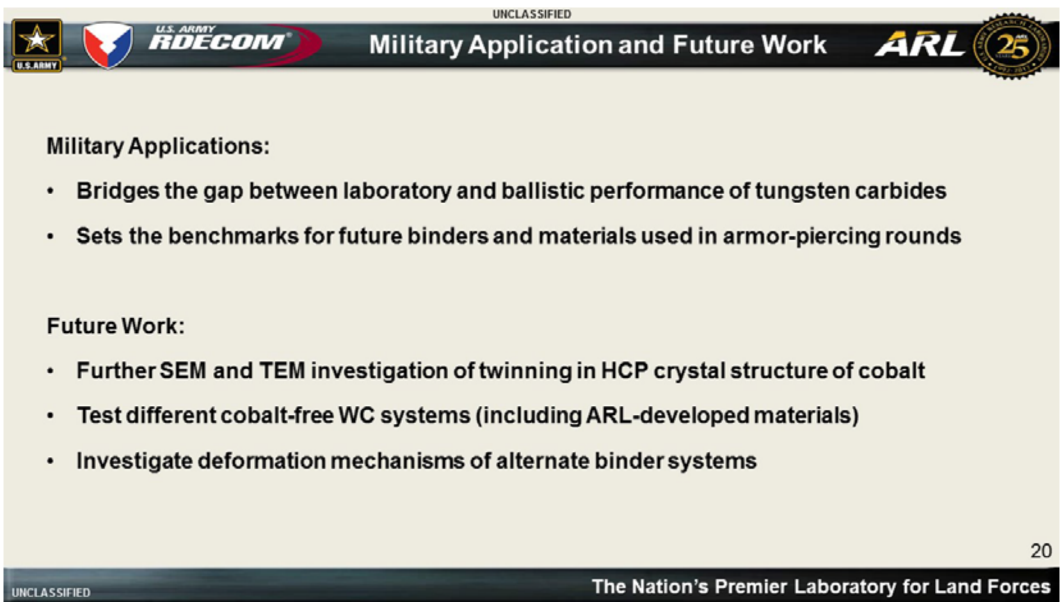
18

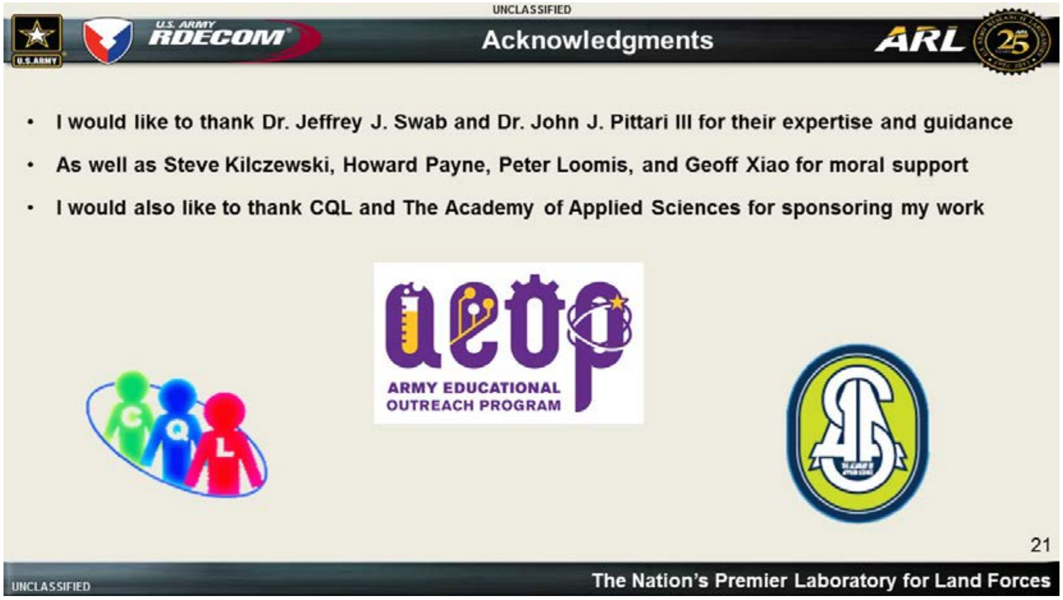
UNCLASSIFIED

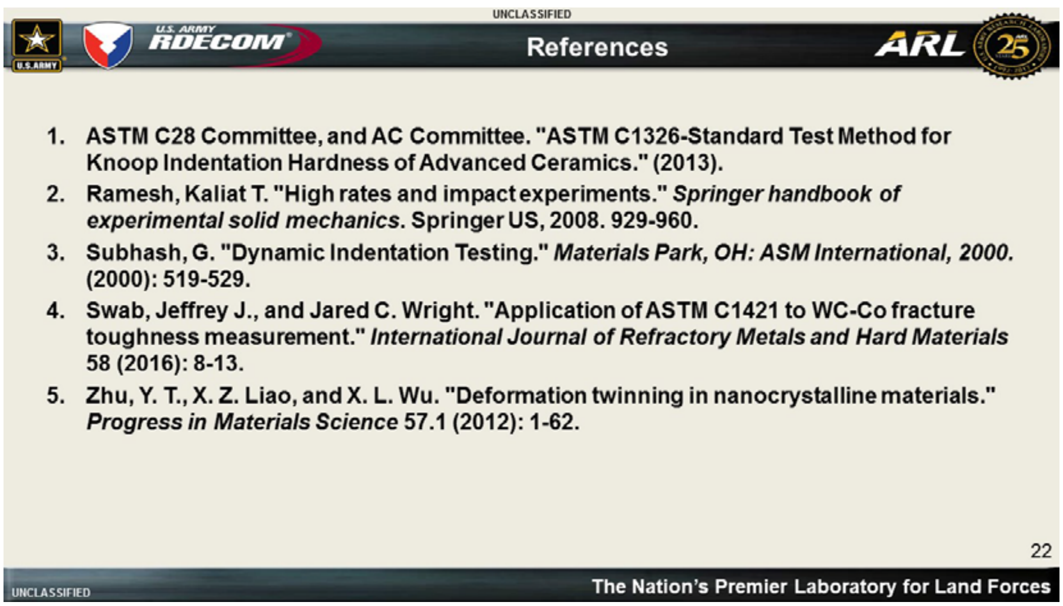
The Nation's Premier Laboratory for Land Forces

Approved for public release; distribution is unlimited.


UNCLASSIFIED
U.S. ARMY
RDECOM
Conclusions
ARL
25
• Dynamic Knoop hardness is greater than quasi-static Knoop hardness
• As binder % and grain size increase, larger % increase in dynamic hardness.
• Linear relationship between quasi-static hardness and % increase of dynamic hardness
• Twinning in the Co binder a possible reason for these trends
19
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Military Application and Future Work
ARL
25
Military Applications:
• Bridges the gap between laboratory and ballistic performance of tungsten carbides
• Sets the benchmarks for future binders and materials used in armor-piercing rounds
Future Work:
• Further SEM and TEM investigation of twinning in HCP crystal structure of cobalt
• Test different cobalt-free WC systems (including ARL-developed materials)
• Investigate deformation mechanisms of alternate binder systems
20
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Acknowledgments
ARL
• I would like to thank Dr. Jeffrey J. Swab and Dr. John J. Pittari III for their expertise and guidance
• As well as Steve Kilczewski, Howard Payne, Peter Loomis, and Geoff Xiao for moral support
• I would also like to thank CQL and The Academy of Applied Sciences for sponsoring my work
aeop
ARMY EDUCATIONAL OUTREACH PROGRAM
C Q L
21
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

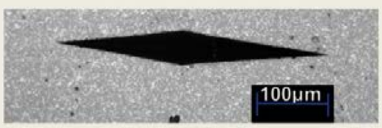

UNCLASSIFIED
U.S. ARMY
RDECOM
References
ARL
1. ASTM C28 Committee, and AC Committee. "ASTM C1326-Standard Test Method for Knoop Indentation Hardness of Advanced Ceramics." (2013).
2. Ramesh, Kaliat T. "High rates and impact experiments." Springer handbook of experimental solid mechanics. Springer US, 2008. 929-960.
3. Subhash, G. "Dynamic Indentation Testing." Materials Park, OH: ASM International, 2000. (2000): 519-529.
4. Swab, Jeffrey J., and Jared C. Wright. "Application of ASTM C1421 to WC-Co fracture toughness measurement." International Journal of Refractory Metals and Hard Materials 58 (2016): 8-13.
5. Zhu, Y. T., X. Z. Liao, and X. L. Wu. "Deformation twinning in nanocrystalline materials." Progress in Materials Science 57.1 (2012): 1-62.
22
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

Bio and Questions?

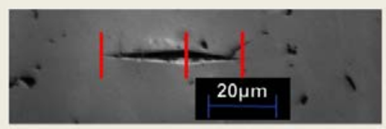
- From Bradenton, FL
- Rising pre-junior at Drexel University in materials science and engineering
- Captain of Drexel Men's Varsity Swimming and Diving
- I enjoy cooking and golf in my spare time

Clipartpanda.com

Bad Indents



Good Indent



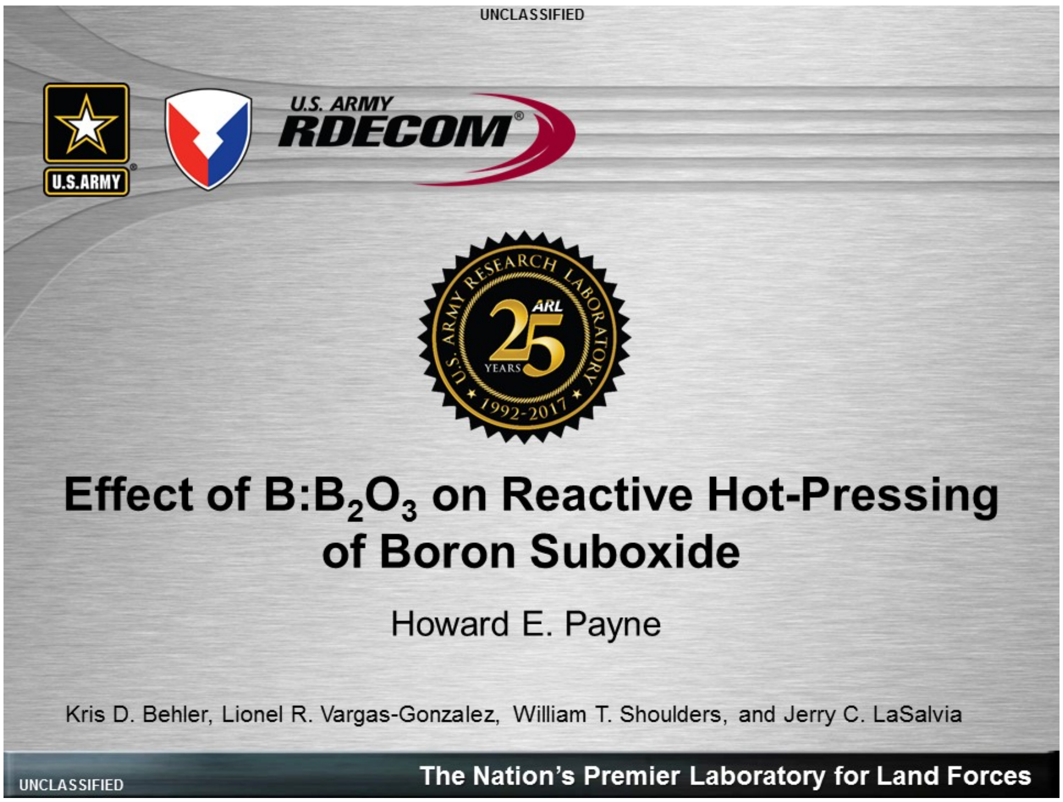
Asymmetric

Double Indent

Heavy Spalling

Howard Payne

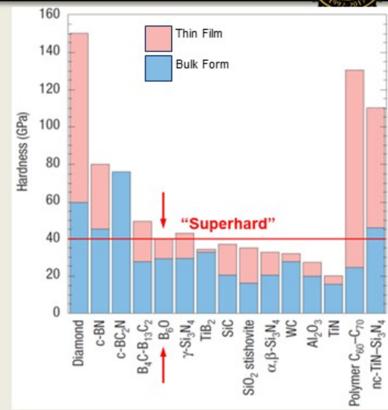
I am a third-year student at the Pennsylvania State University (Penn State), studying material science and engineering. Since my freshman year I have been working in a laboratory on campus, where we focused on binary and tertiary lead-based piezoelectrics under the advisement of Dr Messing. I will be returning to the CTMB branch in WMRD next year for a spring co-op to continue my research. After graduation, I am thinking of possibly going to graduate school to pursue a doctorate in materials or ceramics.



UNCLASSIFIED

BLUF

- Boron suboxide is an attractive armor ceramic
- Current process is very costly → synthesis powder then densify
- Combining synthesis and densification into a single-step ("Reactive Hot-Pressing")
- Has the potential to decrease the cost of manufacturing dense bodies
- Discovered the importance of excess boron oxide on densification, phase purity, hardness, and hot-pressing issues



2

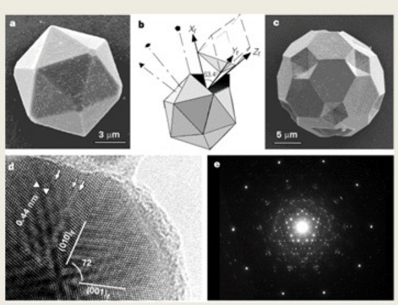
UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

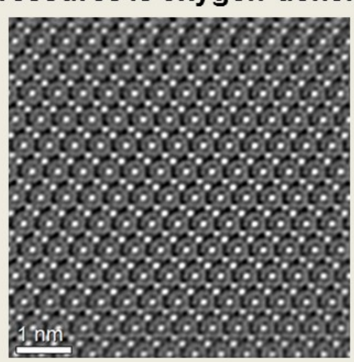
UNCLASSIFIED

Background

- Armor applications
- High Hardness, Low density
- Current processing route is complex
- Boron suboxide synthesized at low pressures is oxygen-deficient … B_6O_{1-x}



nature.com



Courtesy of Dr. Behler

3

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

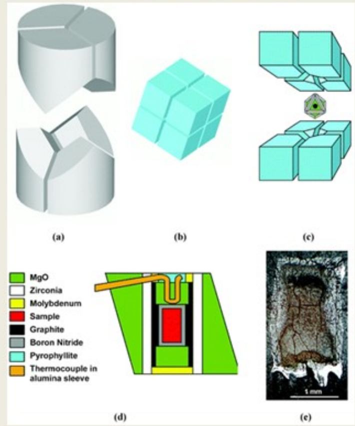
U.S. ARMY RDECOM

Production Methods for Dense Bodies

ARL

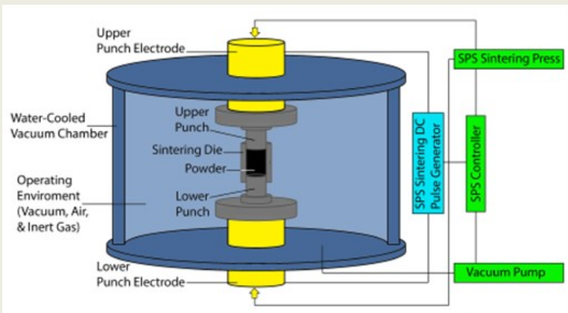
- **SPS (Spark Plasma Sintering)**
- **Multi-anvil**
- **Hot-pressing with B_6O powder**

Multi-anvil



rsc.org

SPS



calnanocorp.com

4

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Benefits of Reactive Hot-Pressing

ARL

- **Eliminate independent powder synthesis steps**
- **Might be able to lower the densification temperature**
- **Enhance industrial viability**
  - **Two less furnace steps needed**
  - **Less amorphous boron needed, highest cost component**
- **In-house production at ARL**

5

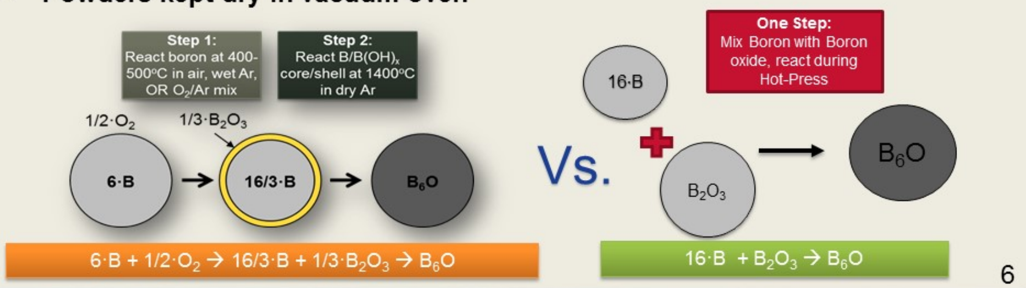
UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

Powder Processing

$$16B + B_2O_3 \rightarrow 3B_6O_{1-x}$$

- **Powder**
  - **B_2O_3: 99.9% Noah Technologies**
  - **B(amorphous): 92.1-96% SB Boron Corporation**
- **Massed in ratios between 0-24 mass % excess Oxygen (O) in reaction**
- **Mixed on Lab Ram acoustic mixer for ~5 min**
- **Powders kept dry in vacuum oven**

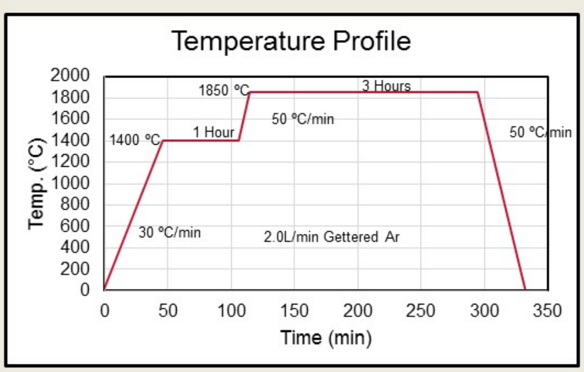
Powder (Mass % O)	B_2O_3 (g)	B (g)
Stoichiometric	3.1565	7.8440
6.8% excess O	4.2422	6.7581
10.2% excess O	2.8217	2.1786
12.3% excess O	6.9714	8.0276
23.7% excess O	9.4668	5.5341



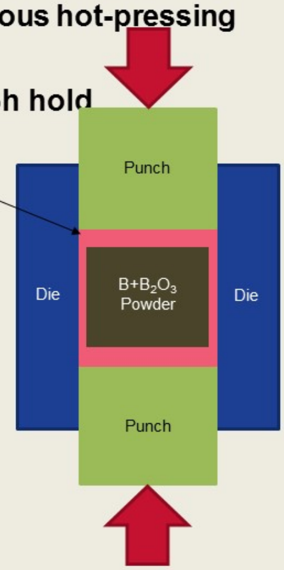
6

Reactive Hot-Pressing

- **Followed typical densification profile as previous hot-pressing**
- **Tested 0-24 mass % excess O**
- **6100 lbf on 1-inch Die (~53.6 MPa) applied at 3h hold**
- **BN coating on graphite die**



Boron Nitride



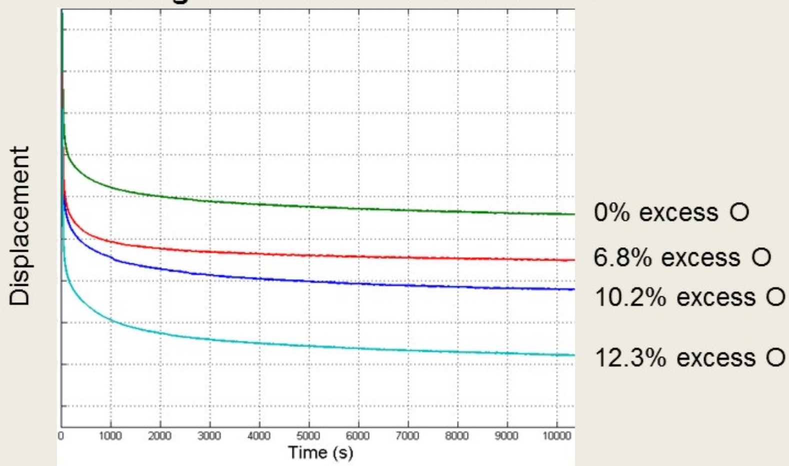
7

U.S. ARMY RDECOM

Densification Behavior

ARL

- Monitored the ram displacement through (Linear Variable Displacement Transducer) LVDT
  - Showing densification and volatilization



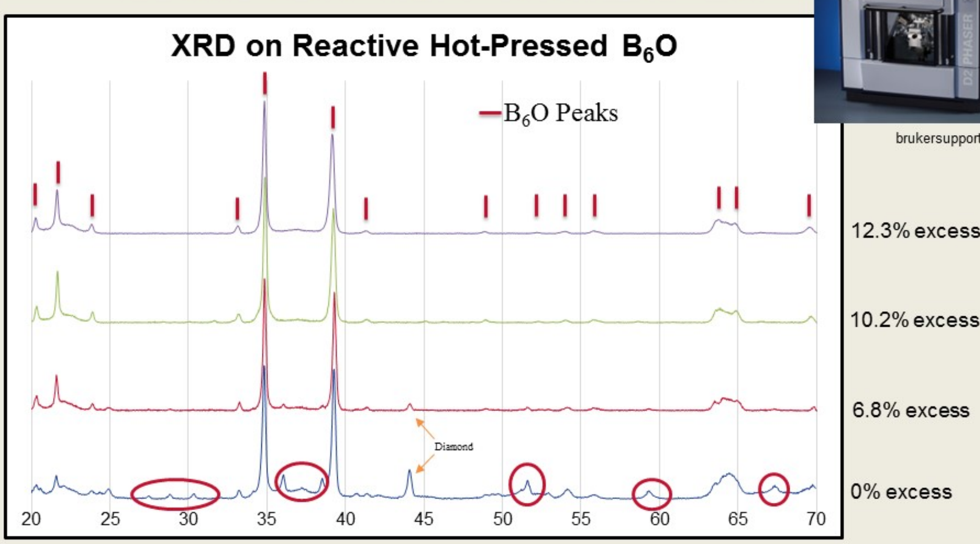
8

U.S. ARMY RDECOM

XRD Phase Analysis

ARL

- Phase identification with Bruker XRD and EVA software



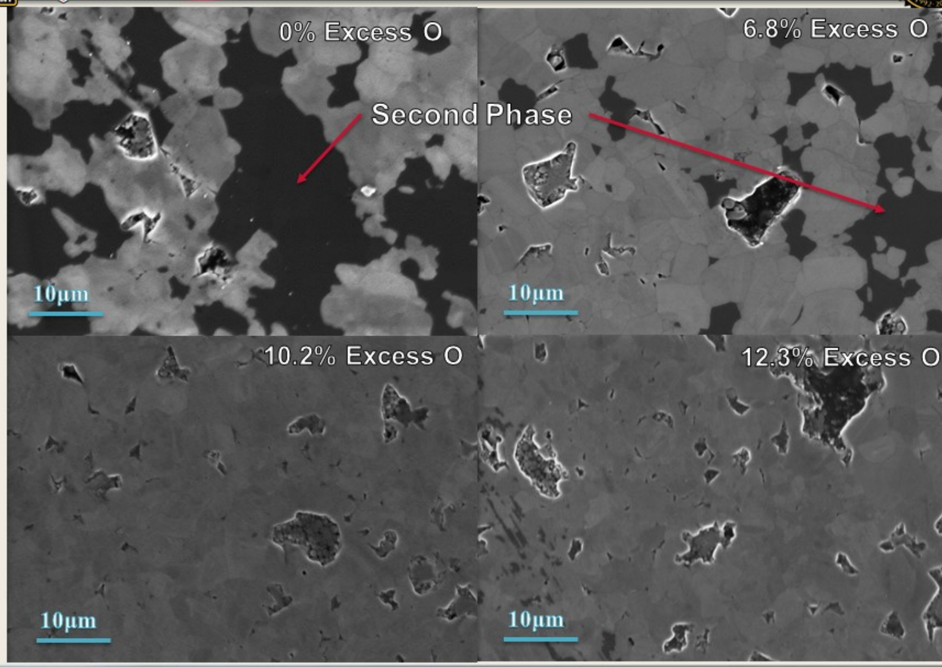
brukersupport.com

9

Approved for public release; distribution is unlimited.

U.S. ARMY RDECOM — ARL

Microstructures



10

U.S. ARMY RDECOM — ARL

Hardness/Densities

- **Hardness: Knoop with 2-kg load, manual indenter**
- **Density: He pycnometer**

Sample	HK (GPa)	Density (g/cc)
Stoichiometric	18.5 ± 0.4	2.462
6.8% excess O	19.8 ± 0.8	2.556
10.2% excess O	18.4 ± 0.6	2.546
12.3% excess O	14.9 ± 1.7	2.490
Coorstek – HIP Courtesy of Dr. Behler	18.9 ± 0.5	2.56

$$HK = 0.014229\frac{P}{d^2}$$

P: Load (N)
D: Length on Long Diagonal (mm)

11

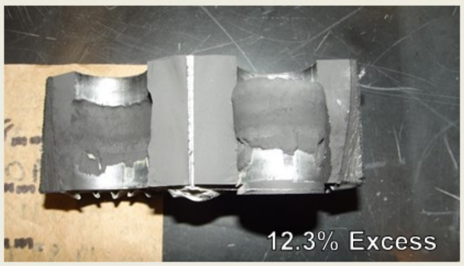
UNCLASSIFIED

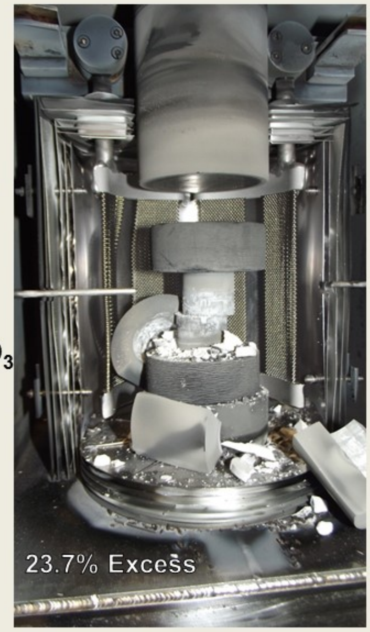
U.S. ARMY RDECOM

Difficulties

ARL

- Reaction of powders with die
  - Learning better methods of coating die with BN
- Hygroscopic powders, need to keep powders in glove box
- Die failure
  - Affected 23.7% test
  - Shows issues with too much B_2O_3





12

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Conclusion/Future Research

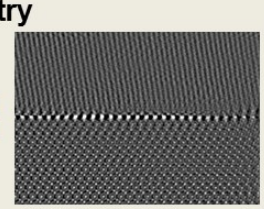
ARL

- For reactive hot-pressing a composition of 6.8-10.2 mass% excess O should be used
  - XRD Data
  - Elimination of 2nd phase in microstructure
  - Highest hardness and density values achieved
- Additives effect on Boron Suboxide
  - Hardness, fracture toughness, density
  - Will the thermodynamics of reaction have any effect?
  - Possible: yttria, silica, mullite, rare earths, etc.
- Redo study with better controlled powder chemistry


B


B_2O_3


Y_2O_3


Courtesy of Dr. Behler

13

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

Approved for public release; distribution is unlimited.

UNCLASSIFIED

Acknowledgements

- I would like to thank both my official and unofficial mentors Dr. Lionel Vargas-Gonzalez, Dr. Kris Behler, and Dr. William Shoulders.
- I am also thankful to Dr. Jeffery Swab, Academy of Applied Science, and the Qualified College Leaders program for the opportunity to be at ARL this summer.
- For moral support: Dr. Jerry LaSalvia, Mr. Steve Kilczewski, Mr. Luke Hanner, and Mr. William Costakis.

ARMY EDUCATIONAL OUTREACH PROGRAM

PennState

14

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Citation

H. Bolmgren, Lundström T., S. Okada, *AIP Conference Proceedings* 1991.

H.C.A. Hubert, L.A.J. Garvie, B. Devouard, P.R. Buseck, W.T. Petuskey, P.F. Mcmillan, *Chemistry of Materials* 1998, *10*, 153

H. Hubert, B. Devouard, *Letters to nature* 1998, *391*, 376.

15

UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

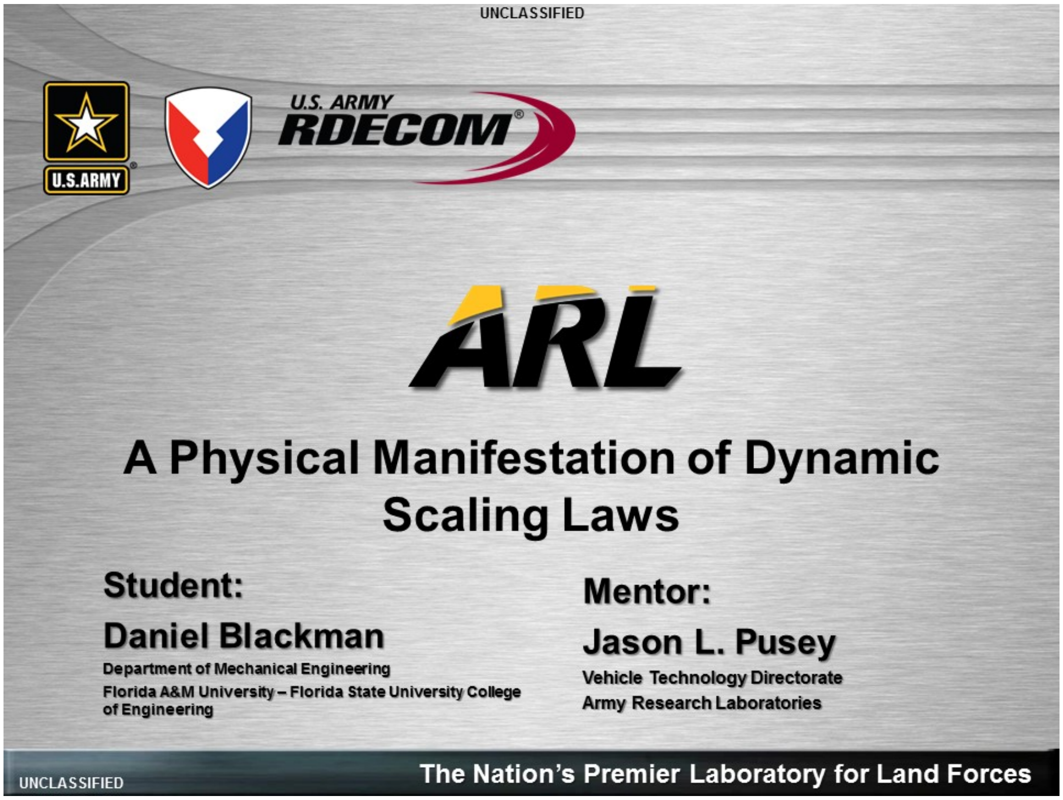
INTENTIONALLY LEFT BLANK.

Graduate Presentations

INTENTIONALLY LEFT BLANK.

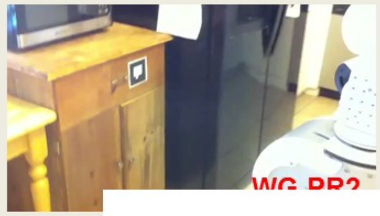
Daniel Blackman

Daniel Blackman is a third-year doctoral student in mechanical engineering at Florida State University under the direction of Dr Jonathan Clark. He received dual bachelor's degrees in biochemistry and physics from Edinboro University, and his master's degree in biomedical engineering from Cornell University. His past research experiences span organic chemistry, metallurgy, biophysics, biomechanics, and bio-inspired robotics. His current research focuses on this last area, specifically relating to the design, dynamics, and control of legged robotic systems. This summer, he focused on the challenges associated with designing these legged systems at different sizes while maintaining the dynamic capabilities required by the armed forces. After completing his doctorate in mechanical engineering, Daniel intends to pursue a medical degree and/or postdoctoral research in the fields of biomechatronic prosthetics and therapeutic exosuits.



Why Build It Bigger?

- Surface manipulation
  - Desks, doors, drawers, etc

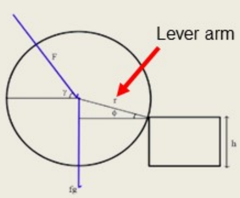


- Optempo Speeds
  - (operations tempo)

- Soldier accessibility

OPTEMPO (Operations Tempo)

- Wheels vs Legs



UNCLASSIFIED

Scaling Robotic Systems

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Background: Dynamic Scaling

TABLE II

SCALE FACTORS FOR SYSTEM VARIABLES OF DYNAMICAL, LEGGED MODELS

Parameter	Scale Factor	General Case	Constraint 1†	Constraint 2‡	Constraints 1† and 2‡
Length	α_l	α_L	α_L	α_L	α_L
Mass	α_m	$\alpha_F \alpha_L^{-1} \alpha_T^{2}$	α_F	$\alpha_L^{4} \alpha_T^{-2}$	α_L^{3}
Stiffness	α_k	$\alpha_F \alpha_L^{-1}$	$\alpha_F \alpha_L^{-1}$	$\alpha_L^{3} \alpha_T^{-2}$	α_L^{2}
Damping	α_b	$\alpha_F \alpha_L^{-1} \alpha_T$	$\alpha_F \alpha_L^{-1/2}$	$\alpha_L^{3} \alpha_T^{-1}$	$\alpha_L^{5/2}$
Frequency	α_ω	α_T^{-1}	$\alpha_L^{-1/2}$	α_T^{-1}	$\alpha_L^{-1/2}$
Gravity	α_g^{*}	$\alpha_L \alpha_T^{-2}$	1	$\alpha_L \alpha_T^{-2}$	1
Touch-Down Velocity	α_v	$\alpha_L \alpha_T^{-1}$	$\alpha_L^{1/2}$	$\alpha_L \alpha_T^{-1}$	$\alpha_L^{1/2}$
Touch-Down Heading	α_δ	1	1	1	1
Touch-Down Leg Angle	α_β	1	1	1	1

~~† Constraint 1: Gravity is scale independent ($\alpha_L = \alpha_T^{2}$).~~

~~‡ Constraint 2: Density is constant ($\alpha_m = \alpha_L^{3}$).~~

∗ The gravity scale factor is equivalent to the acceleration scale factor, though it is not specifically addressed herein.

Miller & Clark (2015)

- Robotic advantages
  - Material selection
  - Planetary constraints

Parameter	RHex	Scaled to Edubot*	Edubot*
Body Length (m)	0.51†	0.37	0.36
Leg Length (m)	0.16†	0.115	0.115
Mass (kg)	7.5†	3.2	3.2
Leg Stiffness (Nm^{-1})	1900†	1130	960
Speed (ms^{-1})	2.7‡	2.29	2.25
Stride Frequency (s^{-1})	4.2	4.95	5.25
Froude Number (–)	4.67	4.67	4.49
Strouhal Number (–)	4.02	4.02	3.86
Specific Resistance (–)	0.84‡	0.84	0.51

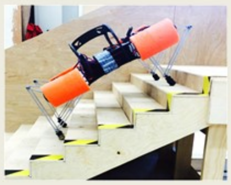
UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

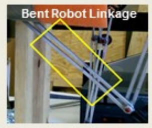
UNCLASSIFIED

Plan of Action

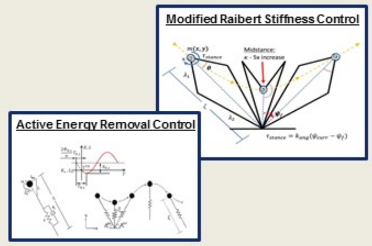
1. Design at the Scale of Interest



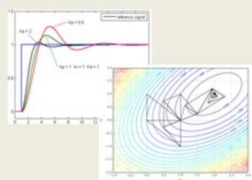
2. Scaling limitations



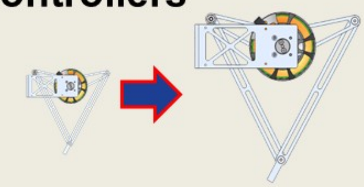
3. Controller Development



4. Controller and Physical Design Optimization



5. Dynamic Scaling of Controllers



UNCLASSIFIED

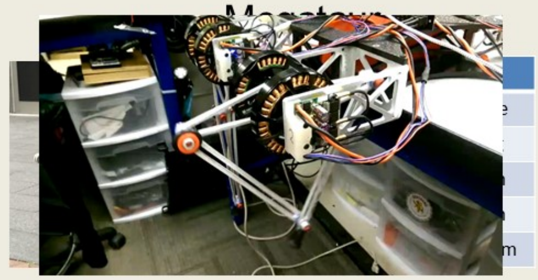
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

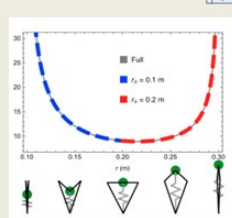
1. Design at Scale: Minitaur

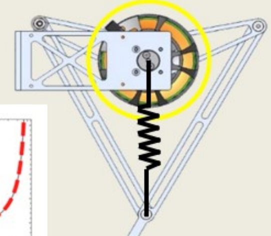
Minitaur

Physical Parameters	
Parameter	Value
Mass	5kg
Length	0.4m
Width	0.22m
Max Height	0.3m



- Unique direct-drive system (5-bar)
  - High speed regions
  - Localization of motor mass
  - Mechanical compliance





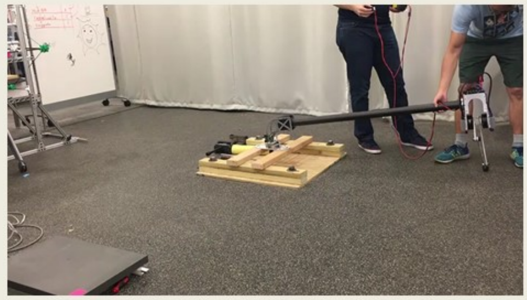
Kenneally and Koditschek (2015)

UNCLASSIFIED

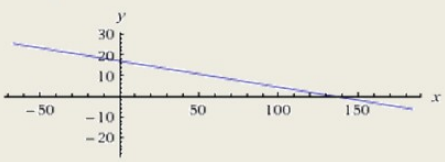
The Nation's Premier Laboratory for Land Forces

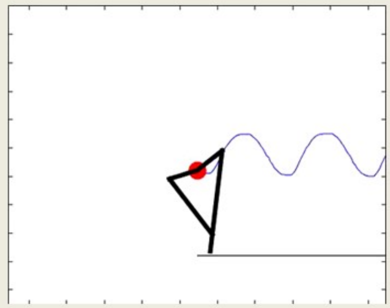
1. Design at Scale: Thumper

Thumper specs:
Upper limb: 0.15 m
Lower limb: 0.3 m
Total mass, without boom: 2.98 kg
Total mass, on boom: 3.467 kg
Boom length (Radius of rotation): 1.38 m
Boom offset + Height of pivot: 0.0758 + 0.22 = 0.2958 m



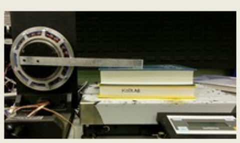
Motor specs: U10 plus
Motor (Torque) Constant Kt: 0.119 Nm/A
Motor Resistance Rm: 0.112 Ohm
Motor back emf constant Ke (same as torque constant): 0.119 V/(rads/s)
According to Avik, since the slope of the motor torque-velocity looks very low, we could neglect the effect of back emf. The curve is
Volt = (Rm/kt) *Torque + ke*speed; or 16 =(0.112/0.119) *Torque + 0.119*speed. It looks something like this

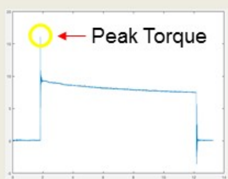


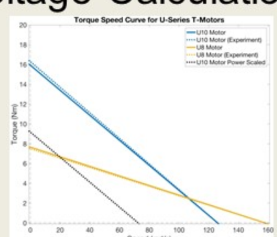


2. System Limitations: Power Theory

Force Plate Measurement Confirms Voltage Calculation







Scaling Motor

– Calculate U10 Power: $P = \frac{V^2}{R_m}$ or $P = \tau_{stall}\omega_{NL}$

– Scaled Power: $P_{scaled} = \alpha_P P = \frac{\alpha_F \alpha_L^2}{\alpha_T^3} P = \alpha_F \sqrt{\alpha_L} P$

– Use U10 values (k_e, k_t, R_m): $V_{scale} = \sqrt{P_{scale} R_m}$

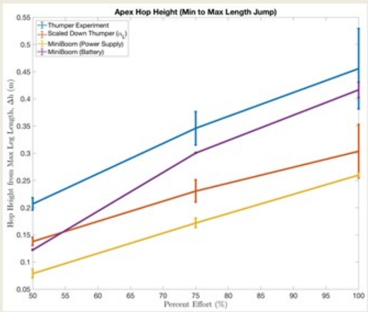
$\tau_{stall} = \frac{k_t V}{R_m}$

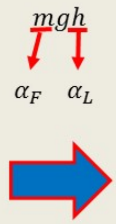
$\omega_{NL} = \frac{V}{k_e}$

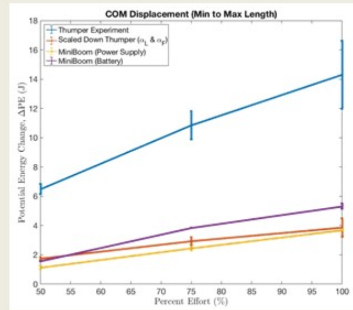
UNCLASSIFIED

2. System Limitations: Energetic Load

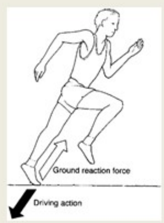
- Single Hop Test

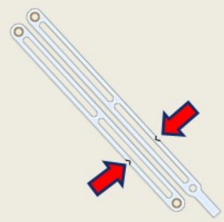






- Leg Structure

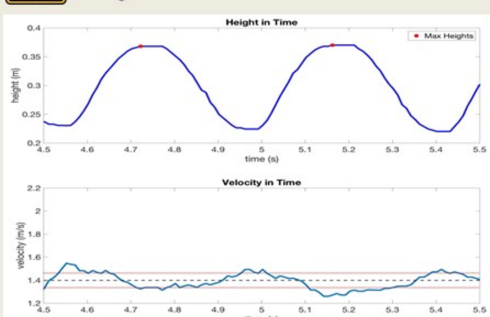


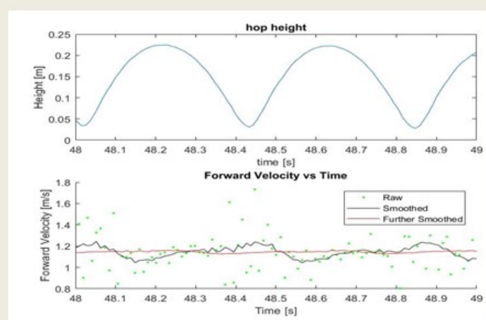


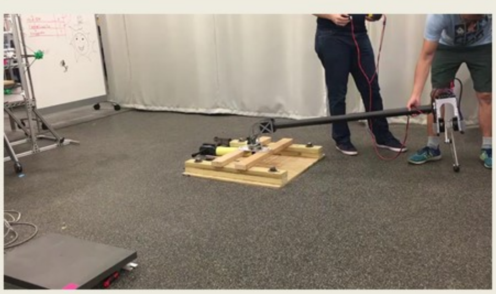
UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

2. System Limitations: Running





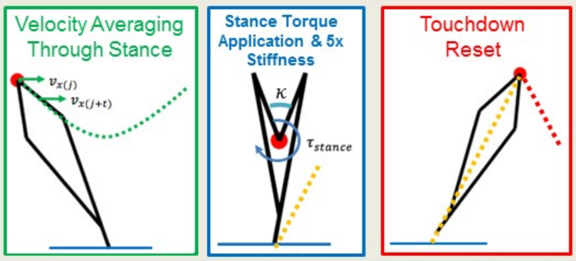


UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

3. Controller Development: Raibert

- Raibert SLIP-based Controller
  - Assume pogo stick motion (**S**pring **L**oaded **I**nverted **P**endulum)
  - Apply thrust in decompression phase

- Modifications
  - Stiffness increase by a factor (2nd half of stance)
  - Touchdown angle modulation
  - Hip rotation torque throughout stance



$$v_{avg} = \frac{\sum_{j=1}^{T} v_{x(j)}}{k_r C_{rate}}$$

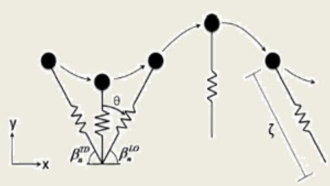
$$\kappa = 5\kappa$$

$$\tau_{stance} = k_a(\psi_{curr} - \psi_f)$$

$$\psi_{TD(n+1)} = \psi_f + k_v v_{avg}$$

3. Controller Development: AER

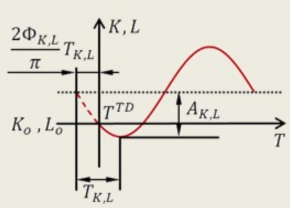
- Raibert SLIP-based Controller
  - Assume pogo stick motion (**S**pring **L**oaded **I**nverted **P**endulum)
  - Apply thrust in decompression phase



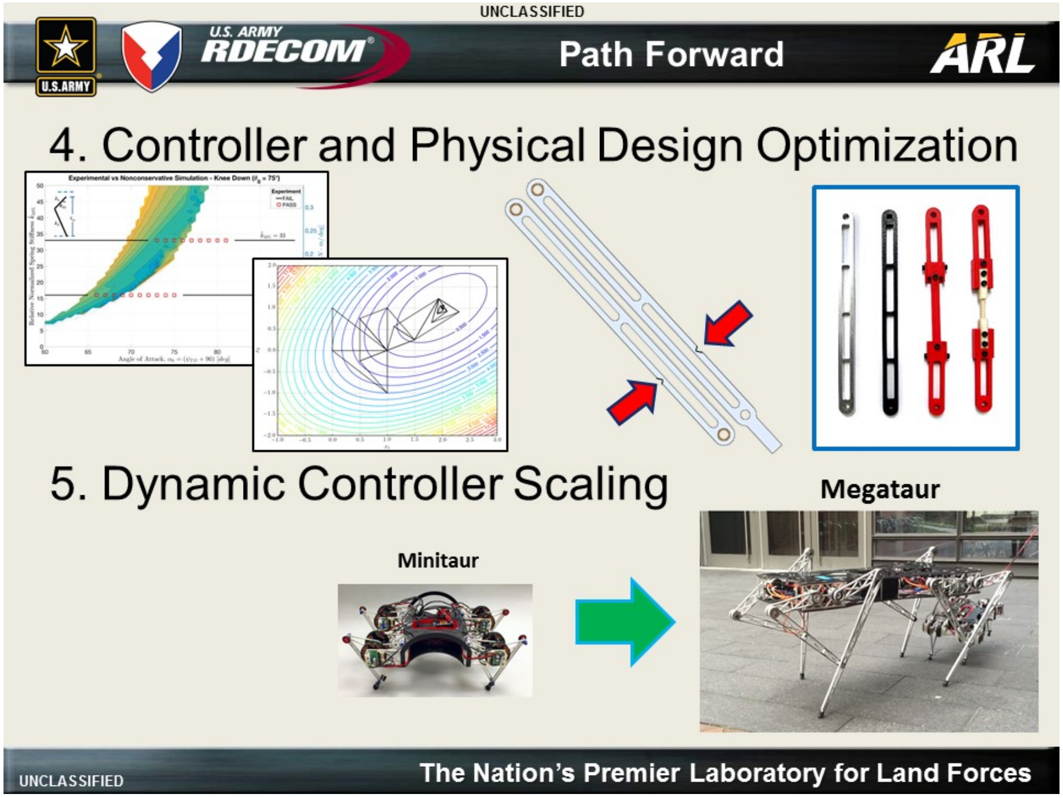
- Modifications
  - Touchdown angle adjustment
  - Energy removal through nominal leg length adjustment

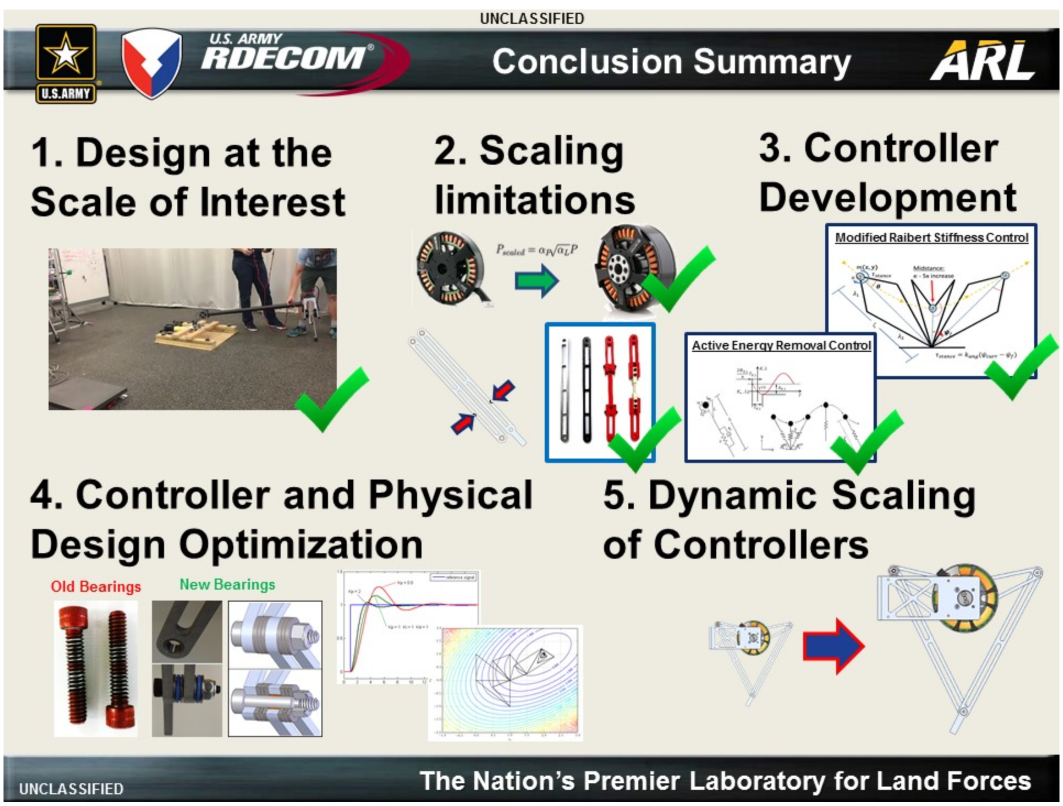
$$\beta^{TD}_{n+1} = \beta^{LO}_n + c\,(\beta^{TD}_n - \beta^{TD}_{des})$$

$$l_0 = l_{nom} - l_{dev}\sin\left(\frac{\pi t}{t_{des}}\right)$$



Approved for public release; distribution is unlimited.


UNCLASSIFIED
U.S. ARMY
RDECOM
Path Forward
ARL
4. Controller and Physical Design Optimization
5. Dynamic Controller Scaling
Minitaur
Megataur
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Conclusion Summary
ARL
1. Design at the Scale of Interest
2. Scaling limitations
3. Controller Development
Modified Raibert Stiffness Control
Active Energy Removal Control
4. Controller and Physical Design Optimization
Old Bearings
New Bearings
5. Dynamic Scaling of Controllers
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Acknowledgements

ARL

- Thank to VTD-ARL for hosting me this summer

- Special thanks to:
  - **Matthew Davis** for breakaway leg design
  - **John Nicholson** and **Wei-hsi Chen** for design and refinement of controllers and implementation on physical platforms
  - **Jason L. Pusey** for inspiring and motivating me throughout the summer as my mentor here at ARL
  - **Harris Edge** for his leadership and guidance in VTD
  - **RCTA** and **Stuart Young** for funding my research both at FSU and throughout this summer program

Robotics Collaborative Technology Alliance

- Funding Source
  - This work was supported by the collaborative participation in the Robotics Consortium sponsored by the US Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD 19-01-2-0012. The US Government is authorized to reproduce and distribute reprints for Government purposes not withstanding any copyright notation thereon.

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

References

ARL

Blackman, D.J., Nicholson, J.V., Ordonez, C., Miller, B.D., and Clark, J.E. "Gait development on Minitaur, a direct drive quadrupedal robot," in SPIE Defense+Security Conference. pp. 98370I-98370I-15, International Society for Optics and Photonics, 2016.

Kenneally, Gavin, and D. E. Koditschek. "Leg design for energy management in an electromechanical robot." Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on. IEEE, 2015.

Miller, Bruce, Ben Andrews, and Jonathan E. Clark. "Improved stability of running over unknown rough terrain via prescribed energy removal." *Experimental Robotics*. Springer Berlin Heidelberg, 2014.

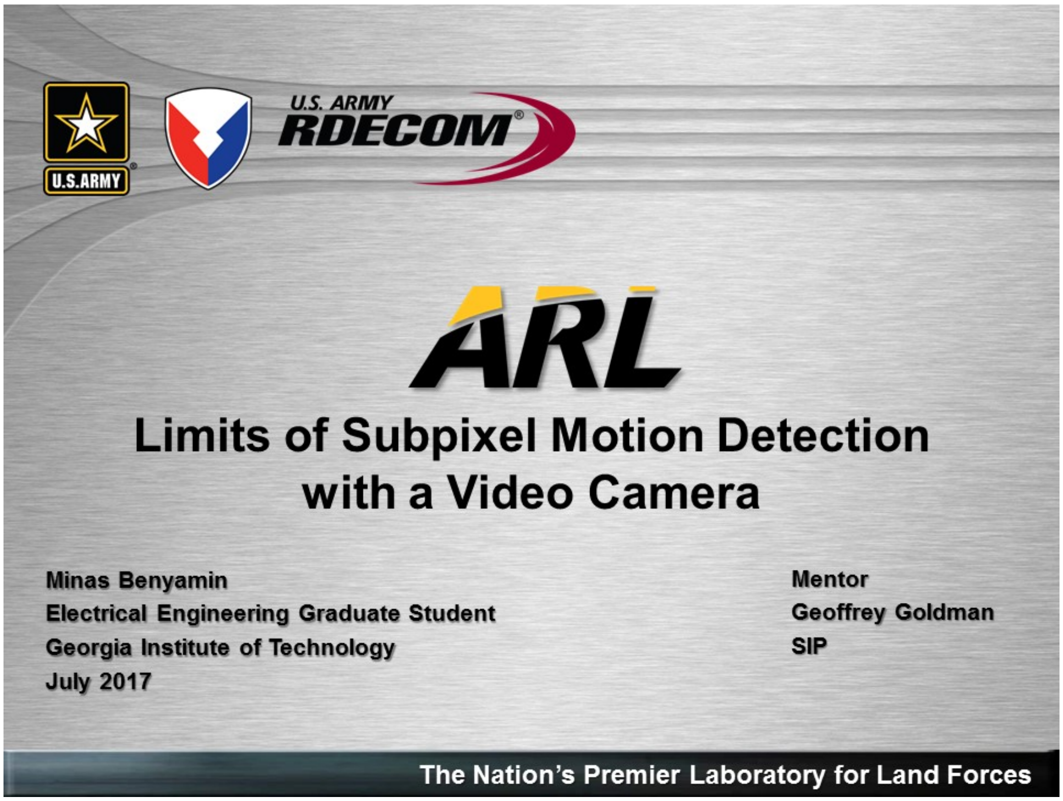
Miller, Bruce D. and Clark, Jonathan E. "Dynamic similarity and scaling for the design of dynamical legged robots" Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on. IEEE, 2015.

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

Minas Benyamin

Minas Benyamin is a graduate of the University of Maryland, Clark School of Engineering. His undergraduate degree was in electrical engineering with a minor in mathematics. I am pursuing graduate studies at the University of Georgia Tech in Atlanta, Georgia, majoring in signal processing and controls. My focus is on signals with experience in radar, computer vision, and machine learning. In the future I see my research as designing robotics with adaptive control systems managed via imaging and other sensor systems.



Outline

Summer Objective: Determine practical limits of subpixel motion detection using a video camera

- Introduction
  - Motivation
  - Experimental Setup
- Signal Processing
  - Outline of Algorithm
  - Edge Finding
  - Subpixel Detection
  - Noise Statistics and Estimation Limits
- Results
  - ROC Curves
  - Simulated
  - Measured
- Conclusion

Motivation and Background

- Video cameras are ubiquitous
- Objects such as paper, clothing, windows, and thin walls move in response to sound waves
- Acoustic data can be extracted from video feed of these objects
- Many environments often pose limitations to acquiring audio
- Interest in analyzing audio spectra of target of interest

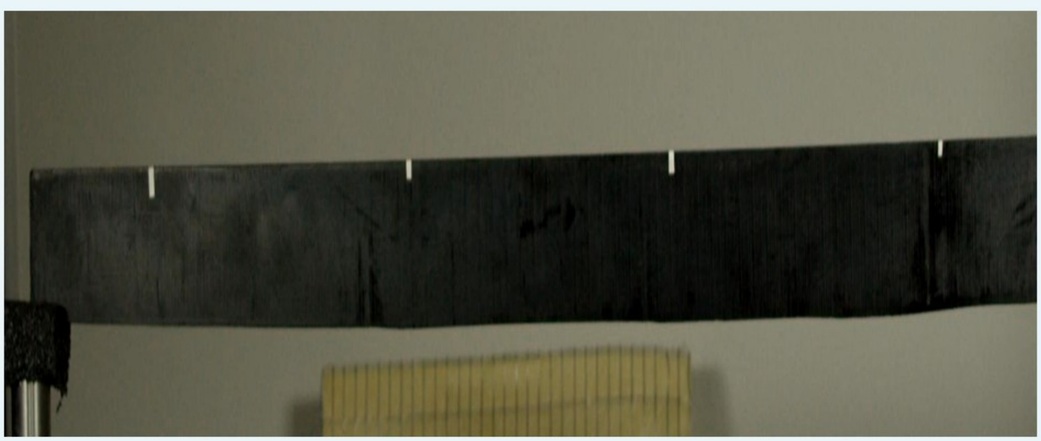
A. Davis, M. Rubinstein, N. Wadhwa, G. Mysore, F. Durand, W. T. Freeman, "The visual microphone: Passive recovery of sound from video", *ACM Trans. Graph.*, vol. 33, no. 4, pp. 79:1-79:10, 2014.

Experimental Setup

- Conducted in ARL Anechoic Chamber to reduce noise
- Measured a motor actuated rod
- Collected moving and static data

ARL 4 The Nation's Premier Laboratory for Land Forces

Moving Target – make better



ARL 5 The Nation's Premier Laboratory for Land Forces

Signal processing

First pass

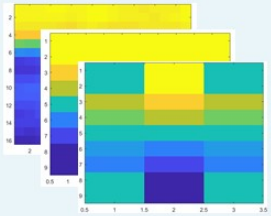
- Find edges using match filters
- Improve estimate using Polynomial Interpolation
- Estimate motion using Fourier techniques

Second pass

- Use motion prediction to Bin Pixel Changes by Subpixel Motion
- Generate detection statistics from randomly sampled PDFs
- Generate ROC curves at various Subpixel Motion levels

Edge Detection

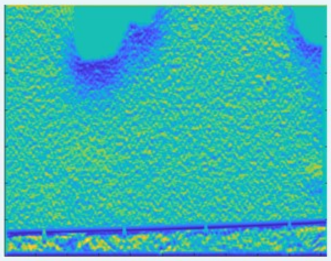
- Sequence of Match Filters to Segment Image and Detect Edge
- Multipass Polynomial Fit with Outlier Removal
- Weighted Polynomial Fit with Matched Filter Coefficients



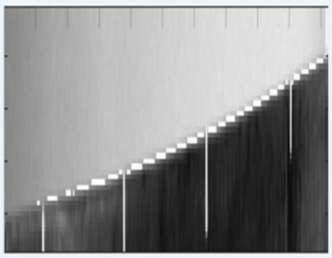
$$p = \frac{(V^T \cdot W \cdot V)}{V^T \cdot W \cdot \vec{x}} - Polynomial$$
$$V = [1\ y\ y^2\ \ \ldots] - Vandermonde$$
$$W\ \ - Weight\ Array$$

Image of rod

Matched filter output



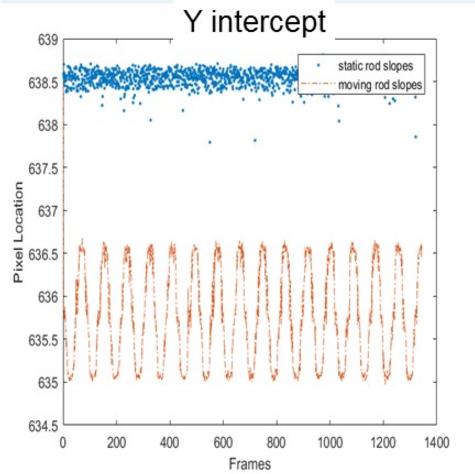
Detected edge

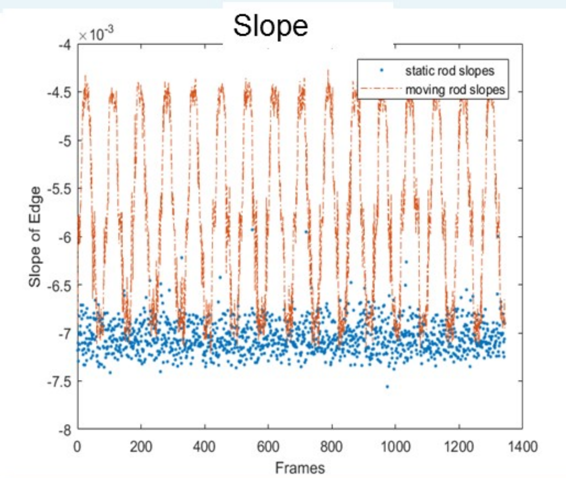


Approved for public release; distribution is unlimited.

U.S. ARMY RDECOM

Polynomial coefficients versus frame

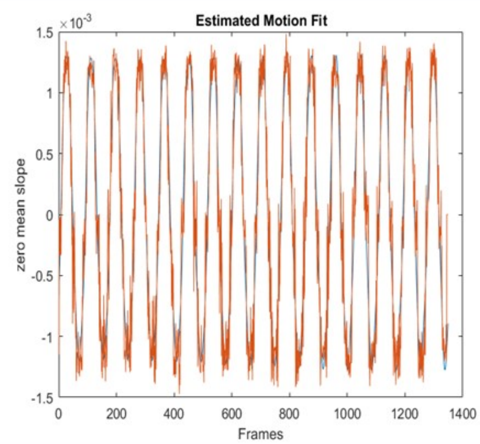


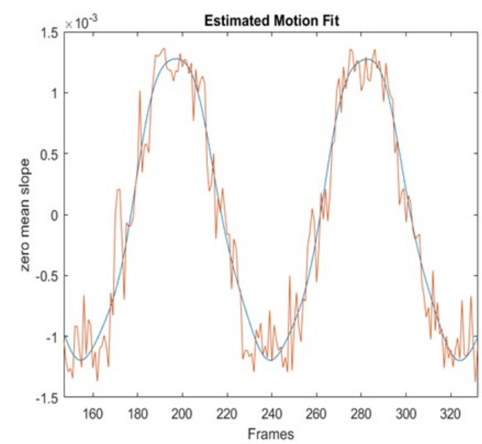


ARL 8 The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Fourier Model Fitting

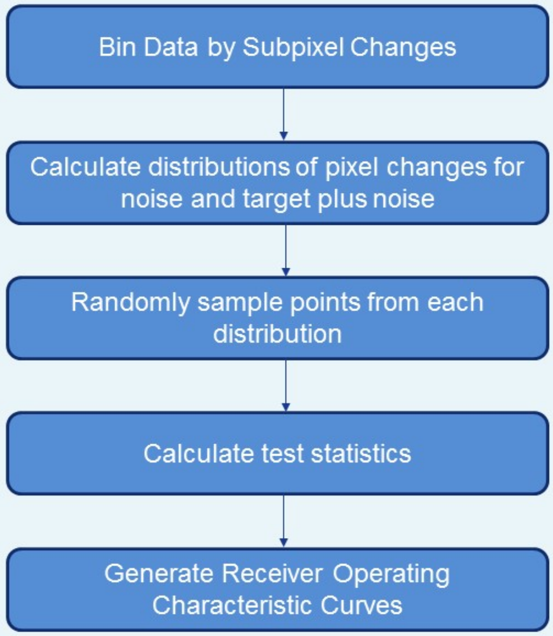




ARL 9 The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Subpixel Detection Algorithm



ARL 10 The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Detection Algorithms

- Binary Detector
- I Observations

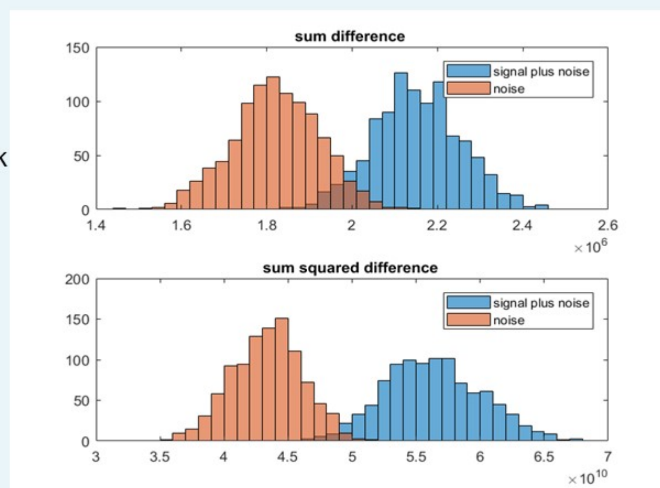
- H_1: No Pixel Shift
- H_2: Pixel Shift

Test Statistics – need work

$$\varphi_1 = \sum_i |diff_i|$$

$$\varphi_2 = \sum_i |diff_i|^2$$

Results for I=100 Pixels



ARL 11 The Nation's Premier Laboratory for Land Forces

Noise Distribution Digital Camera

- Thermal noise (Dark current)
  - Thermal noise power = 4kTBR
  - Capacitor reset power = KT/C
  - additive Gaussian
  - can be bigger in blue channel due to increased amplification
- Impulse noise (salt and pepper noise)
  - ADC errors
  - bit errors
  - photo diode leakage current for slow shutter speeds
- Shot noise – discrete nature of particles
  - thermal generation within a depletion region
  - statically quantum fluctuations in number of photons
  - Poisson distribution with rms level proportional to square root of image intensity
  - $P(X=k)=\lambda^k e^{-\lambda k}/k!$ where $\lambda=E(X) = Var(X)$
  - thermal generation within a depletion region
- Quantization noise
- Periodic noise
  - 60- or 120-Hz noise
- Readout noise
  - CCD: 3-8 electrons
  - CMOS: 2-4 electrons

ARL 12 The Nation's Premier Laboratory for Land Forces

Cramer-Rao Lower Bound for Estimating Subpixel Shift

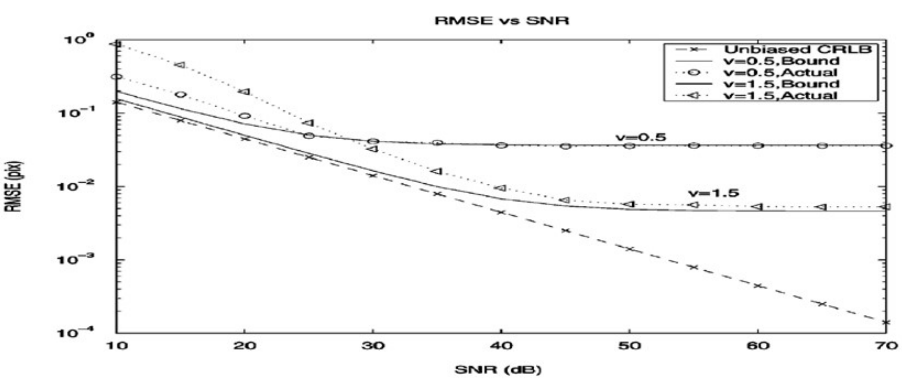
$$mse(\phi) \geq J(\phi)^{-1}$$

$$J(v) = \begin{bmatrix} a1 & a2 \\ a2 & a3 \end{bmatrix}$$

$$a_1 = \sum_{m,n} f_x^2(m - v_1, n - v_2)$$

$$a_2 = \sum_{m,n} f_x(m - v_1, n - v_2) f_y(m - v_1, n - v_2)$$

$$a_3 = \sum_{m,n} f_y^2(m - v_1, n - v_2).$$



D. ROBINSON, P. MILANFAR, "Fundamental Performance Limits in Image Registration", *IEEE Trans. Image Process*, vol. I3, no. 9, pp. 1185-1199, 2004.

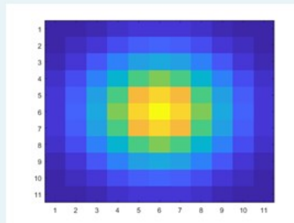
ARL 13 The Nation's Premier Laboratory for Land Forces

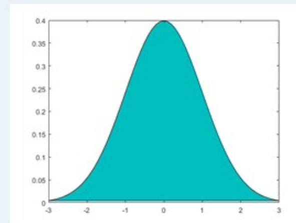
Rod Simulation

Simulate moving rod with Simple Sinusoidal Motion

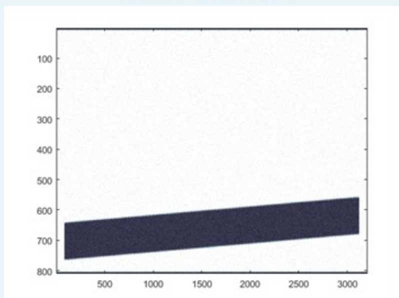
Convolve images with simulated PSF Kernel & add Gaussian Noise

Run through Two-Pass Processing Algorithm

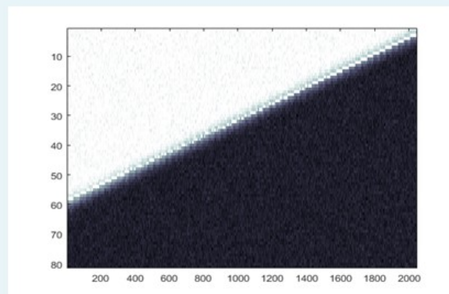




Simulated Rod



Rod Edge Detection



Simulation Roc Curves

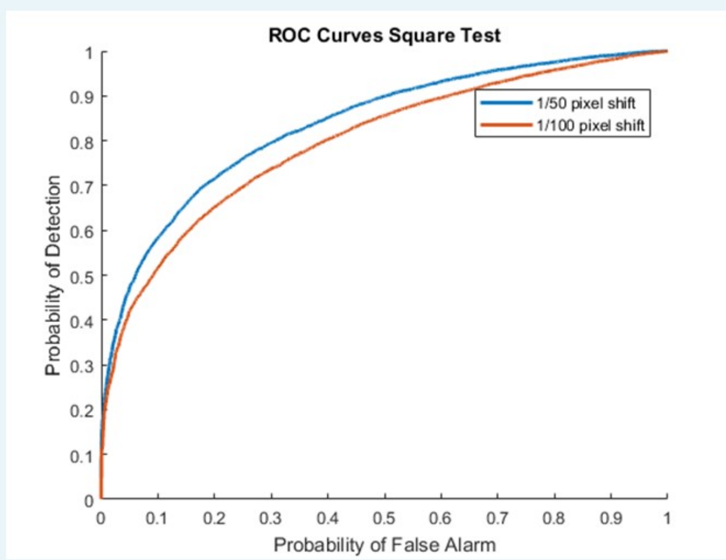
Detection Algorithm:
- Squared Difference

Number of Pixels:
- 25

Number of Samples:
- 10,000

Noise:
- Gaussian
- SNR = 37 dB

PSF:
- Gaussian Kernel

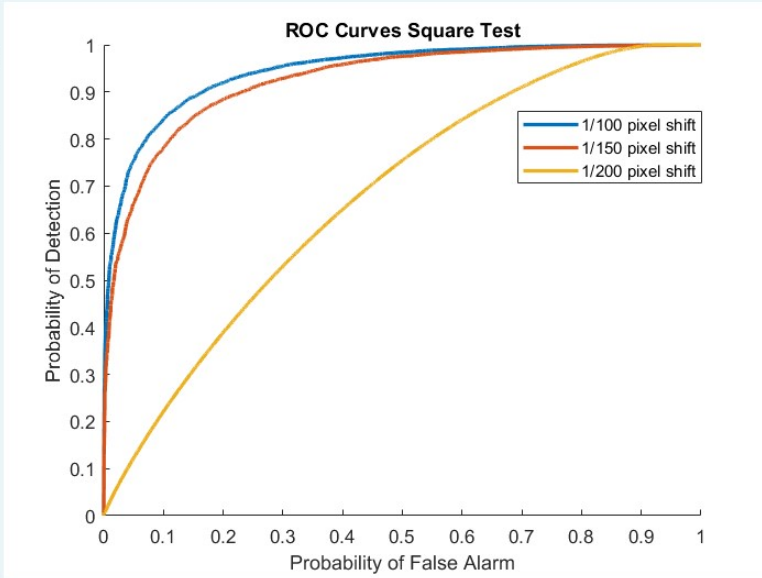


Measured Roc Curves

Detection Algorithm:
- Squared Difference

Number of Pixels:
- 500

Number of Samples:
- 10,000



Conclusion

Conclusions:

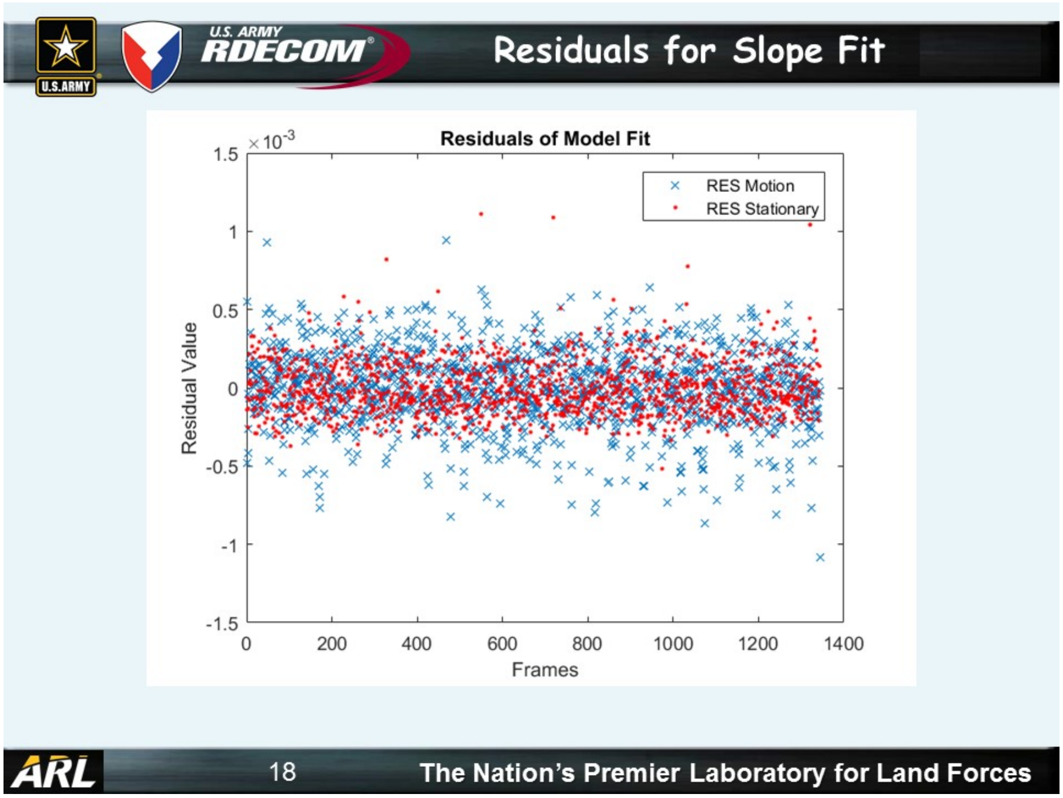
- Built an oscillating rod and measured it in a controlled low vibration environment with a RED video camera.
- Used a bank of match filters and multipass polynomial interpolation to find the moving edge of the rod.
- Motion was fit to a harmonic model for all intercepts to bin subpixel shifts
- Achieved subpixel detection down to 1/200 of a pixel.

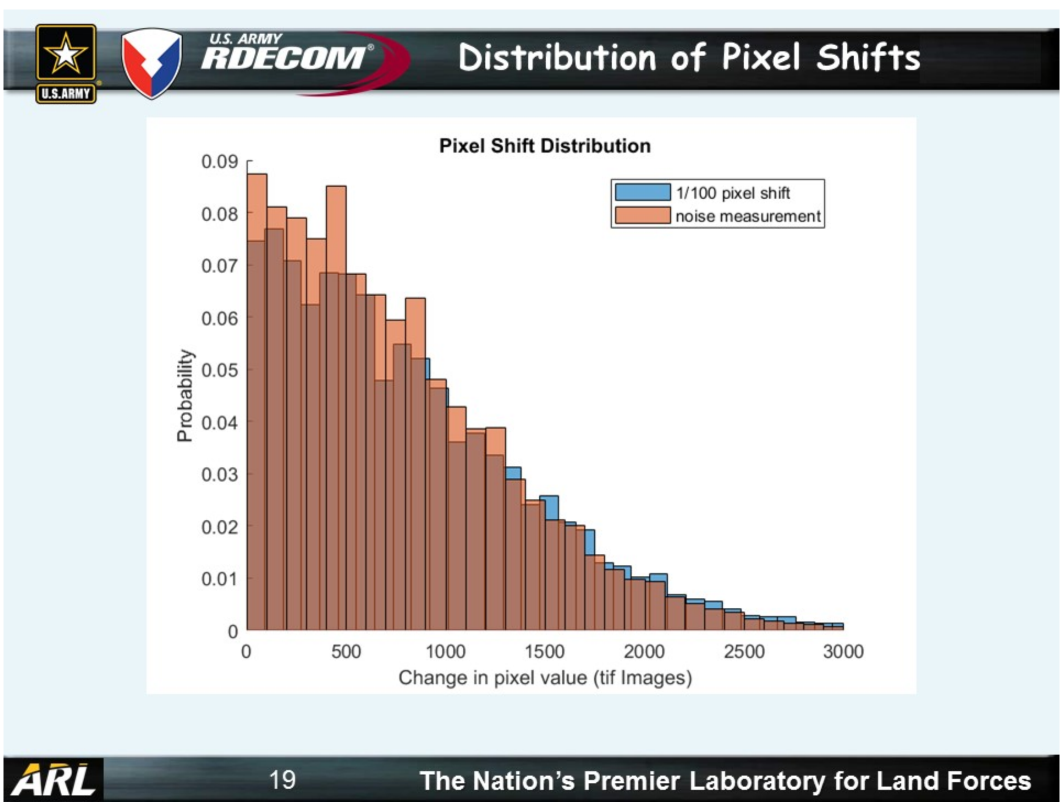
Future Work:

- Extension of measurements and processing to other video systems.
- Application of processing to detecting building vibrations for upcoming field test.
- Approximate high-resolution video as analog and apply CRLB.

Acknowledgements:

- Mr. Goldman and the ARL Acoustics Branch
- ARL, ASEE, & CQL

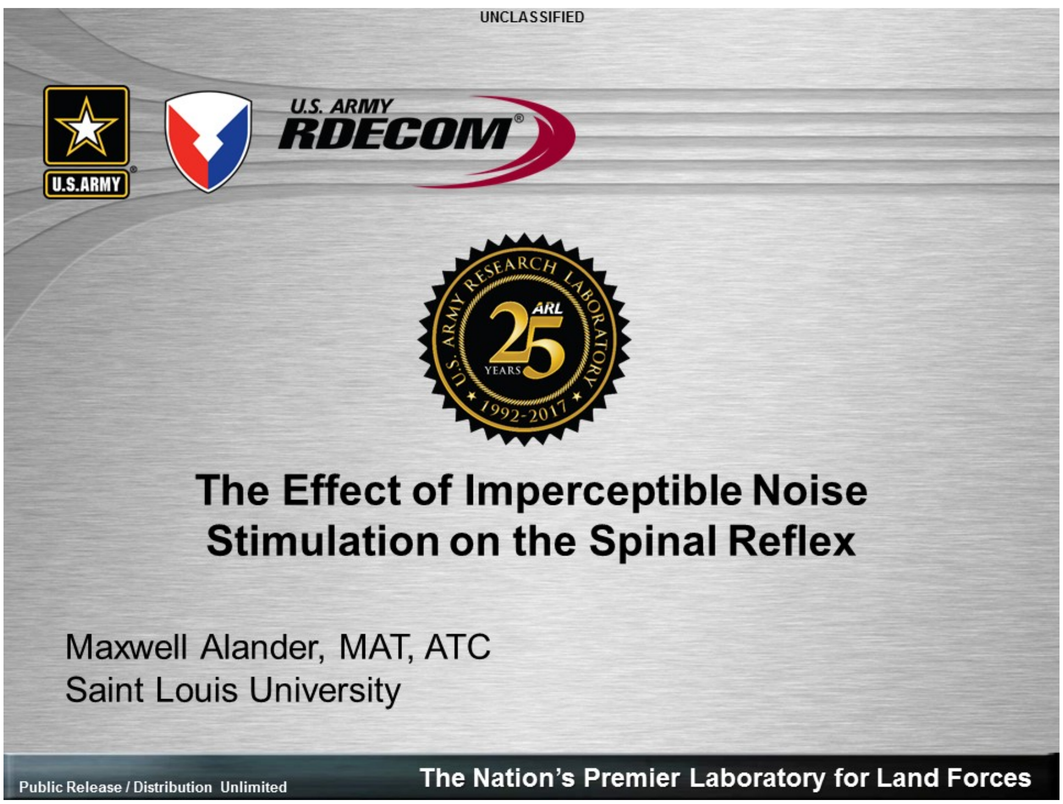




Approved for public release; distribution is unlimited.

Maxwell WH Alander

Maxwell WH Alander made the trip from Missouri to Maryland this summer after graduating with his Master of Athletic Training degree from Saint Louis University. The previous year, he received his BS in Exercise Science from the same institution. Originally a mechanical engineering major, his passion for physiology and performance led him to change his focus. Throughout college, he participated in Division I athletics, Greek life, and served as an assistant to strength and conditioning coaches in the athletics department. When he is not analyzing H-reflex recruitment curves, he can be found paddle boarding in the bay or biking in Susquehanna State Park. His future plans are to explore opportunities in research and sport performance that would allow him to continue contributing to the scientific community.



UNCLASSIFIED

Problem

- Soldiers require fine motor control for various tasks.
  - Marksmanship
- Tremor can result in a decrease in fine motor control.
  - Deviation from intended or ideal movement
  - Stress and physical exertion (Puschmann et al, 2011)

2

Public Release /Distribution Unlimited

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Introduction

- Vibratory noise stimulation has elicited performance increases relevant to Soldiers
  - Works by enhancing sensitivity of sensory input, which in turn affects motor output
- Imperceptible vibratory noise
  - Decrease tremor (Kouzaki et al, 2012)
  - Increase agility (Miranda, 2016)
  - Improve sensorimotor performance (Mendez-Balbuena et al, 2012)
  - Enhance postural stability (Ross et al, 2007)

3

Public Release /Distribution Unlimited

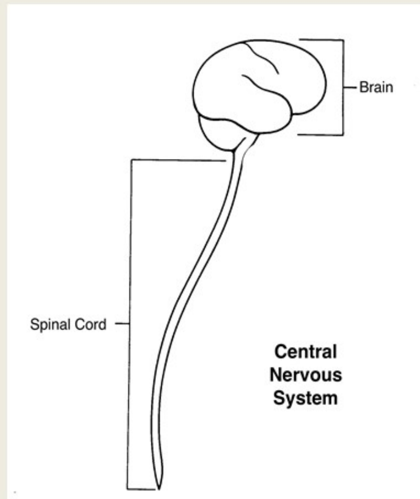
The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Background

ARL

- Movement is the product of the integration of motor centers with sensory information.
  - Many moving parts
- The aim of this project is to explore motor adaptation to imperceptible noise in the form of vibration on the spinal reflex.
  - Attempt to understand short term adaptation to the motor system



4

UNCLASSIFIED

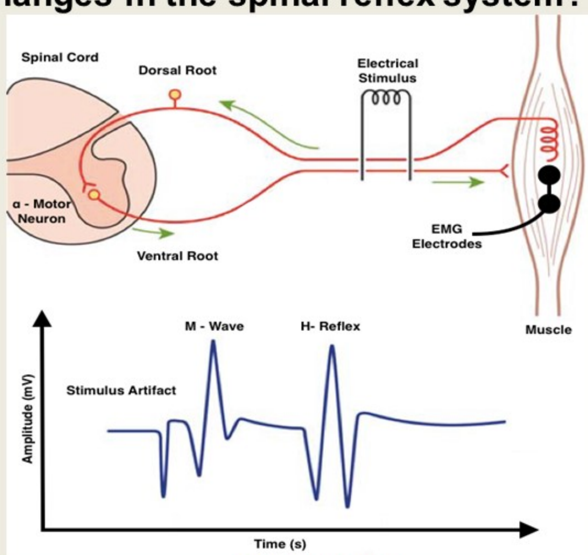
U.S. ARMY RDECOM

Background

ARL

How do we measure changes in the spinal reflex system?

- Tendon tap (myotatic) reflex
- Hoffman reflex

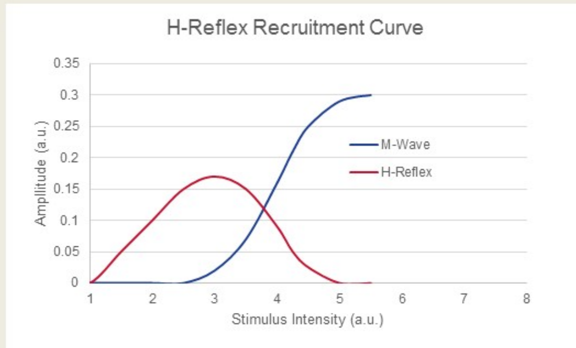


(Wynne et al, 2006)

5

Background

- H – reflex recruitment curves are used to account for variability between participants.
  - Series of stimulations with increasing intensities
  - Give insight into how an individuals unperturbed spinal reflexes operate



6

My Question

How does imperceptible vibratory noise affect the spinal reflex?

Hypothesis:

Vibratory noise stimulus will decrease the spinal reflex

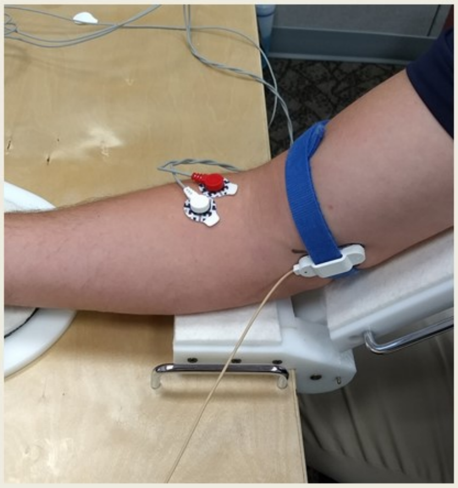
(Armstrong et al, 2008)

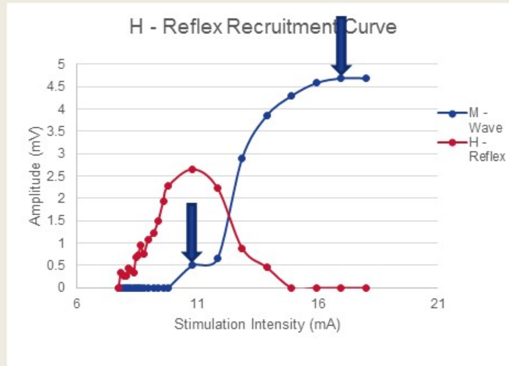
7

Approved for public release; distribution is unlimited.

Methods and Analysis

- A recruitment curve was collected for each of our 12 male participants





- Onset of M-wave
  - Standardize stimulation level
- Maximal M-wave
  - Maximum number of MUs that can be recruited

8

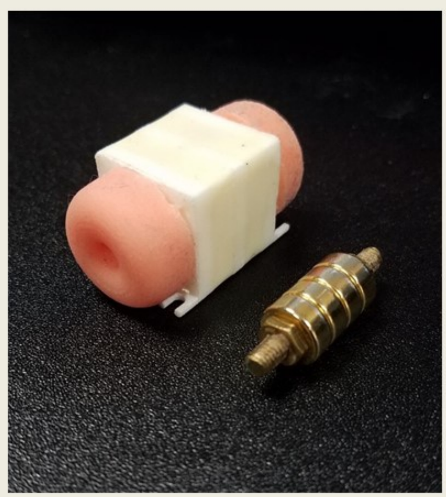
UNCLASSIFIED

U.S. ARMY RDECOM

Methods and Analysis

ARL

- The H – reflex was then gathered under either a randomized vibratory stimulus condition or sham.
  - Stimulated 10 times in one minute
- H-reflex amplitude under both conditions was then normalized to the maximal M-wave for each subject.



9

Public Release /Distribution Unlimited

The Nation's Premier Laboratory for Land Forces

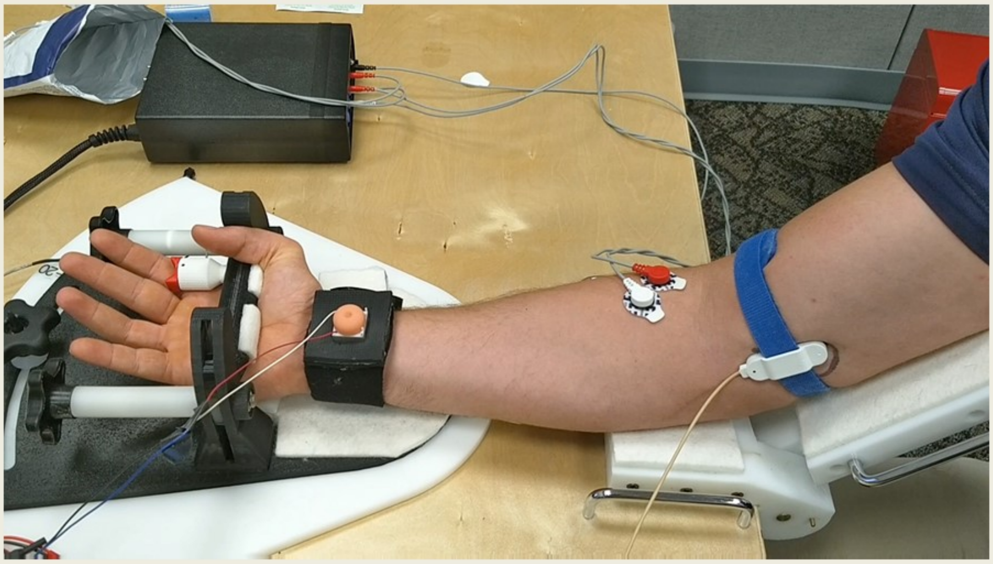
Approved for public release; distribution is unlimited.

UNCLASSIFIED

U.S. ARMY RDECOM

Methods and Analysis

ARL



10

Public Release /Distribution Unlimited

The Nation's Premier Laboratory for Land Forces

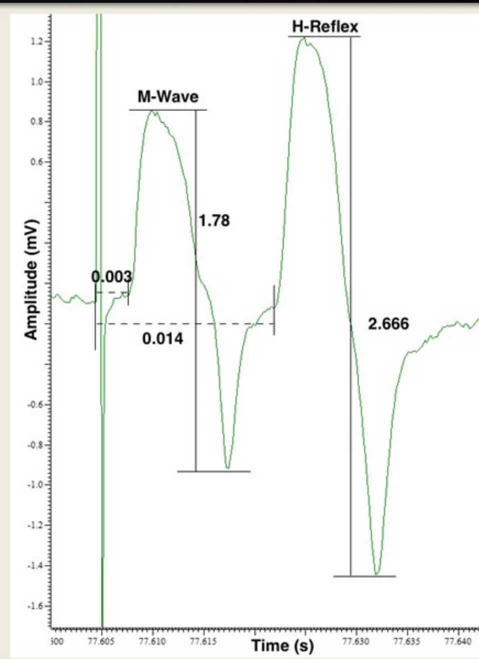
UNCLASSIFIED

U.S. ARMY RDECOM

Methods and Analysis

ARL

- Stimulus artifact
- M-wave
- H-wave
- Latency
- Amplitude



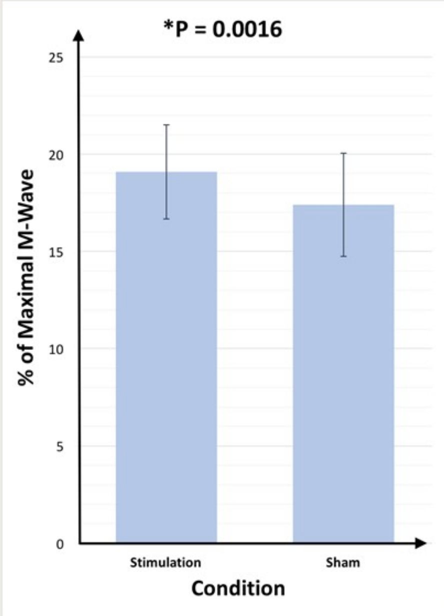
11

Public Release /Distribution Unlimited

The Nation's Premier Laboratory for Land Forces

Results

- Generalized linear model
  - Accounts for multiple observations on each subject
- Hypothesis testing performed via Chi square test
  - Does not make assumptions about the distribution of underlying data
- Imperceptible vibration stimulation produced a 1.73% increase in H-reflex amplitude



12

Discussion

- The data gathered shows a small but statistically significant increase in the spinal reflex with an imperceptible vibration stimulation.
  - Results did not support my hypothesis
    - Spinal reflex plays a role in motor adaptation induced by vibratory stimuli
- Behavioral outcomes
- Motor level matters
  - Determines…
    - Stimulation time needed to elicit effects
    - Duration of effects

13

UNCLASSIFIED

Benefits and Future Directions

- How can this benefit Soldiers in the field?
  - Potentially increase weapon stability and control
    - Marksmanship task
  - Combat medic
  - Load carriage
  - Other applications

Army.mil

- Next steps
  - Analyzing the effects of noise stimulation on other motor centers
  - Applying noise stimulation to real-world tasks

14

Public Release /Distribution Unlimited

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Acknowledgements

- I would like to thank Dr. Matthew Tenan and Dr. Courtney Haynes for their guidance, expertise, and mentorship.

15

Public Release /Distribution Unlimited

The Nation's Premier Laboratory for Land Forces

Approved for public release; distribution is unlimited.

U.S. ARMY RDECOM

Citations

ARL

- Mendez-Balbuena I, Manjarrez E, Schulte-Mönting J, Huethe, F, Tapia, JA, Hepp-Reymond, MC, & Kristeva, R (2012). Improved sensorimotor performance via stochastic resonance. *The Journal of Neuroscience*, *32*(36), 12612-12618.
- Kouzaki M, Kimura T, Yoshitake Y, Hayashi T, & Moritani T (2012). Subthreshold electrical stimulation reduces motor unit discharge variability and decreases the force fluctuations of plantar flexion. *Neuroscience letters*,*513*(2), 146-150.
- Ross SE, Arnold BL, Blackburn JT, Brown CN, Guskiewicz KM. (2007). Enhanced balance associated with coordination training with stochastic resonance stimulation in subjects with functional ankle instability: an experimental trial. *Journal of neuroengineering and rehabilitation.* Dec 17 2007;4:47. doi:10.1186/1743-0003-4-47.
- Griffin L, Garland SJ, Ivanova, T and Gossen, ER. (2001), Muscle vibration sustains motor unit firing rate during submaximal isometric fatigue in humans. The Journal of Physiology, 535: 929–936. doi:10.1111/j.1469-7793.2001.00929.x
- Palmieri RM, Ingersoll CD, Hoffman MA. The Hoffmann Reflex: Methodologic Considerations and Applications for Use in Sports Medicine and Athletic Training Research. *Journal of Athletic Training.* 2004;39(3):268-277.
- Wynne MM, Burns JM, Eland DC, Conatser RR, Howell JN. Effect of Counterstrain on Stretch Reflexes, Hoffmann Reflexes, and Clinical Outcomes in Subjects With Plantar Fasciitis. *J Am Osteopath Assoc* 2006;106(9):547-556.
- Puschmann A, Wszolek ZK. Diagnosis and Treatment of Common Forms of Tremor. *Seminars in neurology*. 2011;31(1):65-77. doi:10.1055/s-0031-1271312.
- Armstrong WJ, Nestle HN, Grinnell DC, et al. The Acute Effect of Whole-Body Vibration on the Hoffmann Reflex. *The Journal of Strength & Conditioning Research.* 2008;22(2):471-476. doi:10.1519/JSC.0b013e3181660605.
- Miranda DL, Hsu WH, Gravelle DC, et al. Sensory enhancing insoles improve athletic performance during a hexagonal agility task. Journal of biomechanics. May 03 2016;49(7):1058-1063. doi:10.1016/j.jbiomech.2016.02.022.

The Nation's Premier Laboratory for Land Forces

Kevin Corder

I am a third-year computer science PhD student at the University of Delaware (UD), where I also received my BS in computer science. I work under Dr Keith Decker in the Multi-Agent Systems Lab at UD, and my research is generally in cooperative multi-agent systems. I have 2 conference papers in review: an approximation method for the Shapley value in feature games, and an improved model for the cooperative information gathering problem.

After this summer project is completed and written up, I plan to continue working with Manny Vindiola at ARL through the remainder of my degree. Through a project in collaboration with Stanford, I will study cooperative deep reinforcement learning and how its neural nets may be implemented on neuromorphic hardware.

U.S. ARMY RDECOM

About Me

ARL

- Third-year computer science PhD Student
- University of Delaware
- Studying Multi-agent Systems/Distributed AI with Dr. Keith Decker
- This is my 10th week at ARL
- Mentor: Manny Vindiola

UNIVERSITY OF DELAWARE

2

U.S. ARMY RDECOM

About the Project

ARL

- This project aims to efficiently solve a computationally hard problem—vertex cover—on IBM TrueNorth, a highly distributed and low-power neuromorphic processor.
- Vertex cover can represent many real-world problems, like finding the minimal number of gateways in ad hoc or wireless sensor networks where expensive solutions may be infeasible.
- To compute vertex cover, we use a distributed Metropolis-Hastings simulation of an Ising model formulation where we converge to a solution by lowering over time the probability of exploration.

3

NPC on Neuromorphic Chip

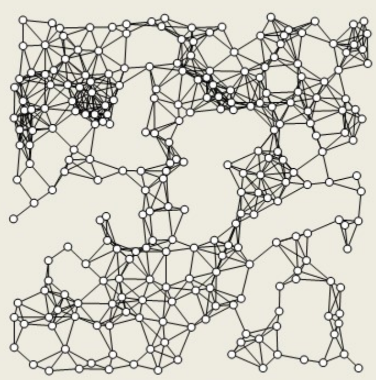
- Finding the computational limits of neuromorphic architectures is an open question.
- Our group previously showed TrueNorth to be *Turing complete* (implemented Conway's Game of Life).
- Efficiently solving Minimum Vertex Cover would be proof by example of a neuromorphic processor being able to solve NP-hard problems.
- By NPC reducibility, could potentially solve or provide insights into solving many related hard problems for future neuromorphic architectures.

4

UNCLASSIFIED

Wireless Ad Hoc Networks

- *Ad hoc networks* are dynamic, self-adjusting wireless networks where nodes may move freely
- *Wireless sensor networks:* type of ad hoc network where many small sensors send data to a base station
  - Typically multi-hop to minimize communication energy, where energy efficiency is a major challenge
  - Clustering is common in practice, or…
- Possible application in future: finding minimum number of data-forwarding nodes with Vertex Cover problem
  - Nodes have an edge between them if they are within wireless range
  - All nodes assumed equally good candidates for forwarding data
  - Data forwarding is proactive/hybrid



https://en.wikipedia.org/wiki/Wireless_ad_hoc_network

5

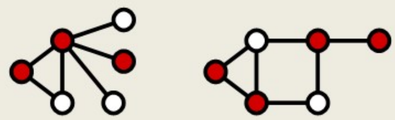
UNCLASSIFIED The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

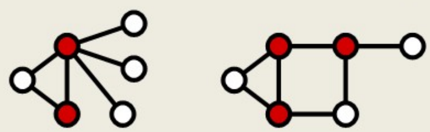
Vertex Cover

ARL

- Given an undirected graph $G = (V, E)$, the *Vertex Cover problem* (VC) consists of finding a set of vertices V' such that every edge has at least one endpoint in V'
  - V' is said to *cover* the graph G



- The *minimum Vertex Cover problem* (MVC) is finding a vertex cover V' with the least possible number of nodes
  - There are ≥ 1 minimum vertex covers for any graph G



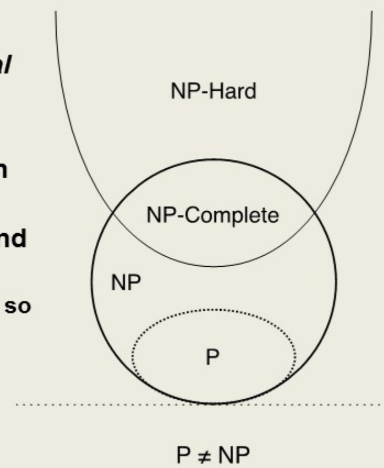
https://en.wikipedia.org/wiki/Vertex_cover

U.S. ARMY RDECOM

Vertex Cover is NP-hard

ARL

- However, computing MVC is very difficult for traditional computers.
- *NP problems* can be computed by a *nondeterministic* Turing machine in *polynomial time.*
  - Can be *verified* in polynomial time by computer
- *NP-hard* problems are not solvable in less than exponential time (… unless P=NP).
- *NP-complete* (NPC) problems are in both NP and NP-hard.
  - *Every* problem in NP is reducible to any in NPC, so every NPC problem is reducible to every other.
- Vertex Cover Problem is *NP-complete*; Minimum Vertex Cover Problem is *NP-hard.*
  - Our implementation could solve other NPC problems reduced to Vertex Cover.
- Vertex Cover may be efficiently computable on a neuromorphic architecture.



https://en.wikipedia.org/wiki/NP-completeness

Approved for public release; distribution is unlimited.

UNCLASSIFIED

U.S. ARMY RDECOM

Ising Spin Model

ARL

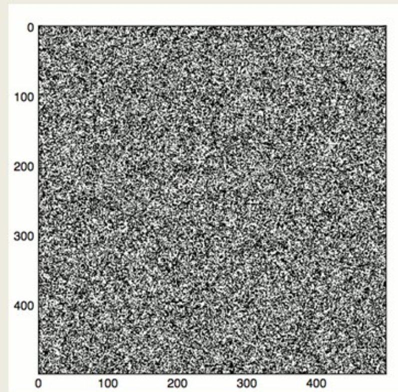
- Several NPC problems have been mapped to the ***Ising Spin Model***, a model for ferromagnetism from statistical mechanics.
- It models the magnetic dipole moments of atomic integer-spins (+1 or -1) and is used to identify phase transitions.
- Each particle has a spin (σ_i) and interacts with its neighbors.
  - E.g., 4 neighbors in a 2D grid
  - *Local* updates lead to *global* change
- The energy of the spin configuration is given by the Hamiltonian

$$H(\sigma) = -\sum_{i,j} J_{i,j}\sigma_i\sigma_j - \mu\sum_j h_j\sigma_j$$

for *spin interaction* $J_{i,j}$, *magnetic moment* μ, and external field h_j

- Spin-site configuration probability from the Boltzmann distribution with inverse temperature $\beta = (k_B T)^{-1} \geq 0$:

$$P_\beta(\sigma) = \frac{e^{-\beta H(\sigma)}}{\sum_\sigma e^{-\beta H(\sigma)}}$$



https://en.wikipedia.org/wiki/Ising_model

8

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Ising Spin Model Simulation

ARL

- The Ising Model has been simulated on CPU/GPU in 2D with the ***Metropolis-Hastings*** Monte Carlo algorithm using the configuration probability for ***Boltzmann exploration.***
- The simulation stochastically reduces the system's energy over time with Boltzmann exploration of a simplified Hamiltonian:

$$H(\sigma) = -\sum_{i,j} \sigma_i\sigma_j$$

- The Metropolis-Hastings Ising Model simulation can be summarized as:
  1. Choose a spin site k with probability $\frac{1}{N}$ (for N spin sites)
  2. Compare its local energy contribution to the energy if σ_k were flipped
  3. If new energy is less, keep flipped state
  4. If new energy is more, keep new state with probability $e^{-\beta(H_\nu - H_\mu)}$
  5. Repeat

9

UNCLASSIFIED

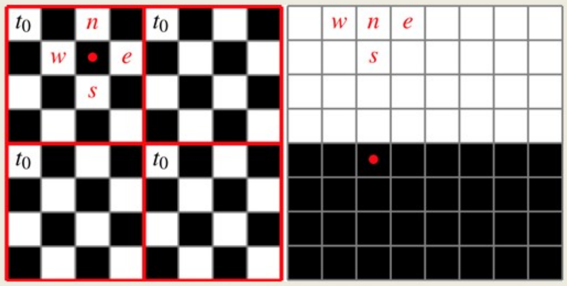
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Ising Model Metropolis Simulation

- This simulation is slow when run sequentially, so it has also been adapted for GPU implementations [2].
- Since each spin site only depends on its 4 neighbors (in 2D grid), the GPU implementation updates all non-adjacent sites simultaneously.
  - Done with a ***checkerboard decomposition*** for efficient GPU implementation
  - Decomposition is non-trivial in dimensions ≥ 2 and for non-uniform number of neighbors, like graph nodes' degrees



10

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

U.S. ARMY RDECOM

Vertex Cover as Ising Model

- The general Ising spin model is NP-complete [3] and a 2014 paper provides mappings of many NP problems to Ising model formulations [1]
  - Vertex Cover is among the few mappings without a complete graph
- State of node v is $x_v \in \{0,1\}$ (1 if contained in vertex cover V', or particle has +1 spin), and the system Hamiltonian is $H = H_A + H_B$
  - Constraint that every edge has at least one colored endpoint is

$$H_A = A \sum_{u,v \in E} (1 - x_u)(1 - x_v)$$

  - Also want to minimize the number of colored vertices with

$$H_B = B \sum_{v} x_v$$

  - Require that $B < A$ so total energy is never lowered by uncoloring a vertex that ruins the solution

11

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

Vertex Cover as Ising Model

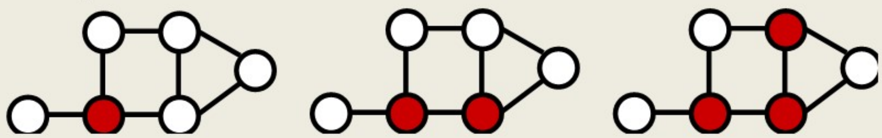
- State of node v is $x_v \in \{0, 1\}$, system Hamiltonian is $H = H_A + H_B$, and $B < A$
  - Every edge has at least one colored endpoint:

$$H_A = A \sum_{u,v \in E} (1 - x_u)(1 - x_v)$$

  - Minimize the number of colored vertices with

$$H_B = B \sum_{v} x_v$$

- Example with $A = 4, B = 1$:



$H_A = 4A$	$H_A = 2A$	$H_A = 0$
$H_B = 1B$	$H_B = 2B$	$H_B = 3B$
$H = 17$	$H = 10$	$H = 3$

Vertex Cover as Ising Model

- The vertex cover Hamiltonian can be rewritten for local energy contribution for each vertex v_i:

$$H = B \sum_{v} x_v + A \sum_{u,v \in E} (1 - x_u)(1 - x_v)$$

$$= \sum_{i}^{V} \underbrace{\left[B x_i + \frac{A}{2}(x_i - 1) \cdot \sum_{u:(i,u) \in E} (x_u - 1) \right]}_{H_{local}}$$

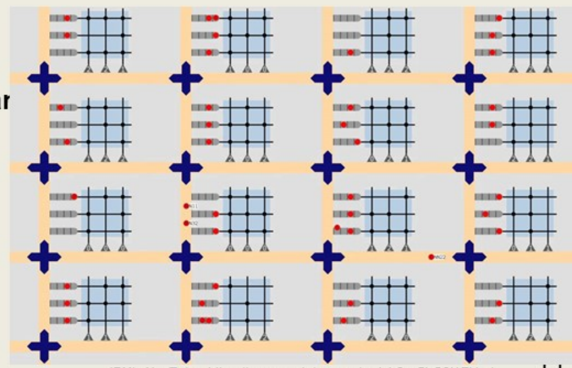
- Just as the other Metropolis-Hastings simulations, we'll lower the temperature over time to converge to a solution.
  - Lower environment temperature → lower exploration probability
  - The speed of lowering temperature is a hyperparameter: we'll need to find speeds that result in global optima for different graph sizes.

U.S. ARMY RDECOM

IBM TrueNorth

ARL

- TrueNorth: "Brain-inspired chip" boasting very low power and massively distributed model of computation
- 4096 cores, each with 256 neurons and 256 axons arranged in crossbar
- Neurons *spike* if the *potential*, the weighted sum of synapses plus leak, exceeds the threshold α and send to only one axon
- All parameters fixed during execution
- Orders of magnitude slower than traditional CPUs, but parallelism can compensate
- First generation of this chip, ar neuromorphic computing is young—could be significant in the future



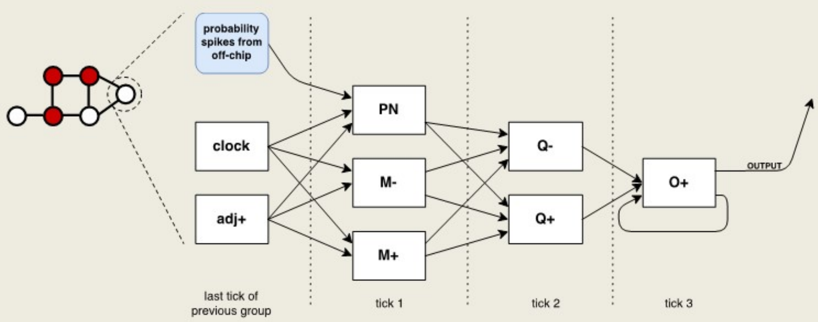
IBM's YouTube: https://www.youtube.com/watch?v=5izS3IAZHml

U.S. ARMY RDECOM

TrueNorth Implementation

ARL

Each node $v \in V$ becomes a *node circuit* in the TrueNorth implementation of the Ising model formulation, each connected to other node circuits



But before mapping nodes/connections, we must first determine:

1. Which nodes should go together on cores (and how to set inter-core edges)
2. Which nodes can be updated simultaneously (groups of non-adjacent nodes, similar to "checkerboard decomposition")

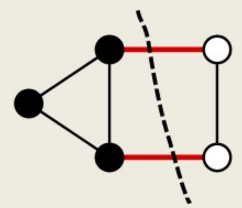
U.S. ARMY RDECOM

Implementation Setup

ARL

1. Which nodes should go together on cores?

- **Connected nodes must send/receive spikes to each others' circuits.**
- **Since a neuron can only send to 1 axon on 1 core, where all neurons on that core can read its spikes, more intercore edges wastes space.**
  - ➢ **Want the *most connected subgraphs* to share the same core**
- **This becomes a *graph partitioning problem* to find the *minimum cut* of the graph (find least number of edges to bisect graph).**
  - **Another NP-hard problem!**
  - **We use spectral bisection, a greedy solution, for time efficiency at the expense of non-optimal space.**
- **Bisected graph may not fit on a core, so we *recursively partition each subgraph* until it does.**



A minimum cut.
https://en.wikipedia.org/wiki/Cut_(graph_theory)

16

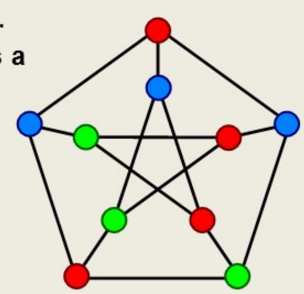
U.S. ARMY RDECOM

Implementation Setup

ARL

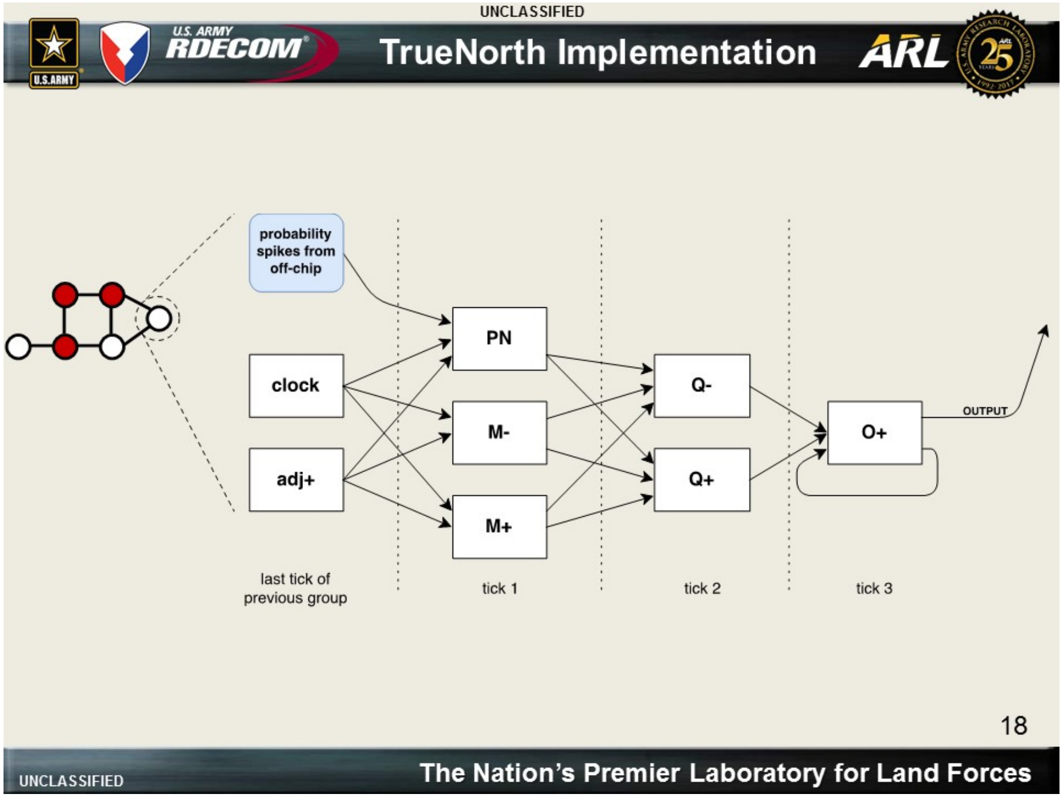
2. Which nodes can be updated simultaneously?

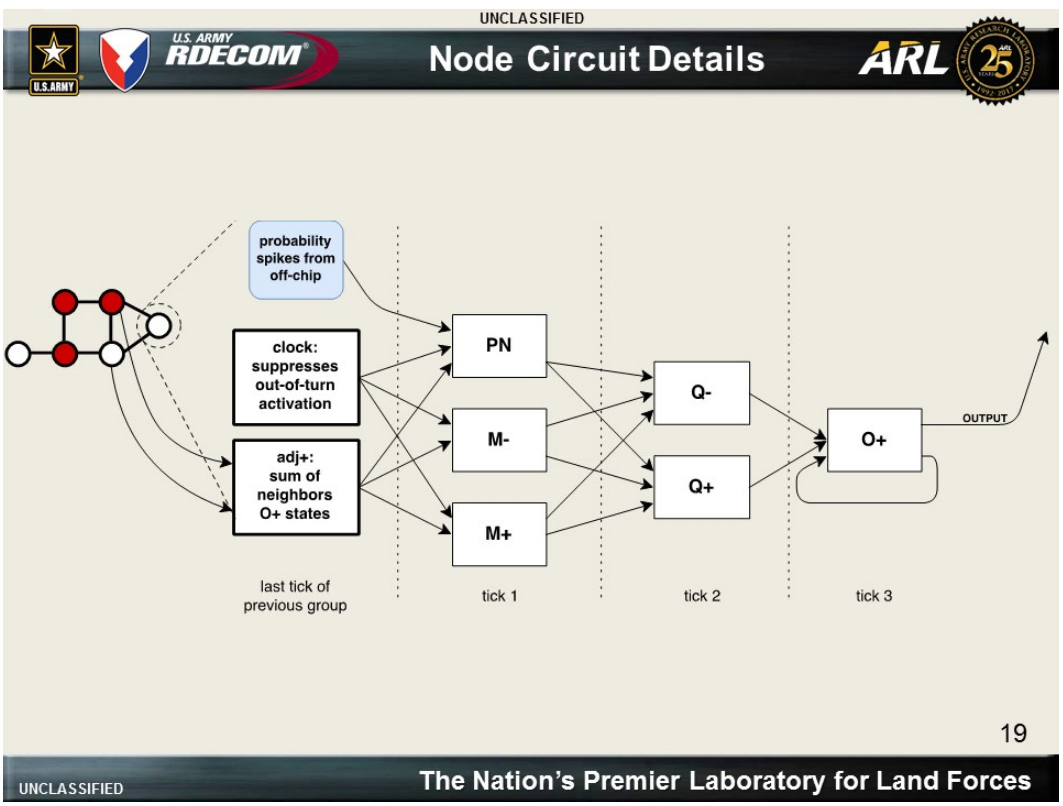
- **Need groups of non-adjacent nodes, like the "checkerboard decomposition" for the 2D Ising model simulation.**
- **Each node v may update concurrently with each non-adjacent node $u \in V : (u, v) \notin E$.**
- **This is a *graph coloring problem*: find the minimum number of colors needed to assign every node $v \in V$ a color such that no 2 adjacent nodes have the same color.**
  - **Also NP-hard! Again, we use a greedy solution.**
- **The nodes assigned the same color becomes a *group* of nodes that may be updated simultaneously.**
- **Nodes' circuits will be activated by a group *clock neuron* according to their graph coloring result.**



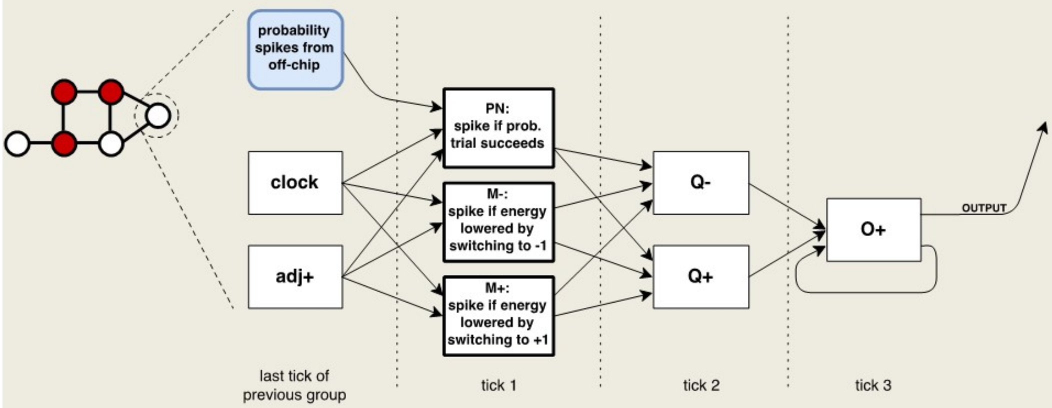
https://en.wikipedia.org/wiki/Graph_coloring

17


UNCLASSIFIED
U.S. ARMY
RDECOM
TrueNorth Implementation
ARL
probability spikes from off-chip
clock
adj+
PN
M-
M+
Q-
Q+
O+
OUTPUT
last tick of previous group
tick 1
tick 2
tick 3
18
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces


UNCLASSIFIED
U.S. ARMY
RDECOM
Node Circuit Details
ARL
probability spikes from off-chip
clock: suppresses out-of-turn activation
adj+: sum of neighbors O+ states
PN
M-
M+
Q-
Q+
O+
OUTPUT
last tick of previous group
tick 1
tick 2
tick 3
19
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

Node Circuit Details

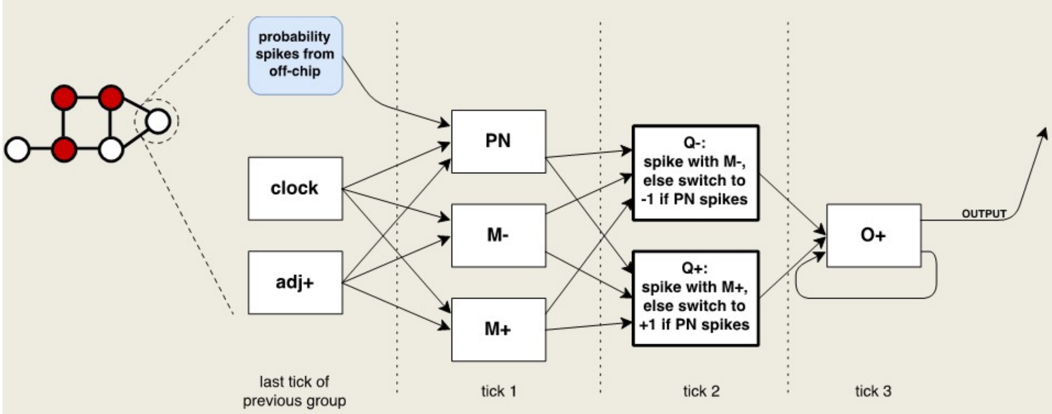


- **Number of sent probability spikes is equal to maximum graph degree $d_{max} + 1$**
  - **Off-chip probabilities: $p_0 < p_1 < \cdots < p_{d_{max}-1} = p_{d_{max}}$**
- **PN determines if probability spikes are sufficient for current neuron**
  - **A neuron's probability is p_{adj+} ⇒ PN spikes if # of prob. spikes > adj+**

20

UNCLASSIFIED

Node Circuit Details

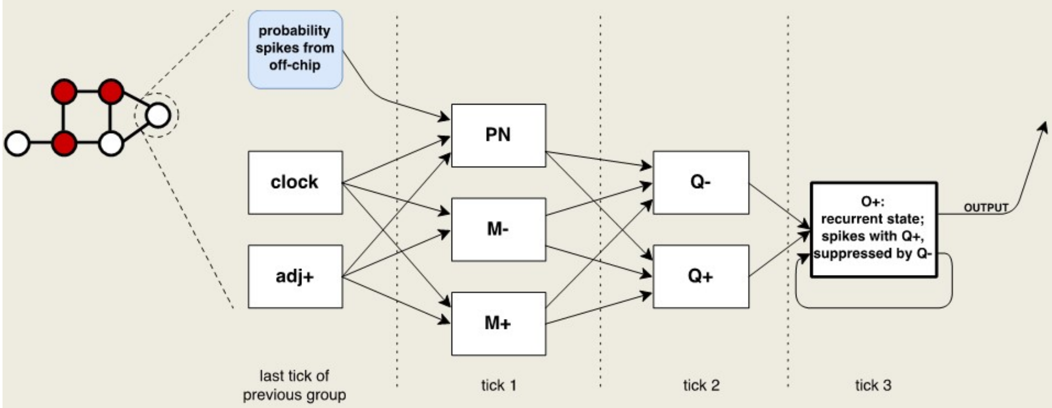


* At most one of M-, M+ will fire,
at most one of Q-, Q+ will fire

21

U.S. ARMY RDECOM — ARL

Node Circuit Details



22

UNCLASSIFIED

U.S. ARMY RDECOM — ARL

Results

- Implementation is under way!
  - Currently unit testing components, testing them together after
- Timeline in weeks:
  - 1-2: learned about TrueNorth architecture and corelet programming
  - 3: learned about Ising models and their simulations
  - 4: wrote TrueNorth corelet for 2D Ising simulation until determined feasible
  - 5: Found mappings of NP problems to Ising; chose Vertex Cover
  - 6-9: Designing the TrueNorth Ising simulation for Vertex Cover
  - 10: Started implementing pieces for small graphs
- After implemented, we will test the solution quality vs. the speed of lowering environment temperature for various graphs to learn a good boundary dependent on graph degree.
- For various graphs, we will then compare solution quality, runtime, and power consumption of our implementation against:
  - CPU/GPU Ising simulations solving Vertex Cover
  - Greedy, polynomial solutions
  - Exact solution (exponential-time ground truth)

23

Limitations

- **Hardware:**
  - Probabilities need to be computed off-chip (can't adjust parameters to affect probability dynamically).
  - Adding/removing graph nodes or edges requires reinitializing because of fixed connection.
  - Graphs with large degree may not fit on the chip to solve at all.
- **Method:**
  - Takes unknown number of iterations of lowering system temperature to converge, and may not find global optima if lowered too quickly (but guaranteed with enough time).
    - ➢ Need to learn this hyperparameter with trials

Conclusion & Future Work

- In this project, we've detailed a simulation to solve the NP-hard Vertex Cover problem on a neuromorphic processor, which could have significant impact on future neuromorphic algorithms for solving hard problems.
- This could be used in situations like ad hoc wireless sensor networks on the battlefield, where a minimal number of gateways may need to be computed frequently and with low power.
- To improve this project, could increase efficiency by reusing probability axons between update groups.
- We want to reduce to Vertex Cover a different NPC problem (perhaps Set Cover) and see quality of results for NPC problems, in general.

References

[1] E. E. Ferrero, J. P. De Francesco, N. Wolovick, and S. A. Cannas, "Q-state Potts model metastability study using optimized GPU-based Monte Carlo algorithms," *Comput. Phys. Commun.*, vol. 183, no. 8, pp. 1578–1587, 2012.

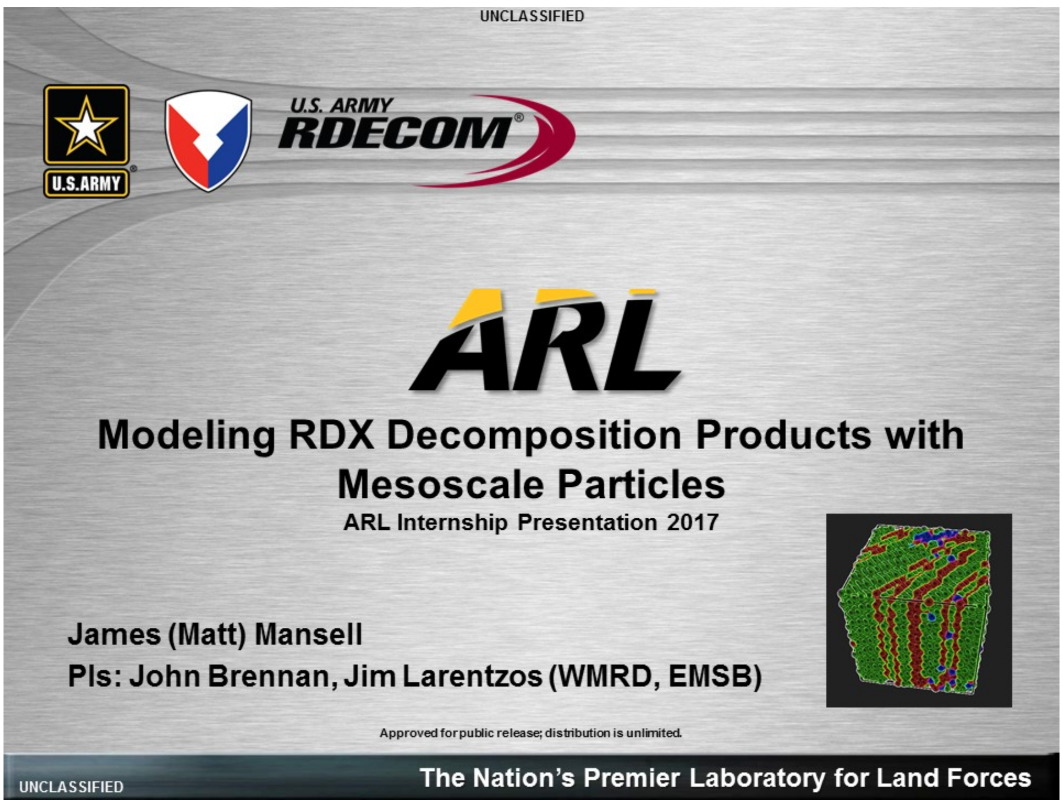
[2] A. Lucas, "Ising formulations of many NP problems," Frontiers in Physics 2, 5. pp. 1–15, 2013.

[3] F. Barahona, "On the computational complexity of Ising spin glass models," *J. Phys. A Math. Gen*, vol. 15, pp. 3241–3253, 1982.

Questions?

Matt Mansell

I am originally from Birmingham, Alabama. I obtained my bachelor's degree in chemical engineering and mathematics from Vanderbilt University. For several years, I worked for NASA as a Life Support Systems Development Engineer at the Marshall Space Flight Center in Huntsville, Alabama. I am now a full-time graduate student entering my third year at North Carolina State University (NCSU), where I am advised by Profs Keith Gubbins and Erik Santiso. At NCSU, I use theory and simulations at the quantum and atomistic scale to study fluids in extreme confinement. My future plans are to complete my PhD, and then continue pursuing my passion for molecular simulation and theories of fluids, as well as my passion for teaching and communicating science, either as a professor or at a US government laboratory.



Bio

Professional

- BE in Chemical Eng and Math (Vanderbilt University)
- NASA Marshall Space Flight Center (Huntsville, AL)
- NC State University, Dept. of Chemical & Biomolecular Engineering
  - Academic advisors: Keith Gubbins, Erik Santiso
  - Topics: Molecular theory of fluids, quantum/DFT/atomistic simulation

NC STATE UNIVERSITY

Personal

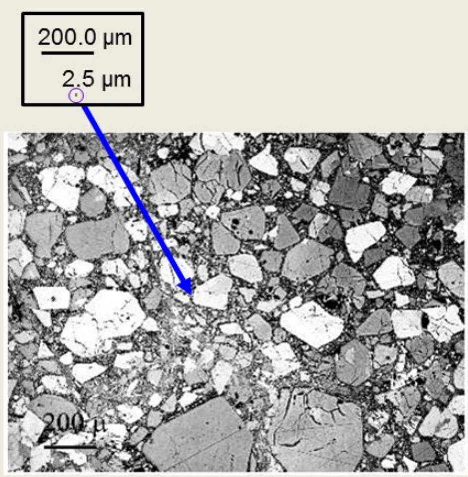
- **I got married!** 2017-06-24, Durham, NC

Future Plans

- Continue working in theory/simulation of fluids and interfaces, ideally in an academic setting or government lab

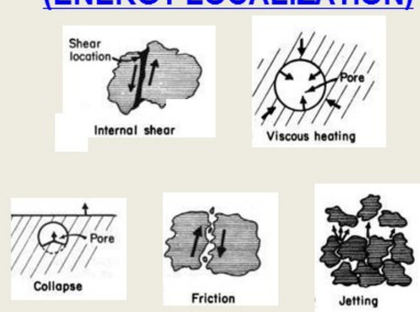
Energetic Material Structure

Microstructure Feature Scales



Skidmore, C.B., Phillips, D.S., Howe, P.M., Mang, J.T., and Romero, J.A., 1998, 11th International Detonation Symposium, Snowmass Village, Colorado, pp. 556.

Hot spot mechanisms (ENERGY LOCALIZATION)

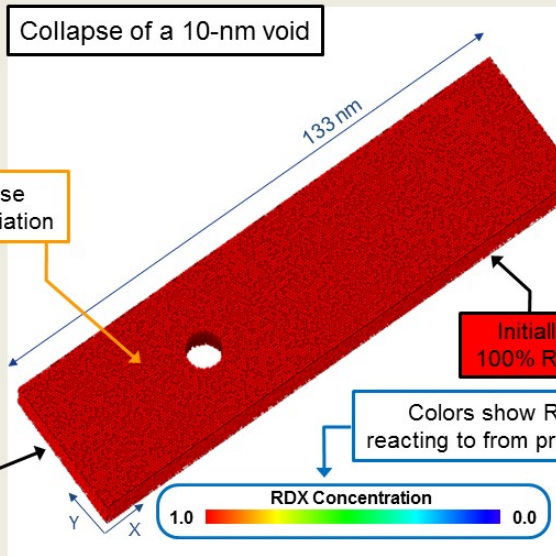


- ❑ **EM composites are highly microstructured**
- ❑ **Sensitivity and performance believed to be due to "hot spots"**

Microstructure Hot Spot Mechanisms

Hot Spot Simulation: Void Collapse

Collapse of a 10-nm void



Void collapse enhances initiation

Initially 100% RDX

Colors show RDX (red) reacting to from products (blue)

Impact begins decomposition

4

Approved for public release; distribution is unlimited.

unclassified

The Nation's Premier Laboratory for Land Forces

Why use DPD?

Representing Every Atom Explicitly is Not Feasible

Initial # RDX Molecules	# of Processor Cores	Explicit Atom Simulation Time (Estimated)	DPD Simulation Time
20,452,820	10,368	7.3 years	3.75 hours
126,259,367	63,232	7.4 years	4.34 hours
1,126,926,339	564,480	7.4 years	5.59 hours

Simulations used the same time step size and total time.

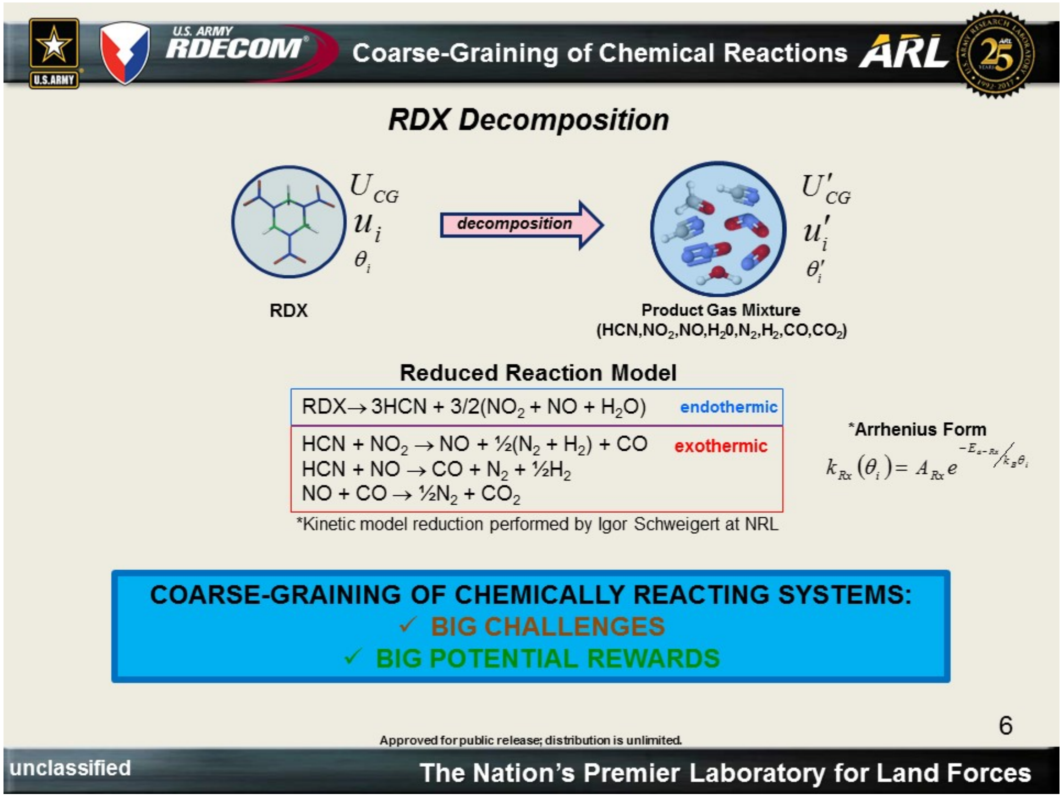
*Simulations ran on the Trinity KNL (Phase 2) supercomputer, located at Los Alamos National Laboratory

5

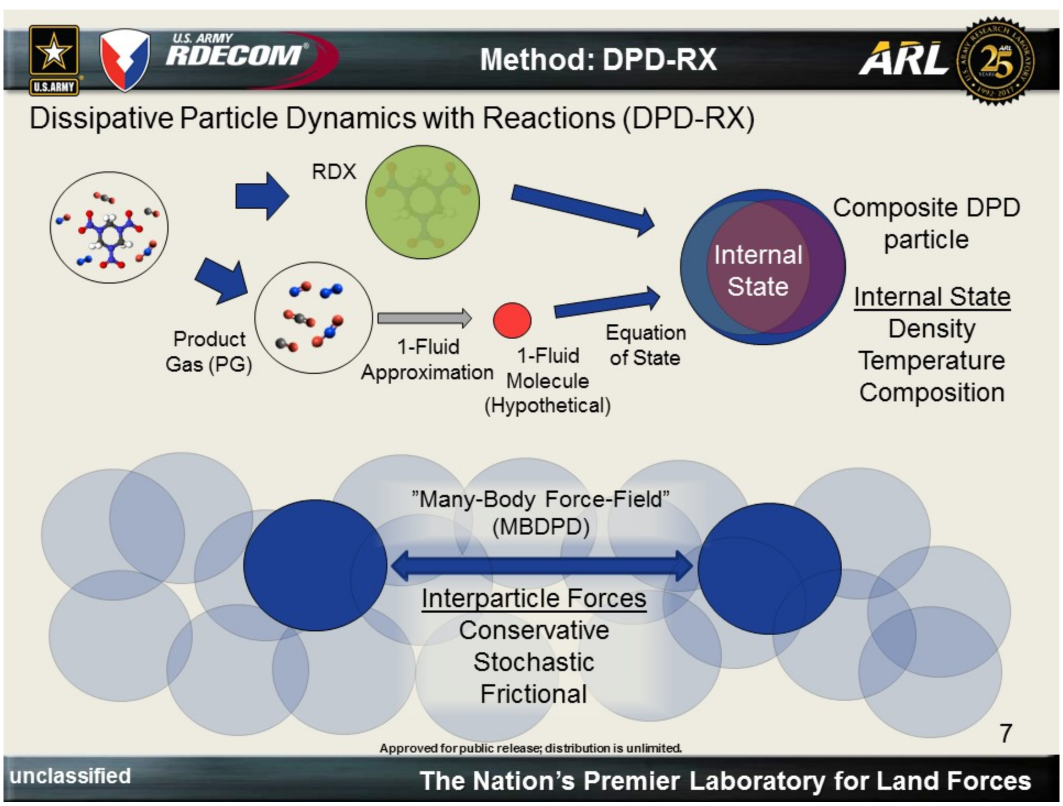
Approved for public release; distribution is unlimited.

unclassified

The Nation's Premier Laboratory for Land Forces



Coarse-Graining of Chemical Reactions
RDX Decomposition
U_{CG}
u_i
θ_i
decomposition
U'_{CG}
u'_i
θ'_i
RDX
Product Gas Mixture
($HCN, NO_2, NO, H_2O, N_2, H_2, CO, CO_2$)
Reduced Reaction Model
$RDX \rightarrow 3HCN + 3/2(NO_2 + NO + H_2O)$ endothermic
$HCN + NO_2 \rightarrow NO + ½(N_2 + H_2) + CO$ exothermic
$HCN + NO \rightarrow CO + N_2 + ½H_2$
$NO + CO \rightarrow ½N_2 + CO_2$
*Kinetic model reduction performed by Igor Schweigert at NRL
*Arrhenius Form
$k_{Rx}(\theta_i) = A_{Rx} e^{-E_{a-Rx}/k_B\theta_i}$
COARSE-GRAINING OF CHEMICALLY REACTING SYSTEMS:
✓ BIG CHALLENGES
✓ BIG POTENTIAL REWARDS
Approved for public release; distribution is unlimited.
6
unclassified
The Nation's Premier Laboratory for Land Forces



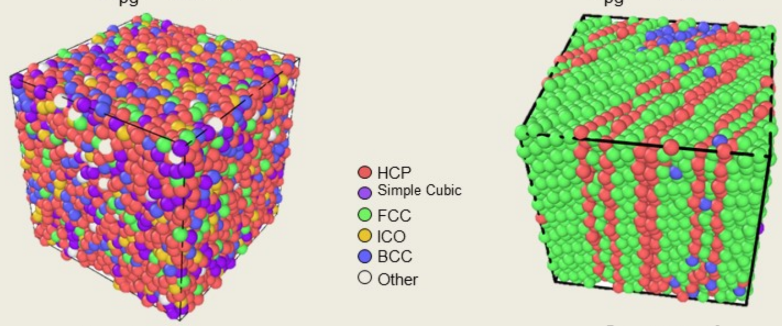
Method: DPD-RX
Dissipative Particle Dynamics with Reactions (DPD-RX)
RDX
Composite DPD particle
Internal State
Product Gas (PG)
1-Fluid Approximation
1-Fluid Molecule (Hypothetical)
Equation of State
Internal State
Density
Temperature
Composition
"Many-Body Force-Field"
(MBDPD)
Interparticle Forces
Conservative
Stochastic
Frictional
Approved for public release; distribution is unlimited.
7
unclassified
The Nation's Premier Laboratory for Land Forces

Motivation

- Deficiencies of the current Product Gas Model (PGM):
  1. crystallization/ordering PG structure

1-Fluid Simulation:
1.8 g/cc, 3445 K
N_{pg} = 8.684.

1-Fluid Simulation:
1.8 g/cc, 2836 K
N_{pg} = 7.721.



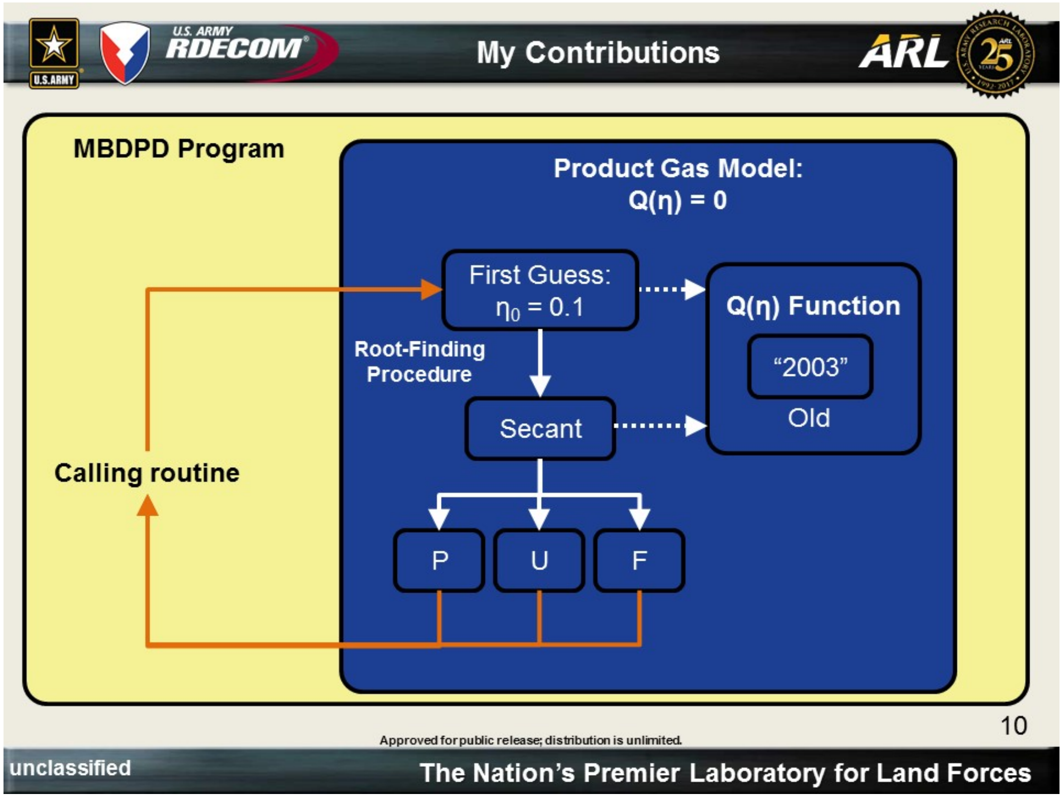
Unstructured **Structured**

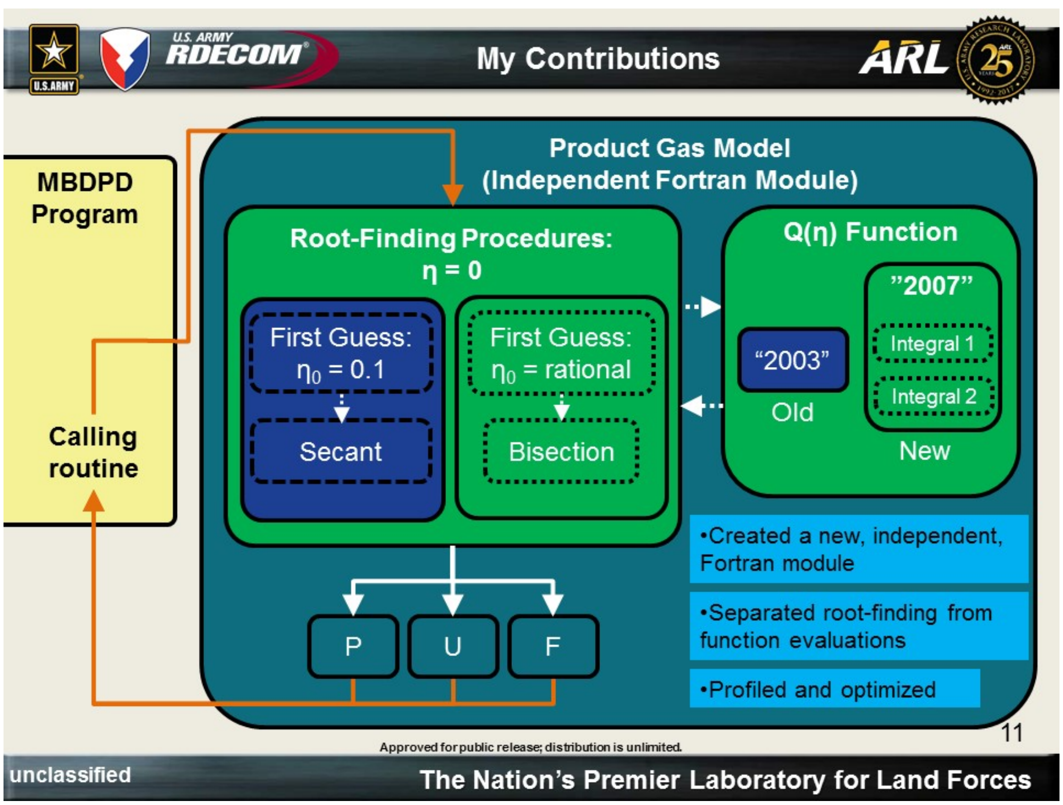
Motivation

- Deficiencies of the current Product Gas Model (PGM):
  1. crystallization/ordering PG structure
  2. thermodynamic properties off by 20-50% or more
  3. ad-hoc scaling

Hypothesis

- A new PGM will be more accurate and versatile, and at least as computationally efficient as the current PG Model.


U.S. ARMY
RDECOM
My Contributions
ARL
MBDPD Program
Product Gas Model:
Q(η) = 0
First Guess:
η0 = 0.1
Root-Finding
Procedure
Secant
Q(η) Function
"2003"
Old
Calling routine
P
U
F
10
Approved for public release; distribution is unlimited.
unclassified
The Nation's Premier Laboratory for Land Forces


U.S. ARMY
RDECOM
My Contributions
ARL
MBDPD
Program
Product Gas Model
(Independent Fortran Module)
Root-Finding Procedures:
η = 0
First Guess:
η0 = 0.1
Secant
First Guess:
η0 = rational
Bisection
Q(η) Function
"2003"
Old
"2007"
Integral 1
Integral 2
New
Calling
routine
•Created a new, independent, Fortran module
•Separated root-finding from function evaluations
•Profiled and optimized
P
U
F
11
Approved for public release; distribution is unlimited.
unclassified
The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

The "2007" Equation of State

ARL

Exponential-6 Potential:

$$\phi(r) = \frac{\varepsilon_0}{\alpha - 6}\left[6e^{\alpha(1-r/r_e)} - \alpha\left(\frac{r_e}{r}\right)^6\right] \qquad (7)$$

Equation of State for a Fluid Composed of Exponential-6 Particles

$$Q(\eta) = \frac{4-2\eta}{(1-\eta)^3} - (1/2 + 2\eta + 2\eta^3) + \frac{\partial}{\partial\eta}\frac{F_1}{NkT} = 0 \qquad (16)$$

$$\frac{\partial}{\partial\eta}\frac{F_1}{NkT} = \frac{1}{\eta}\left(\frac{F_1}{NkT} - \frac{PV}{NkT} + 1\right) - \frac{\eta\beta\varepsilon_0}{\alpha-6} \times \left[72e^{\alpha}G''_{\eta t}(\alpha\lambda^{-1}) + (\alpha\lambda^6/2)\int_0^{\infty} G'_{\eta}(t)t^4\,dt\right] \qquad (17)$$

$$\frac{F_1}{NkT} = -\frac{\eta\beta\varepsilon_0}{\alpha-6}\left[72e^{\alpha}G'_t(\alpha\lambda^{-1}) + (\alpha\lambda^6/2)\int_0^{\infty} G(t)t^4\,dt\right] \qquad (12)$$

$$\frac{PV}{NkT} = 1 + \frac{24\eta\beta\varepsilon_0}{\alpha-6}e^{\alpha}\alpha\lambda^{-1}\cdot G''_{tt}(\alpha\lambda^{-1}) - \frac{\alpha\eta\beta\varepsilon_0}{\alpha-6}\lambda^6\int_0^{\infty} G(t)t^4\,dt \qquad (14)$$

$$\lambda = (r_e/d) = (\eta_e/\eta)^{1/3}, \quad \eta_e = \pi\rho r_e^3/6 \qquad (8)$$

$$G(t) = \frac{tL(t)}{Q(t)} \qquad (A1)$$

$$Q(t) = 12\eta L(t) + S(t)e^t \qquad (A2)$$

$$Q'_{\eta}(t) = 12L(t) + 12\eta L'_{\eta}(t) + S'_{\eta}(t)e^t \qquad (A3)$$

$$Q'_t(t) = 12\eta L'_t(t) + S'_t(t)e^t + S(t)e^t \qquad (A4)$$

$$Q''_{\eta t}(t) = 12L'_t(t) + 12\eta L'_{\eta t}(t) + S'_{\eta t}(t)e^t + S'_{\eta}(t)e^t \qquad (A5)$$

$$Q''_{tt}(t) = S''_{tt}(t)e^t + 2S'_t(t)e^t + S(t)e^t \qquad (A6)$$

$$L(t) = (1 + \eta/2)t + (1 + 2\eta) \qquad (A7)$$

$$S(t) = (1-\eta)^2t^3 + 6\eta(1-\eta)t^2 + 18\eta^2 t - 12\eta(1+2\eta) \qquad (A8)$$

$$G'_{\eta}(t) = G(t)L^{-1}(t)L'_{\eta}(t) - G^2(t)[tL(t)]^{-1}Q'_{\eta}(t) \qquad (A9)$$

$$G'_t(t) = G(t)\left[t^{-1} + L^{-1}(t)L'_t(t)\right] - G^2(t)[tL(t)]^{-1}Q'_t(t) \qquad (A10)$$

$$G''_{\eta t}(t) = G'_t(t)L^{-1}(t)L'_{\eta}(t) + G(t)L^{-2}(t)\left[L(t)L''_{\eta t}(t) - L'_{\eta}(t)L'_t(t)\right] - G^2(t)[tL(t)]^{-2}\left[2Q(t)G'_t(t) - L(t) - tL'_t(t)\right]Q'_{\eta}(t) - G^2(t)[tL(t)]^{-1}Q'_{\eta t}(t) \qquad (A11)$$

$$G''_{tt}(t) = G'_t(t)\left[t^{-1} + L^{-1}(t)L'_t(t)\right] - G(t)\left[t^{-2} + L^{-2}(t)L'_t(t)L'_t(t)\right] - G^2(t)[tL(t)]^{-2}\left[2Q(t)G'_t(t) - L(t) - tL'_t(t)\right]Q'_t(t) - G^2(t)[tL(t)]^{-1}Q''_{tt}(t) \qquad (A12)$$

Sun, J., Wu, Q., Cai, L. & Jing, F. *Chemical Physics Letters* 449, 72–76 (2007).

12

Approved for public release; distribution is unlimited.

unclassified

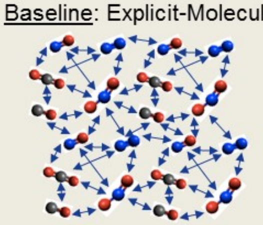
The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

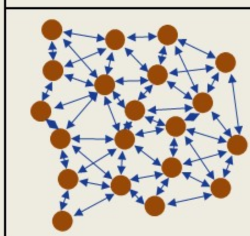
Methods: Testing the PG Model

ARL

<u>Baseline</u>: Explicit-Molecule

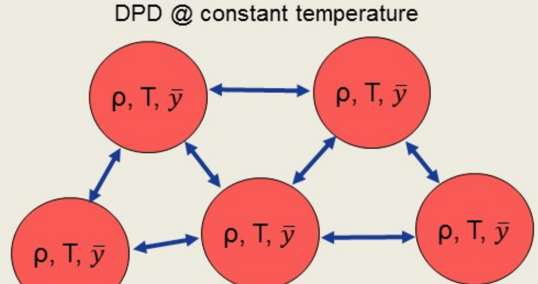


1-Fluid (Molecular Dynamics @ constant energy)



- Simulations defined by:
  - Density
  - Temperature
  - Composition

DPD @ constant temperature

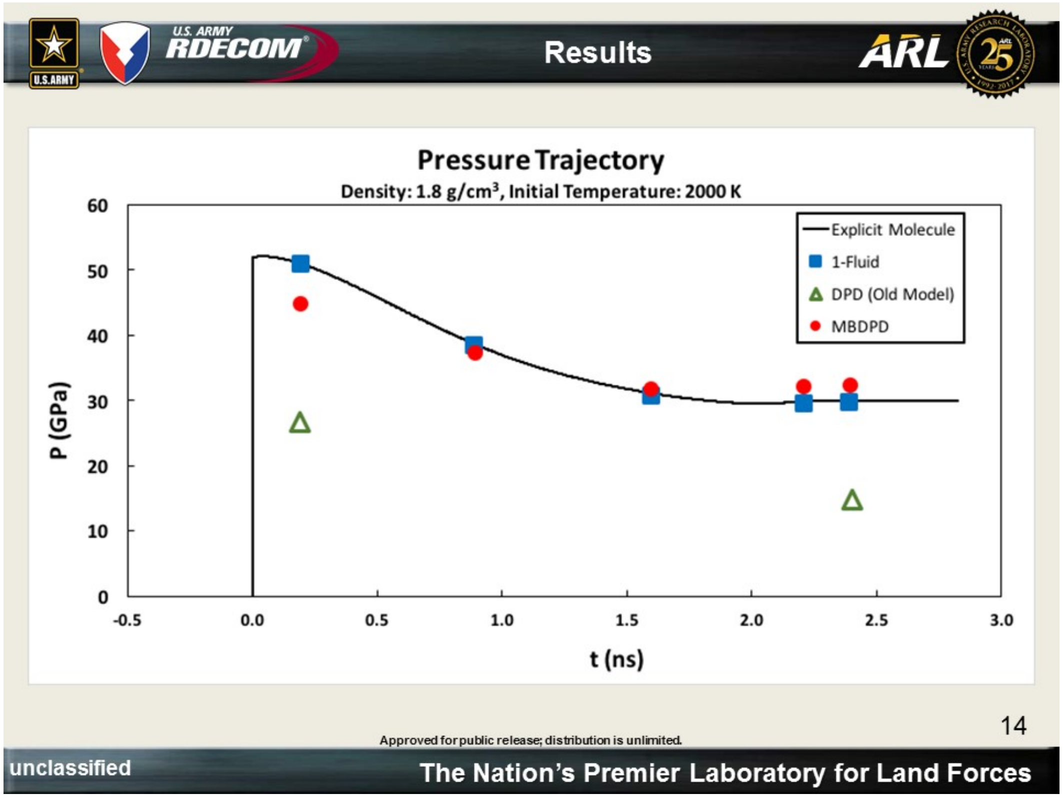


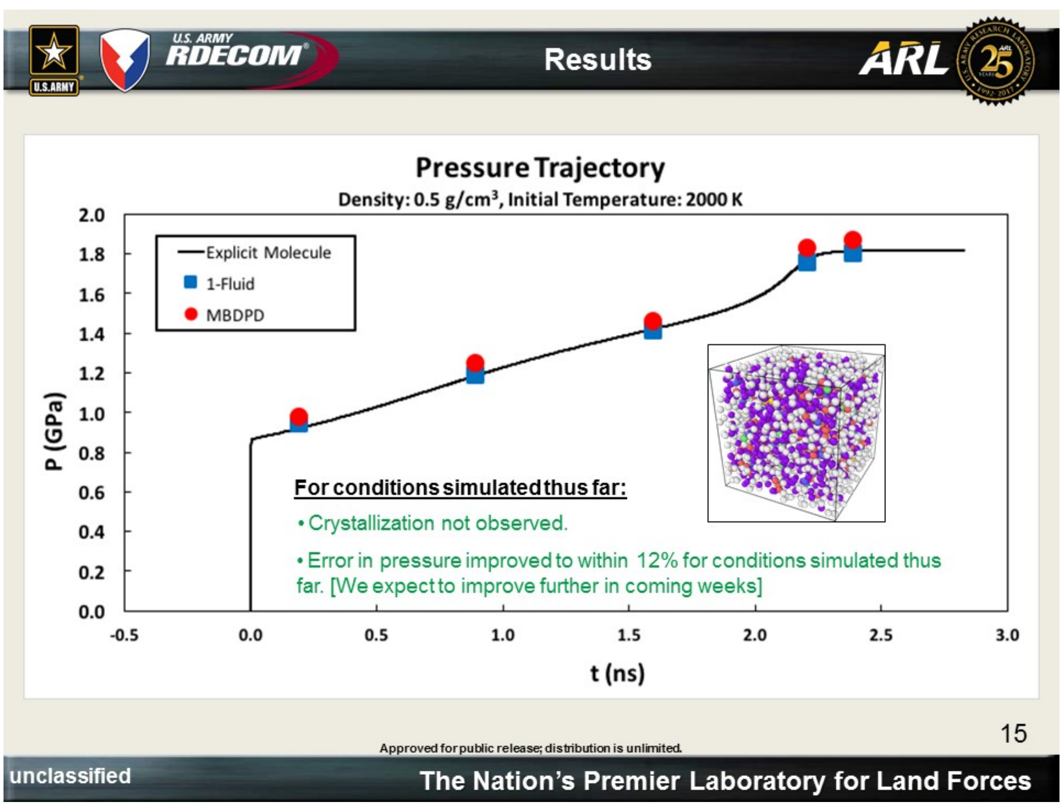
13

Approved for public release; distribution is unlimited.

unclassified

The Nation's Premier Laboratory for Land Forces

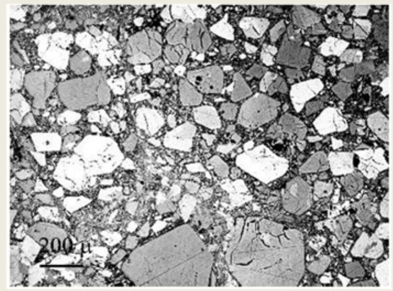

U.S. ARMY
RDECOM
Results
ARL
Pressure Trajectory
Density: 1.8 g/cm³, Initial Temperature: 2000 K
Explicit Molecule
1-Fluid
DPD (Old Model)
MBDPD
P (GPa)
t (ns)
14
Approved for public release; distribution is unlimited.
unclassified
The Nation's Premier Laboratory for Land Forces


U.S. ARMY
RDECOM
Results
ARL
Pressure Trajectory
Density: 0.5 g/cm³, Initial Temperature: 2000 K
Explicit Molecule
1-Fluid
MBDPD
P (GPa)
t (ns)
For conditions simulated thus far:
• Crystallization not observed.
• Error in pressure improved to within 12% for conditions simulated thus far. [We expect to improve further in coming weeks]
15
Approved for public release; distribution is unlimited.
unclassified
The Nation's Premier Laboratory for Land Forces

Conclusions/Significance

- **Advancing a very new and promising field: coarse-graining of chemically reacting systems**
- Performance permitted simulations MUCH faster than explicit molecule simulation
- Potential application to other materials

- Better, larger-scale models = improved understanding of microstructure effects = …
  - Less risk
  - Less cost
  - Higher quality
  - **SAFER SOLDIERS**



Skidmore, C.B., Phillips, D.S., Howe, P.M., Mang, J.T., and Romero, J.A., 11th International Detonation Symposium, Snowmass Village, Colorado, pp. 556.

Approved for public release; distribution is unlimited.

16

unclassified The Nation's Premier Laboratory for Land Forces

Ongoing Work

- Continue development, debugging, integration, and demonstration of the new PGM
- Computational cost comparisons
- Complete planned table of simulations

Future Work

- Publication in progress
- Integration into LAMMPS software (widely used particle simulator)
- Integration into/Demonstration of reactive models

Experience Gained So Far

- Excalibur/HPC
- Parallelization (OpenMP)
- Batch schedulers (PBS)
- Fortran
- Python
- Git
- Code profiling/optimization
  - Dakota
- Engility (Tim Mattox, Mike Lasinski)

Approved for public release; distribution is unlimited.

17

unclassified The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Acknowledgements

ARL

- Mentors
  - John Brennan
  - Jim Larentzos
- Mike Fortunato (HIP and Univ. of Florida)
- HPC Modernization Program (HPCMP)
- HPC Internship Program (HIP)
- HPCMP PETTT Initiative
- Rebecca

Questions?

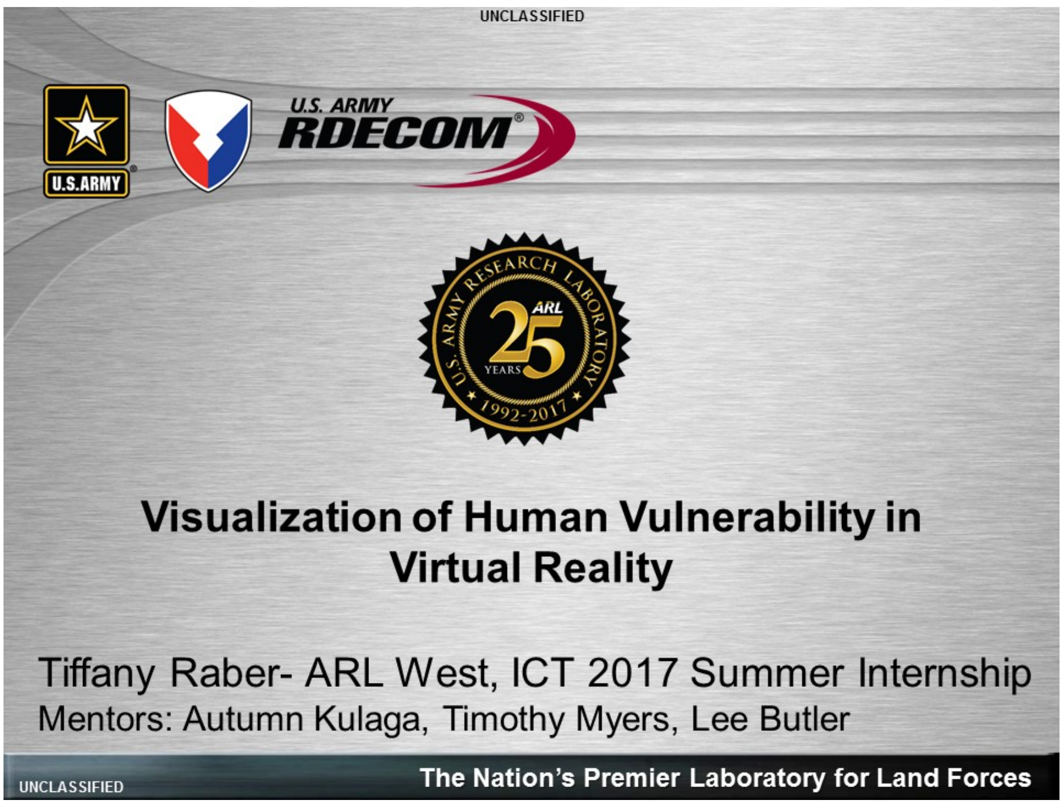
18

unclassified

The Nation's Premier Laboratory for Land Forces

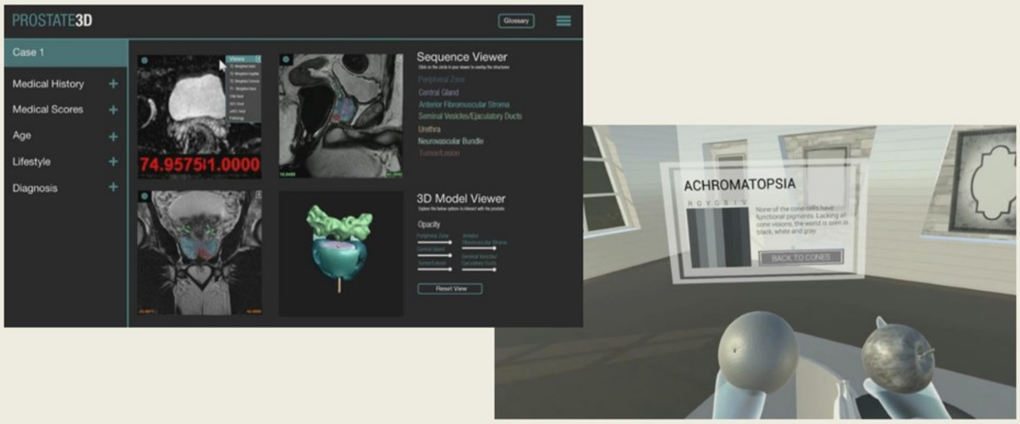
Tiffany Raber

Tiffany Raber is a graduate of the Biomedical Visualization Graduate Program (BVIS) at the University of Illinois at Chicago, having received her master's degree in 2017. As a student, Tiffany grew interested in interactive medical education/simulation techniques, with a specific focus in Unity development and 3D asset creation in the AR/VR space. She believes that the advancement of MedVR will directly impact the field, improving patient experience, surgical training, science education, and user health. Currently, Tiffany is a Visiting Research Assistant, working in modeling and simulation in VR, at The US Army Research Laboratory West, located at the University of Southern California's Institute for Creative Technologies.



UNCLASSIFIED

About Me



2

UNCLASSIFIED

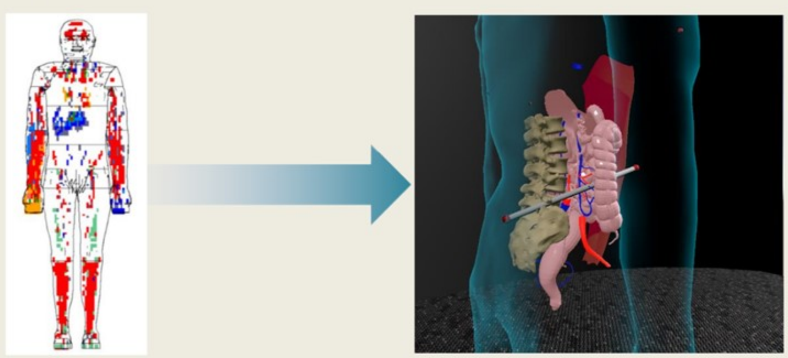
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Background

Project Description

This research explored methods for displaying Operational Requirements Casualty-based Assessment (ORCA) model output in an immersive and interactive environment. We used virtual reality (VR) to explore the use case of a multimodal analysis tool to help understand shot trajectory tracing, output of injury code, and tissue type/name for DoD analyst evaluation of human system-level survivability and lethality studies.



3

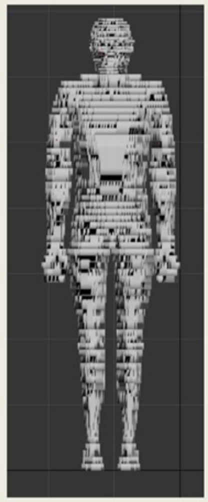
UNCLASSIFIED

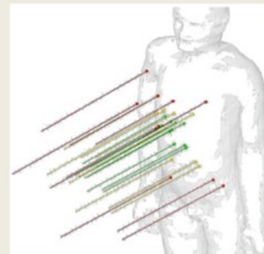
The Nation's Premier Laboratory for Land Forces

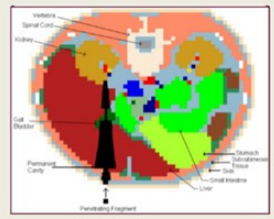
Background

ORCA Methodology Allows For:

- Discrete shot lines through anatomy based on orientation of threat trajectory to personnel
- Projectile penetration mechanics through various anatomical structures
- Velocity retardation of threat through wound track
- Injury description by type, severity, and frequency
- In-depth description of operational effectiveness







Background

Personnel Inputs- Injury (AIS/MAIS)

- ORCA utilizes the **Abbreviated Injury Scale**. AIS is an anatomically based, consensus-derived, international severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale
- MAIS - **Maximum Abbreviate Injury Score**

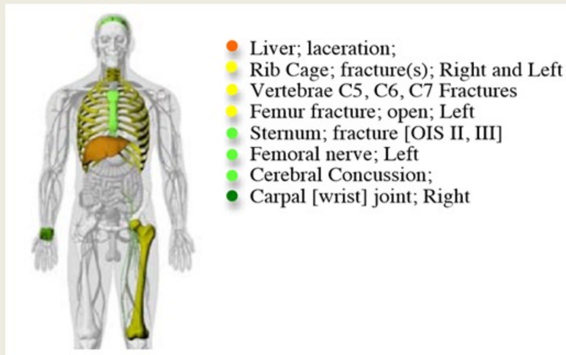
Severity	Injury Level	Example
1	Minor	Bruise
2	Moderate	Major Laceration / Simple Fracture
3	Serious	Femur Fracture
4	Severe	Serious Brain Injury
5	Critical	Cardiac Perforation
6	Maximal	Decapitation
9	Unknown	*Only Region / Tissue Noted*

UNCLASSIFIED

Background

Visual Anatomical Injury Descriptor – (Visual AID)

A web-based graphics tool enabling individuals to illustrate injury onto an anatomical figure and perform discovery operations by inspecting injury patterns using composite information



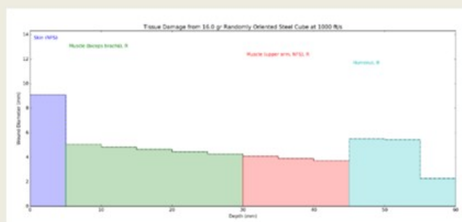
6

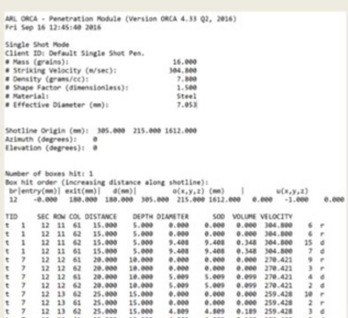
UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Why VR?!





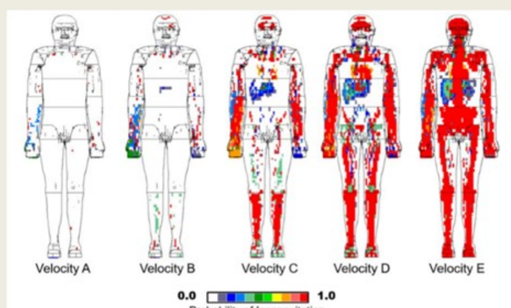
```
ARL ORCA - Penetration Module (Version ORCA 4.33 Q2, 2016)
Fri Sep 16 12:45:40 2016

Single Shot Mode
Client ID: Default Single Shot Pen.
# Mass (grains):                          16.000
# Striking Velocity (m/sec):             304.800
# Density (grams/cc):                      7.800
# Shape Factor (dimensionless):            1.500
# Material:                                Steel
# Effective Diameter (mm):                 7.053


Shotline Origin (mm):  305.000  215.000 1612.000
Azimuth (degrees):     0
Elevation (degrees):   0


Number of boxes hit: 1
Box hit order (increasing distance along shotline):
 br|entry(mm)| exit(mm)|   d(mm)|         o(x,y,z) (mm)      |         u(x,y,z)
 12    -0.000   180.000  180.000  305.000  215.000 1612.000   0.000   -1.000    0.000

TID      SEC ROW COL DISTANCE    DEPTH DIAMETER      SOD  VOLUME VELOCITY
t   1    12  11  61   15.000    5.000    0.000    0.000   0.000  304.800    6  r
t   1    12  11  62   15.000    5.000    0.000    0.000   0.000  304.800    6  r
t   1    12  11  62   15.000    5.000    9.408    9.408   0.348  304.800   15  d
t   1    12  11  61   15.000    5.000    9.408    9.408   0.348  304.800    7  d
t   7    12  12  61   20.000   10.000    0.000    0.000   0.000  270.421    9  r
t   7    12  12  62   20.000   10.000    0.000    0.000   0.000  270.421    3  r
t   7    12  12  61   20.000   10.000    5.009    5.009   0.099  270.421    4  d
t   7    12  12  62   20.000   10.000    5.009    5.009   0.099  270.421    2  d
t   7    12  13  62   25.000   15.000    0.000    0.000   0.000  259.428   10  r
t   7    12  13  61   25.000   15.000    0.000    0.000   0.000  259.428    2  r
t   7    12  13  62   25.000   15.000    4.809    4.809   0.189  259.428    3  d
t   7    12  13  61   25.000   15.000    4.809    4.809   0.189  259.428    2  d
```



7

UNCLASSIFIED

The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Methodology

8

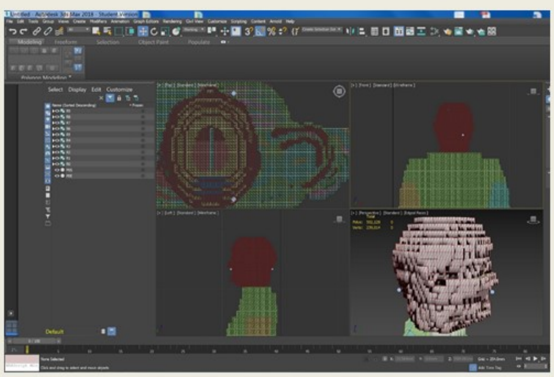
UNCLASSIFIED

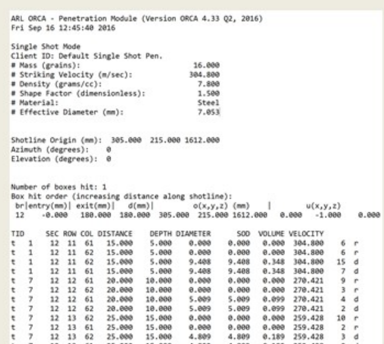
The Nation's Premier Laboratory for Land Forces

UNCLASSIFIED

Methodology

Data Visualization/Geometry Optimization





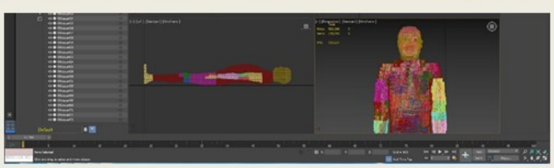
```
ARL ORCA - Penetration Module (Version ORCA 4.33 Q2, 2016)
Fri Sep 16 12:45:40 2016

Single Shot Mode
Client ID: Default Single Shot Pen.
# Mass (grains):                          16.000
# Striking Velocity (m/sec):             304.800
# Density (grams/cc):                      7.800
# Shape Factor (dimensionless):            1.500
# Material:                                Steel
# Effective Diameter (mm):                 7.053


Shotline Origin (mm):  305.000  215.000 1612.000
Azimuth (degrees):    0
Elevation (degrees):  0


Number of boxes hit: 1
Box hit order (increasing distance along shotline):
 br|entry(mm)| exit(mm)|   d(mm)|        o(x,y,z) (mm)     |        u(x,y,z)
 12    -0.000   180.000  180.000  305.000  215.000 1612.000    0.000   -1.000    0.000

TID      SEC ROW COL DISTANCE    DEPTH DIAMETER      SOD  VOLUME VELOCITY
t   1     12  11  61   15.000    5.000    0.000    0.000   0.000  304.800    6  r
t   1     12  11  62   15.000    5.000    0.000    0.000   0.000  304.800    6  r
t   1     12  11  62   15.000    5.000    9.408    9.408   0.348  304.800   15  d
t   1     12  11  61   15.000    5.000    9.408    9.408   0.348  304.800    7  d
t   7     12  12  61   20.000   10.000    0.000    0.000   0.000  270.421    9  r
t   7     12  12  62   20.000   10.000    0.000    0.000   0.000  270.421    3  r
t   7     12  12  61   20.000   10.000    5.009    5.009   0.099  270.421    4  d
t   7     12  12  62   20.000   10.000    5.009    5.009   0.099  270.421    2  d
t   7     12  13  62   25.000   15.000    0.000    0.000   0.000  259.428   10  r
t   7     12  13  61   25.000   15.000    0.000    0.000   0.000  259.428    2  r
t   7     12  13  62   25.000   15.000    4.809    4.809   0.189  259.428    3  d
t   7     12  13  61   25.000   15.000    4.809    4.809   0.189  259.428    2  d
```



9

UNCLASSIFIED

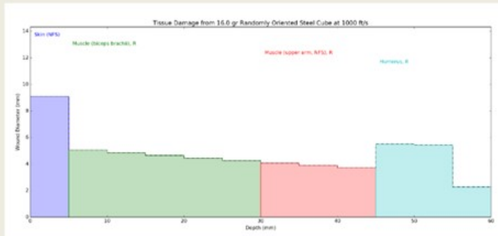
The Nation's Premier Laboratory for Land Forces

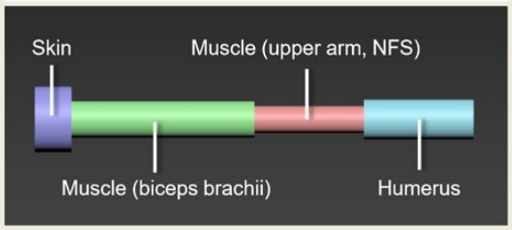
Approved for public release; distribution is unlimited.

Methodology

Trajectory Visualization

Penetration plot of tissue damage from 1.6.0 gr steel cube and corresponding shot line geometry representing depth and diameter of tissue damage:

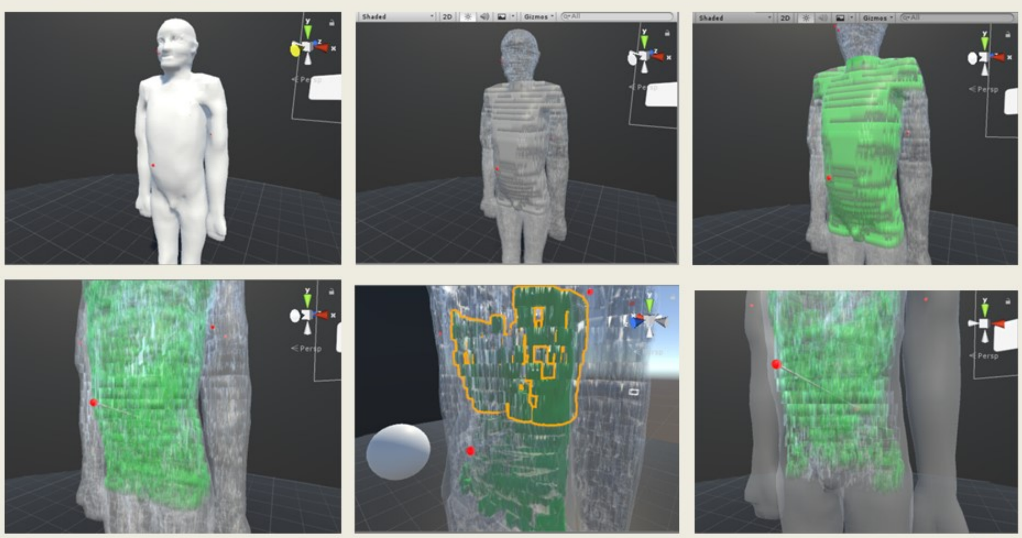




UNCLASSIFIED

Methodology

Tissue Visualization



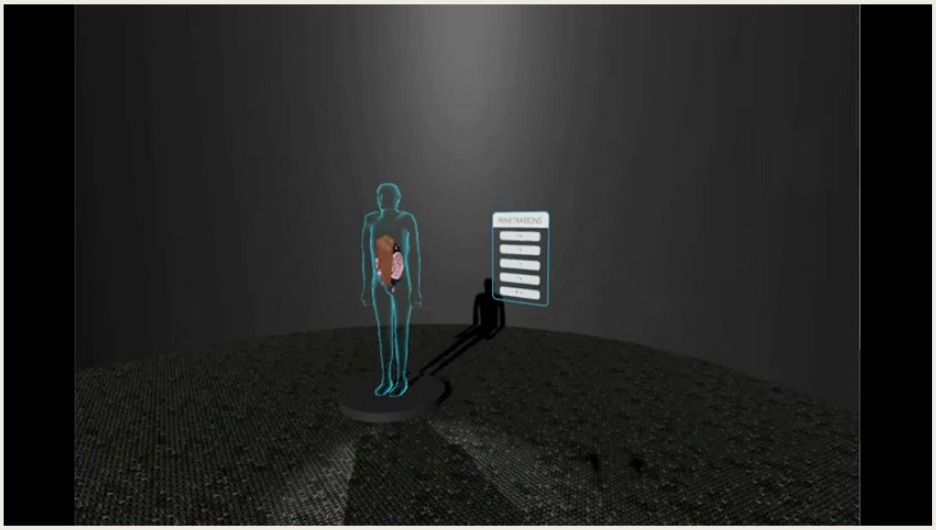
UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

U.S. ARMY RDECOM

Methodology

ARL

Interactive Virtual Reality Example- Teleportation



12

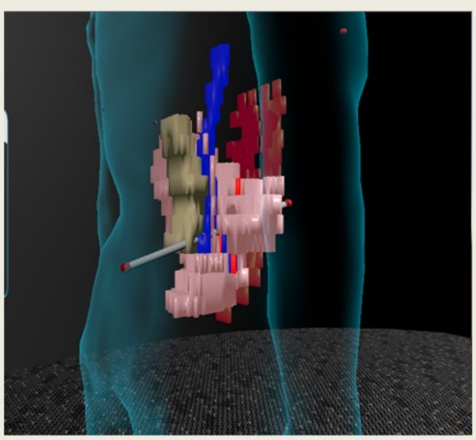
UNCLASSIFIED

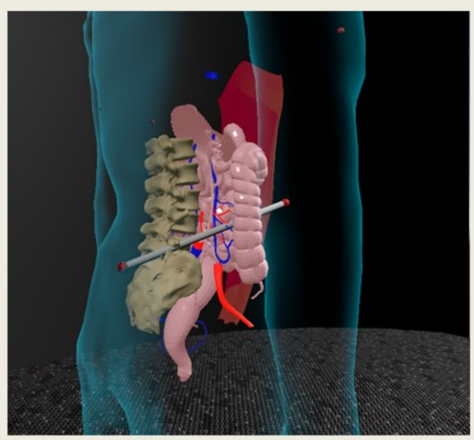
U.S. ARMY RDECOM

Results

ARL

ORCA vs. Visual AID

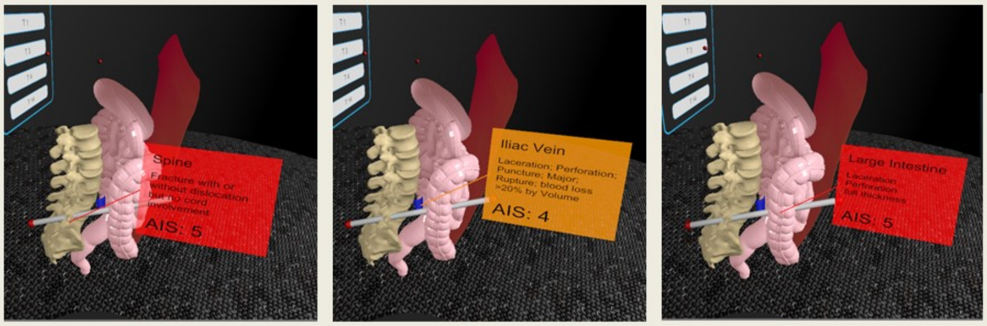




13

Results

User Interface



14

UNCLASSIFIED

Potential Future Work

- User Note Taking/Image Saving
- Custom data importing
- Clipping plane
- Wound-track animation
- Co-operative design mode
- Population of models (anthropometrics & postured)
- Context relevant environments (vehicle systems)

UNCLASSIFIED
The Nation's Premier Laboratory for Land Forces

Acknowledgements

A special thank you:

Autumn Kulaga

Timothy Myers

Lee Butler

ARL

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDF)	DIR ARL IMAL HRA RECORDS MGMT RDRL DCL TECH LIB
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
1 (PDF)	ARL RDRL WML B R PESCE-RODRIGUEZ