Objective: The goal of this project is to challenge and expand the current understanding of how numerical methods and emerging computational architectures can be used to predict the dynamics of dry granular systems. At mesoscale, the research will seek high fidelity Direct Numerical Simulation (DNS) methodologies that increase the size of the granular systems tackled in a fully resolved, discrete, fashion by three orders of magnitude. At macroscale, the research will investigate expeditious continuum representations suitable for granular dynamics simulation. Finally, kinematically consistent homogenization and discretization approaches are envisioned to bridge computational nonlinear dynamics, many-body dynamics, friction and contact, numerical methods, differential variational problem, quadratic optimization.
Report Title
Final Report: MATHEMATICAL SCIENCE: A Homogenization-Driven Multiscale Approach for Characterizing the Dynamics of Granular Media and its Implementation on Massively Parallel Heterogeneous Hardware Architectures

ABSTRACT

Objective: The goal of this project is to challenge and expand the current understanding of how numerical methods and emerging computational architectures can be used to predict the dynamics of dry granular systems. At mesoscale, the research will seek high fidelity Direct Numerical Simulation (DNS) methodologies that increase the size of the granular systems tackled in a fully resolved, discrete, fashion by three orders of magnitude. At macroscale, the research will investigate expeditious continuum representations suitable for granular dynamics simulation. Finally, kinematically consistent homogenization and discretization approaches are envisioned to bridge the meso/macro scales and lead to variable resolution, hybrid continuum-discrete numerical solution methods.

Approach: The proposed approach builds on a multi-scale, i.e., mesoscale-macroscale, and multi-resolution, i.e., discrete-continuum, vision for the computer-enabled analysis of granular systems. At mesoscale, the computer is envisioned to play the role of a research instrument capable of providing detailed information about the state of the system: contact forces, element orientation, angular velocities, etc., that is subsequently used to synthesize new constitutive models and rheologies. At macroscale, a fine/coarse-graining, two-way scale bridging will lead to hybrid continuum-discrete approaches enabling the analysis of manufacturing and design engineering problems.

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

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

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<td>2.00 Hammad Mazhar, Toby Heyn, Dan Negrut, Alessandro Tasora. Using Nesterov's Method to Accelerate Multibody Dynamics with Friction and Contact, ACM Transactions on Graphics, (05 2015): 0. doi: 10.1145/2735627</td>
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Number of Papers published in peer-reviewed journals:

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

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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

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TOTAL:

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TOTAL:

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(d) Manuscripts

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TOTAL:

Number of Manuscripts:

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TOTAL:

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TOTAL:

Patents Submitted

Patents Awarded

Awards
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<td>Arman Pazouki</td>
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<td>Hammad Mazhar</td>
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<tr>
<td>Toby Heyn</td>
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FTE Equivalent: 1.50
Total Number: 3

Names of Post Doctorates

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FTE Equivalent: 1.50
Total Number: 3

Names of Faculty Supported

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<tr>
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Names of Under Graduate students supported

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FTE Equivalent: 1.50
Total Number: 3

Student Metrics

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

The number of undergraduates funded by this agreement who graduated during this period: .......
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: .......
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: .......
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): .......
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: .......
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense: .......
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: .......

Names of Personnel receiving masters degrees

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Names of personnel receiving PHDs

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<td>Toby Heyn</td>
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<td>Arman Pazouki</td>
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Total Number: 3

Names of other research staff

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<td>Radu Serban</td>
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FTE Equivalent: 0.50

Total Number: 1

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment.

Technology Transfer

See attachment.
1. Science
a. What is the mathematical objective of your project? What question are you trying to answer?
The mathematical objective was to identify numerical methods that can be used to determine the evolution of many-body dynamics systems. For rigid-body dynamics with friction and contact, the computational bottleneck is the solution of a large scale optimization problems. In this context, the question that I’m trying to answer is: How can I solve expeditiously and robustly a large semi-definite quadratic problem with conic constraints (SD-QPwCC) in millions of variables?

b. What are the challenges in doing this? What makes it difficult?
The source of the SD-QPwCC is the simulation of many-body dynamics in the presence of friction and contact. As such, the dimension of the optimization problem is very large. For instance, in one cubic meter of sand there are about two billion elements. This problem would have about 8 billion contacts, which leads to a QPCC in approximately 25 billion variables. To date, the largest problem that we have solved has approximately 40 million variables. The challenging part is finding numerical methods that are (i) robust to handle problems on this scale; i.e., we can actually solve the problem, and (ii) can be parallelized for leveraging advanced computing; i.e., we can solve the problem reasonably fast so that we can put it to good use in conjunction with practical problems.

c. What is the scientific opportunity that is enabling you to make progress in this difficult area?
Recent advances in optimization techniques provided the motivation to investigate new methodologies for the solution of large many-body dynamics problems. Also, there is great impetus behind the topic of advanced computing – everything from emerging parallel computing hardware to new libraries for CPU/GPU parallel computing. The introduction of new solution methods that leverage new hardware have allowed us to reduce simulation times by a factor of 25 over the last five years. The research conducted during this project has provided support to make this leap possible. We are now capable of analyzing significantly larger problems that open up new avenues for computing-enabled discovery and innovation.

d. Please attach one (or a few if you wish) graphic that best represents what your project is about. People are visual; one graphic can help them grab onto your project much quicker.
Rather than attaching a graphic, I’m providing a link where there are more than 150 movies that we have generated, most of them over the last three years. These movies can be downloaded. All the recent movies use the numerical methods and software infrastructure advances made possible by the research sponsored by Dr. Myers. Still images from any movie at the links below can be provided upon request:
https://vimeo.com/uwsbel
http://sbel.wisc.edu/Animations/

2. Collaborations
a. Name and give organization of anybody in the Army/DoD/govt who you have collaborated with in the course of this project.
- Dr. Paramsothy Jayakumar of US Army TARDEC
- Mr. Mike Letherwood of US Army TARDEC
- Dr. Mihai Anitescu of Argonne National Lab
- Dr. James Schneider of US Navy NAVFAC EXWC
b. Describe the nature of the collaboration. Include co-authoring with them, giving talks at their place, inviting them to your school, getting scenarios or data or ideas from them, conducting joint workshops or seminars, etc.

Dr. Jayakumar: I have had extensive collaborations with him. I have co-authored several journal and conference manuscripts with him and he and several of his colleagues from US Army TARDEC have had multiple visits to my lab. I have visited with him at US Army TARDEC on several occasions and I have given several seminars there over the last three years (see list of talks provided in this document). My lab is in the process of organizing a joint “Machine-Ground Interaction Consortium” (MaGIC) meeting in Novi, Michigan, right next to TARDEC on August 3-4, 2016 in collaboration with Dr. Jayakumar.

Mr. Letherwood: My interaction with Mr. Letherwood has been very similar to my collaboration with Dr. Jayakumar.

Dr. Mihai Anitescu: We worked together on modeling approaches for granular material. I provided material for his presentations and he served on the PhD thesis committee of one of my students (Toby Heyn) who was funded through this ARO project.

Dr. James Schneider: He attended one of the meetings organized by the PI in Madison, see MaGIC meeting below. He is interested in using the software infrastructure Chrono that embeds the numerical solution advances made under this project.

c. If any of your students, postdocs, or faculty were hired by the Army or DoD, please give details.

Graduate student Daniel Melanz is currently employed by US Army TARDEC and he is anticipating graduating with a PhD degree in May 2016.

3. Transitions: Describe anything from this project that you transitioned to anybody else (whether Army, DoD, govt, commercial, or other).

a. Who did you give it to, and what is their organization?

The research that was funded by Dr. Myers led to a numerical method that is now the workhorse in a frictional contact solver used in a physics-based simulation engine called Chrono. Chrono is an open source parallel computing infrastructure that is being developed under a $1.8 million project funded through an Army Rapid Innovation Fund award that is managed by Dr. Jayakumar of US Army TARDEC. Chrono has more than 200,000 lines of code and runs rigid body dynamics, flexible body dynamics, and fluid-solid interaction problems. The funding from Dr. Myers’ project allowed us to further develop the code.

Links:
- https://github.com/projectchrono/chrono
- http://projectchrono.org/chronoengine/

Chrono is also currently undergoing testing by Oshkosh Corporation. They are evaluating Chrono to understand whether it will allow them to accurately simulate the JLTV on deformable terrain. There is no other software capability today, commercial or open source, which can provide this type functionality. In addition to being used for off-road mobility studies, Chrono is being used by UC-San Diego for the motion of molecules as well as by NASA, by US Army ERDC, by Statoil in Norway, etc. for various applications.

b. What did you give them? Code, papers, algorithms...

We provided free open source code, papers, algorithms, models, presentation, and software documentation. We also ran a tutorial on how to use our software, which was attended by individuals from US Army TARDEC and ERDC.

c. What eventual application might this enable?
Chrono has been selected to participate in a NATO-run process to recommend what simulation tool(s) should replace the current NATO Reference Mobility Model (NRMM) which has been used for mobility go/no-go studies for more than four decades. Beyond this, Chrono has already been used to study additive manufacturing, oil spill capping designs, vehicle dynamics, etc.

d. What was your scientific accomplishment that enabled this?

Development of
- New numerical techniques
- New modeling approaches (cohesion)
- Techniques for collision detection between deformable geometries
- Design of algorithms that can leverage parallel computing (matrix free, GPU computing, AVX support)

4. Awards/honors: By you and anybody funded by this project: students, postdocs, faculty ...

   a. Include awards, prizes, Fellow/Society election, best paper prizes (especially student), elected positions, papers in Science or Nature, ...
      - As of October of 2015, I am the Chair of the Technical Committee on Multibody System and Nonlinear Dynamics of the American Society of Mechanical Engineers. I’ll serve in this capacity for two years.
      - I serve on the editorial board of three journals
      - I have been awarded a 2014-2016 Vilas Fellowship for recognition of contributions to research made at the University of Wisconsin-Madison. This is one of the most prestigious research accolades at the University of Wisconsin-Madison
      - I have been awarded the NVIDIA CUDA Fellow status for contributions in parallel computing on the GPU six consecutive times
      - I have been awarded the 2016 College of Engineering “Equity and Diversity Award” at UW-Madison
      - I have been invited to give several keynote talks in Europe/North America/Asia, one of them in conjunction with a NATO meeting on advanced computing in ground mobility topics
      - I was a member of the following steering committees:
        o 2014 International Conference on Multibody System Dynamics, Soul, S. Korea
        o 2016 International Conference on Multibody System Dynamics, Montreal, Canada
      - I was the conference chair for the International Conference on Multibody Systems, Nonlinear Dynamics, and Control (MSNDC),
        o 10th edition, Buffalo, NY, 2014

5. Metrics related to your grant:

   a. # peer-reviewed papers (related to this grant)
      - Hammad Mazhar, Toby Heyn, Dan Negrut, and Alessandro Tasora. 2015. Using Nesterov’s Method to Accelerate Multibody Dynamics with Friction and Contact. ACM Trans. Graph. 34, 3, Article 32 (May 2015)

b. manuscripts (related to this grant)
- If this counts, there is a series of technical reports that we produced and are related to this project, http://sbel.wisc.edu/Publications/

c. presentations.
All presentations mentioned below acknowledged the Army funding support:
3. “Chrono-Gazebo: An open source integrated framework for intelligent vehicle on/off-road mobility analysis,” NATO Advanced Vehicle Technology Committee meeting, Prague, Czech Republic, October 14, 2015
15. “Getting Shape into Computational Dynamics. Getting Computational Dynamics in Shape,” Department of Mechanical Engineering, University of Michigan, April 7, 2014


International Conference on Multibody System Dynamics (IMSD), June 30-July 3 2014, Busan, South Korea


d. patents submitted (funded by this grant)
None.

e. # grad students/yr (funded by this grant)
one/year, year 1 and 2
   - Toby Heyn
   - Arman Pazouki

f. #postdocs/yr (funded by this grant)
Assistant Scientist: 1/year, year 3 (Radu Serban).

g. PhD degrees awarded (funded by this grant)
Two: Toby Heyn and Arman Pazouki.

h. MS degrees awarded (funded by this grant)
None.

6. Anything else of note we should know about and tell the BOV about?
Three years ago I organized a Machine-Ground Interaction Consortium (MaGIC) meeting in Madison, WI that was set up to facilitate the transfer of technology from academia to industry/gov. labs. This effort has continued as a series of twice a year meetings with a continually increasing number of participants. We are well positioned to support a vigorous technology transfer effort since all of our code/papers/tech reports are in a public repository (GitHub) or are on the lab website and as such are open to everyone. Our simulation engine is open source and free for unrestricted use, distribution, copying, editing, and resale. In 2015 we organized the third and fourth editions of MaGIC, which brought together industry, government, and academia members interested in understanding how advanced computing is shaping the area of vehicle mobility. So far, the list of participants to these MaGIC events have included: US Army TARDEC, US Army ERDC, US Marine Crops, Open Source Robotics Foundation, Jet Propulsion Laboratory, NASA, Japan Aerospace Exploration Agency, Caterpillar, P&H Mining, MSC.Software, Simertis GmbH, BAE Systems, Eaton Corporation, Rescale, Red Cedar Technology, NVIDIA, Nevada Automotive Test Center, Harley-Davidson Motor Company, Oshkosh Corporation, John Deere, Statoil (Norway), Proctor and Gamble, Cooper Industries, GlaxoSmithKline, HR Wallingford LTD, Motionport, Altair, Hendrickson, Japan Department of Defense, Intuitive Machines, Energid Technologies, SmartUQ, SimLab Soft, Progeneric Systems, Function Bay, Trek Bicycles, Dynamic Simulation Technologies, University of Wisconsin-Madison, Johns Hopkins University, University of Iowa, Georgia Institute of Technology, University of Parma (Italy), Politecnico di Milano (Italy), MIT, Darmstadt University (Germany), University of Illinois at Chicago, University of Aarhus (Denmark), Beijing Technical
Institute (China), Fraunhofer Institute for Industrial Mathematics at Kaiserslautern University (Germany), and Inha College (S. Korea).