COMPUTATIONAL MANUFACTURING AND MATERIALS LABORATORY GROUP RESEARCH THEMES

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Chancellor's Professor, Department of Mechanical Engineering
W. C. Hall Endowed Chair in Engineering

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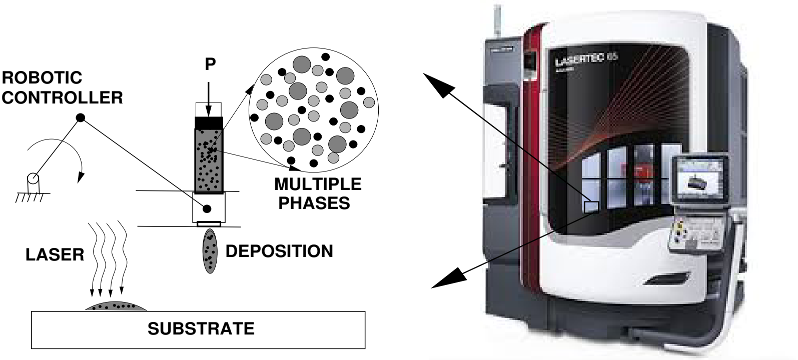
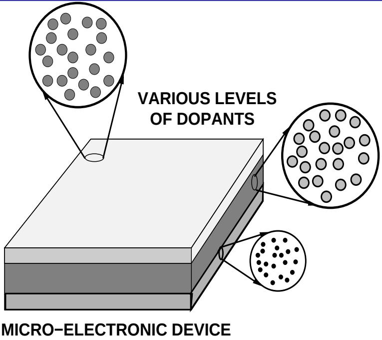
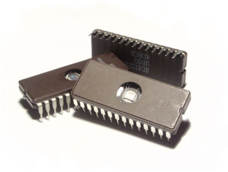
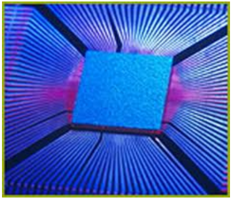
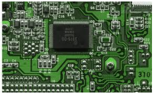


1. INDUSTRIAL GOAL: RAPID SIMULTANEOUS CONTROL OF DEPOSITION, LASERS/HEAT AND MATERIALS
2. 3DP COMBINES: POSITIONING $\leftrightarrow$ DEPOSITION $\leftrightarrow$ HEATING $\leftrightarrow$ FUNCTIONALIZED MATERIALS
3. MULTISTAGE PROCESSES: NEXT-GENERATION MACHINES NEED COMPUTATIONAL GUIDANCE!
4. **NEXT-GEN MACHINE (DMG MORI):** `https://www.youtube.com/watch?v=g8sT8ESfjrg`
5. **RESEARCH COLLABORATORS: AHPCRC, APPLE, ARAMCO, ARL, AUTODESK, BASF, BOEING, DOE, FAA, LAWRENCE BERKELEY, LAWRENCE LIVERMORE, LOCKHEED-MARTIN, DMG-MORI, PEER, POWLEY FOUNDATION, SAMSUNG, SANDIA, SIEMENS, TOYOTA**

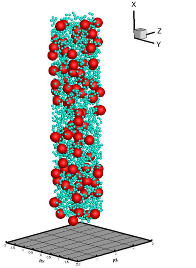


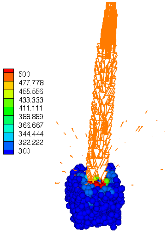


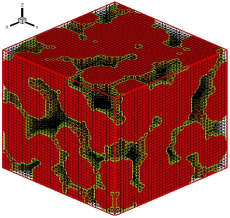




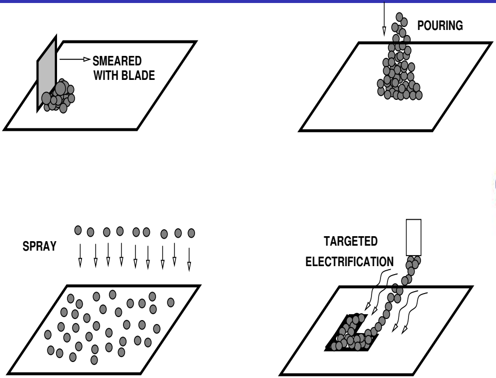
- **DESIRED PROPERTIES: (1) ELASTIC (2) THERMAL (3) ELECTRICAL (4) MAGNETIC (5) OPTICAL ETC.**
- **KEY MOTIVATION: STRATEGIC/RARE MATERIAL REPLACEMENT WITH MICRO-DESIGNED MIXTURES**
- **KEY INGREDIENT: SPECIALIZED PROPERTY DESIGN-BY USE OF FINE-SCALE PARTICLES**
- **ULTIMATE OBJECTIVE: REDUCE PRODUCT DEVELOPMENT TIME AND COSTS THROUGH SIMULATION**

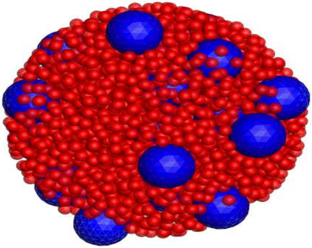






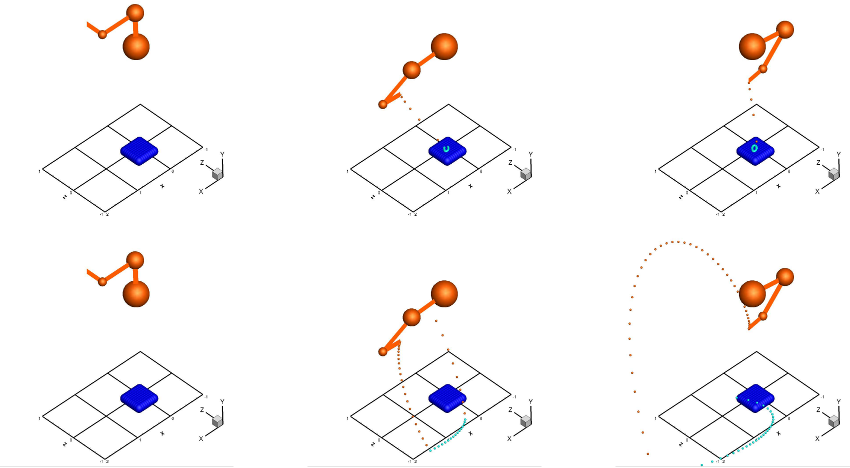
- **KEY COMPONENTS:**
- **PART 1: DETAILED MODELING OF DYNAMIC DEPOSITION OF COMPLEX MIXTURES (DEM)**
- **PART 2: DETAILED MODELING OF LASER PROCESSING OF DEPOSITION (COMPUTIONAL OPTICS)**
- **PART 3: DETAILED MODELING OF CONTINUUM BEHAVIOR (DIGITAL/VOXEL-IMAGE COMPUTATION)**
- **PART 4: MACHINE-LEARNING EXTENSIONS (ARTIFICIAL NEURAL NETWORKS)**
- **INDUSTRIAL GOAL: RAPID SIMULTANEOUS CONTROL OF DEPOSITION, LASERS AND MATERIALS**



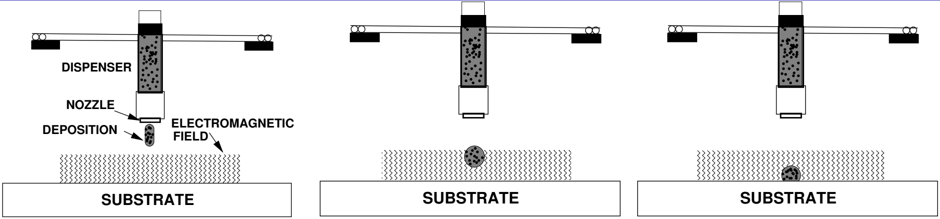


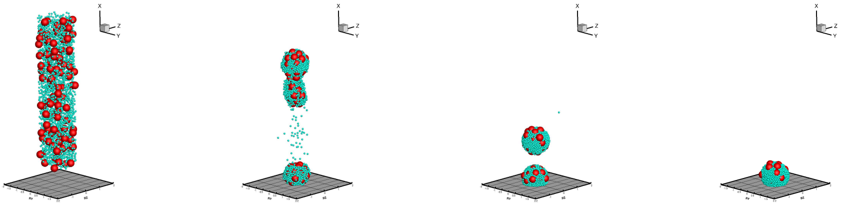
- REGARDLESS OF POST-PROCESSING: CRITICAL FIRST STEP IS TO PLACE PARTICLES ACCURATELY
- METHOD 1: DOCTOR BLADE TO SMEAR PARTICLES-THEN HEAT/LASER (COMMON)
- METHOD 2: POUR FLUIDIZED/INK PARTICLES-THEN HEAT/LASER (COMMON)
- METHOD 3: SPRAY AEROSOLIZED/ATOMIZED PARTICLES-THEN HEAT/LASER (COMMON)
- METHOD 4: ELECTRICALLY GUIDE PARTICLES (MIXTURES)-THEN HEAT/LASER ACCURATE=FUTURE
- PROVIDES EXTREME FAULT-TOLERANCE (ROBOTIC ERROR COMPENSATION)
- ELECTRIFICATION AND CHARGING PRODUCES CONTROLLABLE FLUID-LIKE BEHAVIOR
- SECONDARY (BLUE) PARTICLES FUNCTIONALIZED THE MIXTURE FOR DESIRED PROPERTIES

COMPARISON: WITH AND WITHOUT TARGETED ELECTRIFICATION

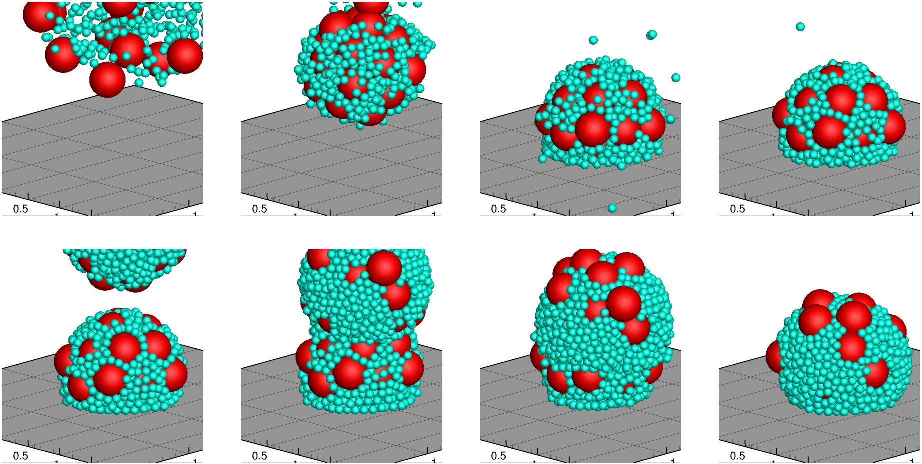


1. INDUSTRIAL GOAL: RAPID SIMULTANEOUS CONTROL OF DEPOSITION, LASERS/HEAT AND MATERIALS
2. 3DP COMBINES: POSITIONING $\leftrightarrow$ DEPOSITION$\leftrightarrow$ HEATING $\leftrightarrow$ FUNCTIONALIZED MATERIALS
3. MULTISTAGE PROCESSES: NEXT-GENERATION MACHINES NEED COMPUTATIONAL GUIDANCE!
4. CRITICAL FIRST STEP IS TO PLACE PARTICLES ACCURATELY-THEN THERMALLY PROCESS

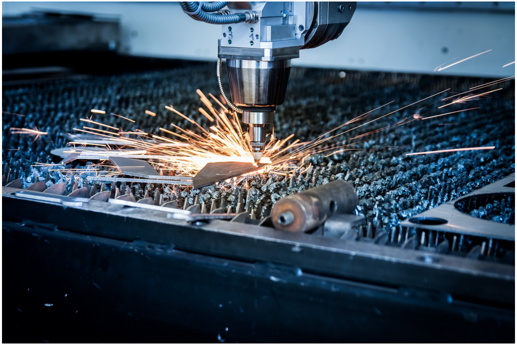


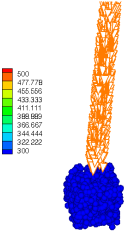


- REPEATED, ACCURATE, CONSISTENT DEPOSITION IS POSSIBLE-LIKE ELECTROSTATIC COPIERS!
- DESPITE PLATEAU-RAYLEIGH-LIKE INSTABILITY
- CHARGE-INDUCED PSEUDO-SURFACE TENSION LEADS TO SURFACE-AREA MINIMIZATION



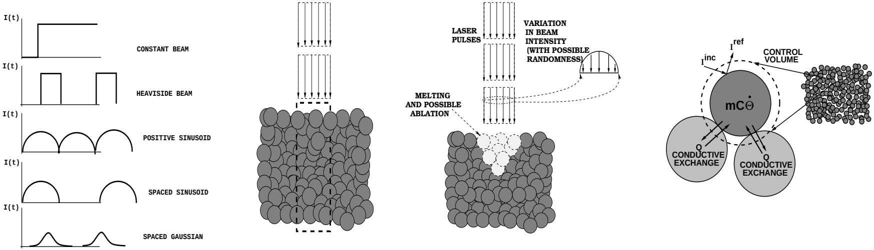
- **CONSISTENT TARGETED DEPOSITION IS ACHIEVABLE-ELECTRICALLY (AND ELECTROMAGNETICALLY)!**

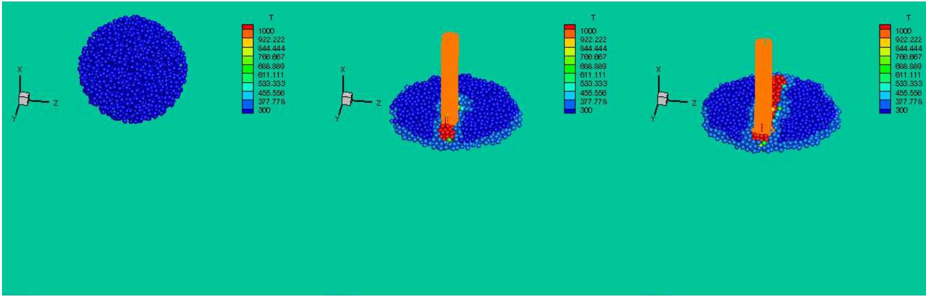


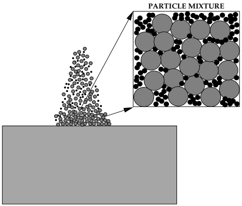


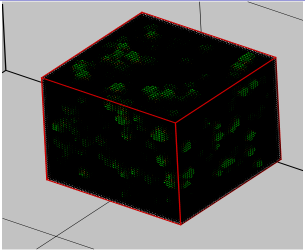
- **Features are added by sintering, melting, vaporizing the materials.**

LASER-BASED POST PROCESSING/FINISHING-MANY POSSIBILITIES

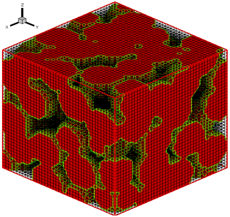








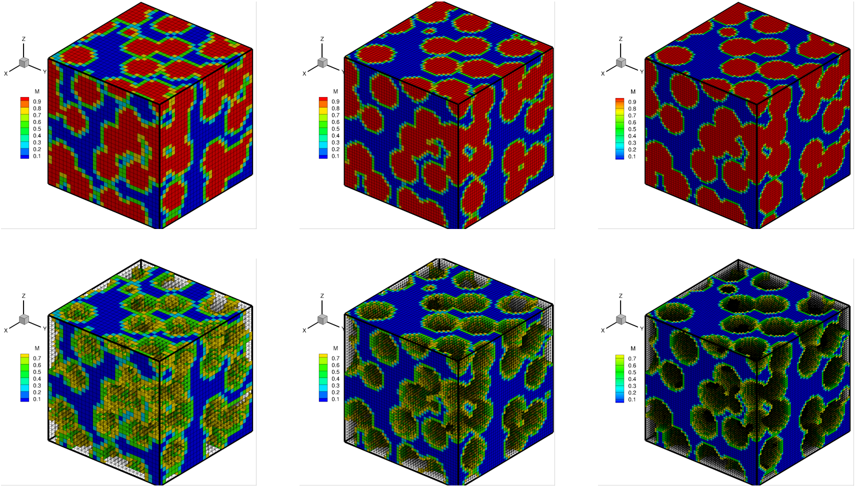
EMBEDDING MESH



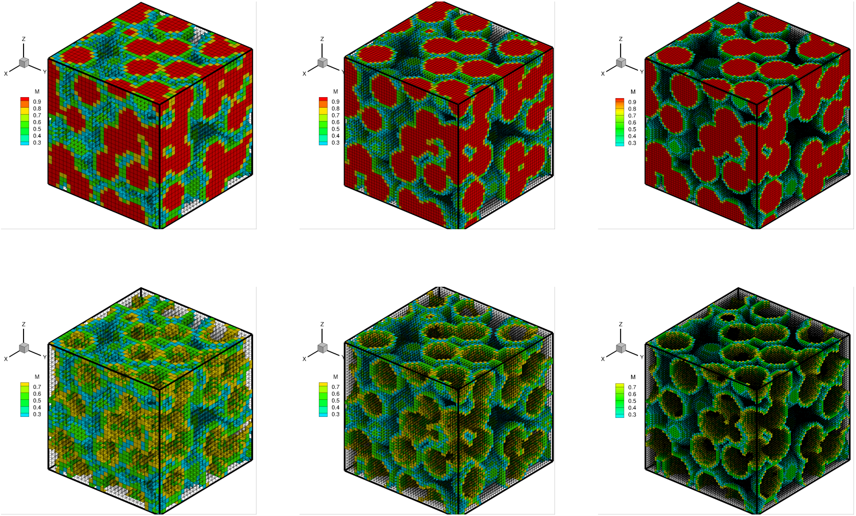
DIGITAL-IMAGE

- **LINEAR MOMENTUM:** $\nabla_x \cdot \boldsymbol{T} + \boldsymbol{f} = \rho \frac{d^2\boldsymbol{u}}{dt^2}$ **AND** $\frac{\partial}{\partial \boldsymbol{X}} \approx \frac{\partial}{\partial \boldsymbol{x}}$ **AND** $\frac{d()}{dt} \approx \frac{\partial()}{\partial t}|_X$
- **CONSTITUTIVE LAW:** $\boldsymbol{T} = \Lambda \boldsymbol{E}_0 : (\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p)$ **WHERE MODULI** $\kappa = \kappa_o e^{a_3 \frac{\theta - \theta_r}{\theta_r}}$ **,** $\mu = \mu_o e^{a_4 \frac{\theta - \theta_r}{\theta_r}}$ **, ETC.**
- **PLASTICITY:** $||\boldsymbol{T}'|| > T_y \Rightarrow \dot{\zeta} = a\left(\frac{||\boldsymbol{T}'||}{T_y} - 1\right)$ **AND** $||\boldsymbol{T}'|| \leq T_y \Rightarrow \dot{\zeta} = 0$ $\quad (T_y = T_{yo} e^{a_1 \frac{\theta - \theta_r}{\theta_r}})$
- **DAMAGE:** $||\boldsymbol{T}'|| > T_d \Rightarrow \dot{\Lambda} = b\left(\frac{||\boldsymbol{T}'||}{T_d} - 1\right)$ **AND** $||\boldsymbol{T}'|| \leq T_d \Rightarrow \dot{\Lambda} = 0$ $\quad (T_d = T_{do} e^{a_2 \frac{\theta - \theta_r}{\theta_r}})$
- **ENERGY:** $\rho_o w = W \approx \frac{1}{2}(\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p) : \boldsymbol{E} : (\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p) + \rho_o \mathcal{C}\theta$
- **FIRST LAW:** $\rho_o C\dot{\theta} = \boldsymbol{T} : (\dot{\boldsymbol{\epsilon}}_\theta + \dot{\boldsymbol{\epsilon}}_p) - \frac{1}{2}(\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p) : \dot{\boldsymbol{E}} : (\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p) + \nabla_X \cdot (\boldsymbol{K} \cdot \nabla_X \theta) + \rho_o z$

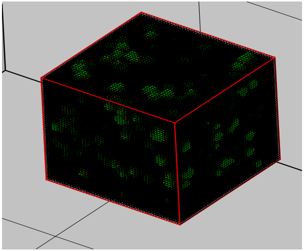
DIGITAL/VOXEL CONVERGENCE: $41 \times 41 \times 41 (206763 DOF) \Rightarrow 61 \times 61 \times 61 (680943 DOF) \Rightarrow 81 \times 81 \times 81 (1594323 DOF)$



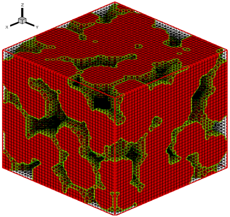
- **DIGITAL/VOXEL-BASED COMPUTATION CAN BE INTERPRETED AS A VARIANT OF:**
- **FDTD-FINITE DIFFERENCE TIME DOMAIN METHOD:** `https://en.wikipedia.org/wiki/Finite-difference_time-domain_method`
- **IBM-IMMERSED BOUNDARY METHOD:** `https://en.wikipedia.org/wiki/Immersed_boundary_method`



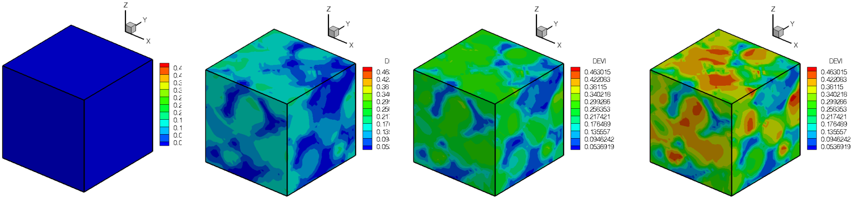
- **PDE-SOLUTION CONVERGENCE CLOSELY CORRELATES TO DIGITAL/VOXEL CONVERGENCE**



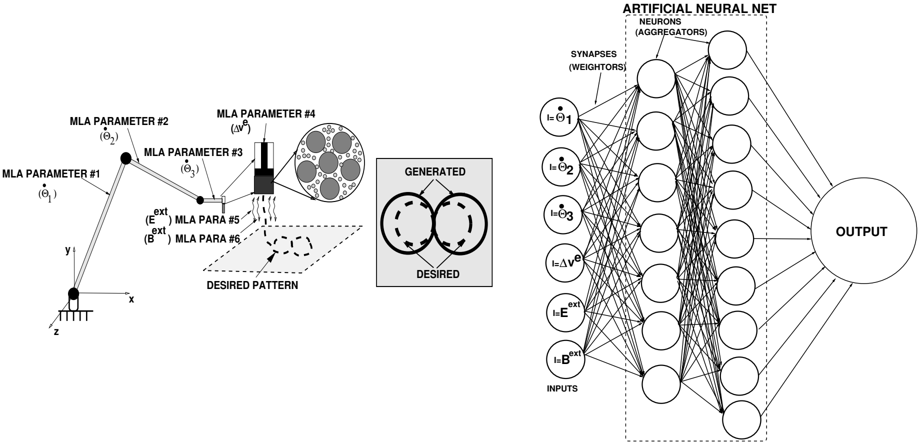
EMBEDDING MESH



DIGITAL-IMAGE

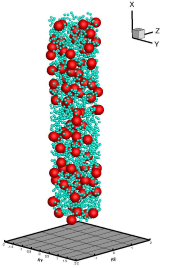


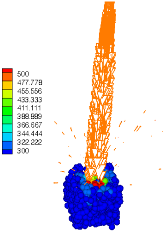
- **LINEAR MOMENTUM:** $\nabla \cdot \boldsymbol{T} + \boldsymbol{f} = \rho_o \frac{\partial^2 \boldsymbol{u}}{\partial t^2}$
- **FIRST LAW:** $\rho_o C\dot{\theta} = \boldsymbol{T} : (\dot{\boldsymbol{\epsilon}}_\theta + \dot{\boldsymbol{\epsilon}}_p) - \frac{1}{2}(\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p) : \dot{\boldsymbol{E}} : (\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_\theta - \boldsymbol{\epsilon}_p) + \nabla \cdot (\boldsymbol{K} \cdot \nabla\theta) + \rho_o z$

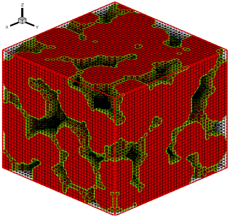


- **FUNDAMENTAL:** $OUTPUT = \mathcal{B}(INPUT, W_1, W_2, \ldots W_N)$ **WHERE $\mathcal{B}$ IS "MIMICED" WITH AN ANN**
- **SYNAPSES:** **MULTIPLY INPUT BY A WEIGHT WHICH REPRESENTS INPUT'S RELEVANCE TO OUTPUT**
- **NEURONS:** **ADD OUTPUTS FROM ALL OF THE SYNAPSES AND APPLY AN "ACTIVATION" FUNCTION**
- **TRAINING:** **RECALIBRATE WEIGHTS FOR DESIRED OUTPUT** $\Rightarrow$ $OUTPUT = \mathcal{B}(INPUT, W_1, W_2, \ldots W_N)$
- **ULTIMATELY, ONE CONSTRUCTS A SYSTEM WITH OPTIMIZED WEIGHTS TO MIMIC A "BRAIN" ($\mathcal{B}$)**

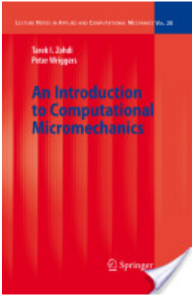
SUMMARY: ADVANCED MANUFACTURING AND 3D PRINTING OF NEW MULTI-FUNCTIONALIZED MATERIALS

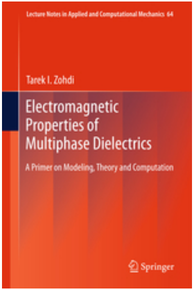


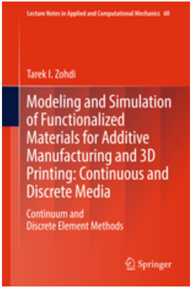




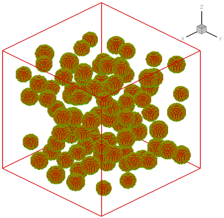
- **MODELING AND SIMULATION INGREDIENTS:**
- **STAGE 1: DYNAMIC DEPOSITION PROCESSING SIMULATION: DISCRETE ELEMENT METHODS**
- **STAGE 2: RAPID LASER PROCESSING SIMULATION: COMPUTATIONAL OPTICS**
- **STAGE 3: CONTINUUM ANALYSIS OF DEPOSITED MATERIAL: DIGITAL/VOXEL-IMAGE COMPUTATION**
- **STAGE 4: MACHINE-LEARNING "WRAPPER": DEEP-LEARNING AND ARTIFICIAL NEURAL NETWORKS**
- **RESEARCH COLLABORATORS: AHPCRC, APPLE, ARAMCO, ARL, AUTODESK, BASF, BOEING, DOE, FAA, LAWRENCE BERKELEY, LAWRENCE LIVERMORE, LOCKHEED-MARTIN, DMG-MORI, PEER, POWLEY FOUNDATION, SAMSUNG, SANDIA, SIEMENS, TOYOTA**



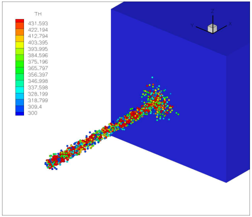




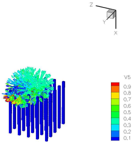
- **Zohdi, T. I. and Wriggers, P. (Book, 2008) Introduction to computational micromechanics. Second Reprinting. Springer-Verlag.**
- **Zohdi, T. I. (Book, 2012) Electromagnetic properties of multiphase dielectrics. A primer on modeling, theory and computation. Springer-Verlag.**
- **Zohdi, T. I. (Book, 2017). Modeling and simulation of functionalized materials for additive manufacturing and 3D printing: continuous and discrete media. Springer-Verlag.**
- **POSTED PAPERS:** http://www.me.berkeley.edu/faculty/zohdi/



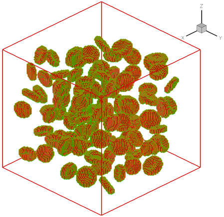
EM-COMPOSITES



CHARGED SPRAYS

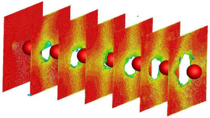


OPTICS

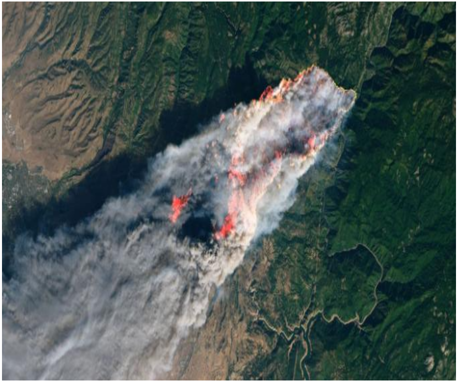


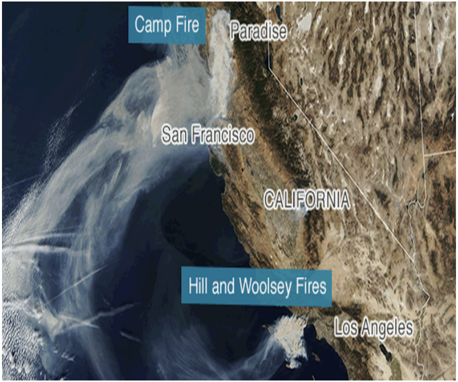
CELL GROUPS

SWARMS(BBC PHOTO)

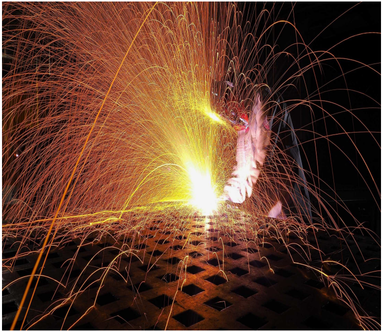


EM-FABRIC

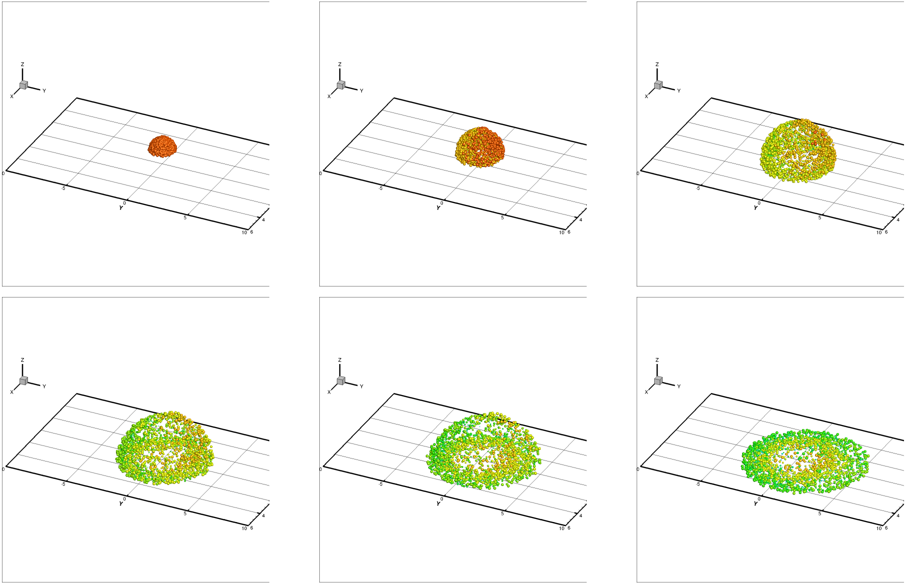




- **LEFT: NASA'S EARTH OBSERVATORY (LANDSAT/MODIS/J. STEVENS)**
- **RIGHT: NASA'S TERRA SATELLITE**



- **DYNAMICS:** $m_i \frac{d\boldsymbol{v}_i}{dt} = m_i \boldsymbol{g} + \frac{1}{2}\rho_a C_D ||\boldsymbol{v}_s - \boldsymbol{v}_i||(\boldsymbol{v}_s - \boldsymbol{v}_i)A_i$
- **THERMO:** $m_i C_i \frac{d\theta_i}{dt} = hA_i^s(\theta_s - \theta_i) + \epsilon\beta A_i^s(\theta_s^4 - \theta_i^4) + \gamma\frac{1}{2}\rho_a C_D ||\boldsymbol{v}_s - \boldsymbol{v}_i||^3 A_i$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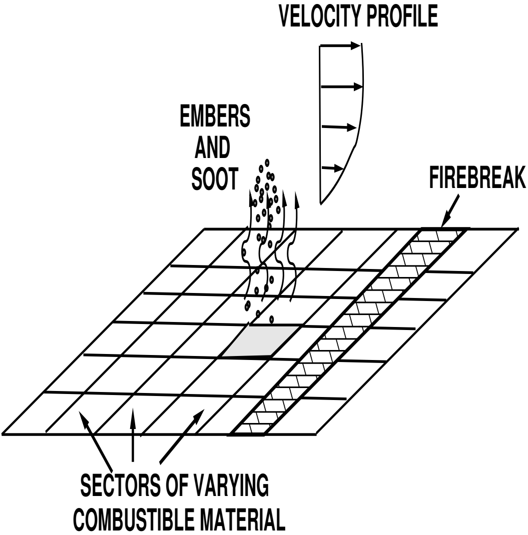
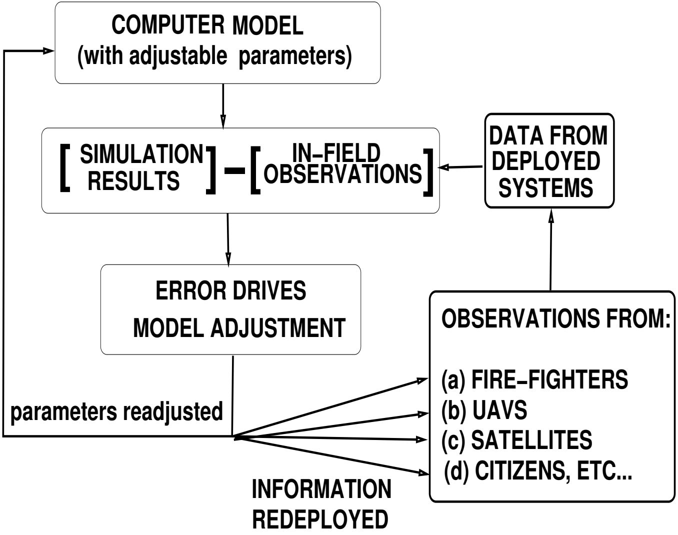
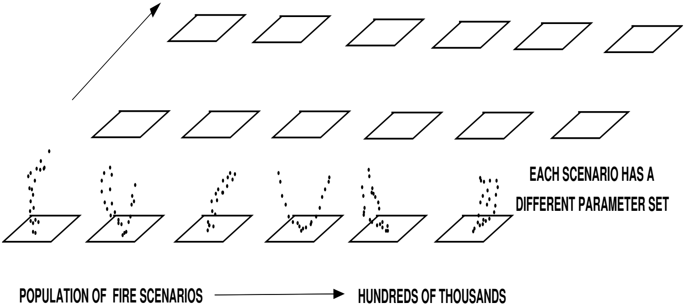
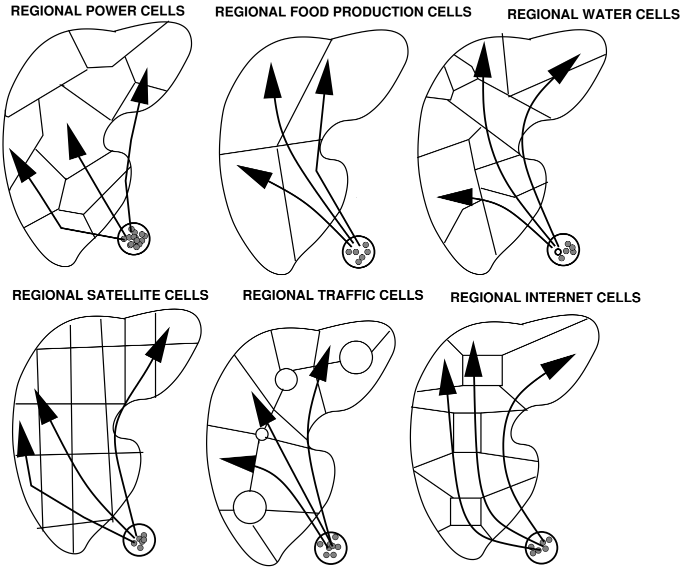

VELOCITY PROFILE
EMBERS AND SOOT
FIREBREAK
SECTORS OF VARYING COMBUSTIBLE MATERIAL


COMPUTER MODEL
(with adjustable parameters)
[SIMULATION RESULTS] – [IN–FIELD OBSERVATIONS]
DATA FROM DEPLOYED SYSTEMS
ERROR DRIVES MODEL ADJUSTMENT
parameters readjusted
OBSERVATIONS FROM:
(a) FIRE–FIGHTERS
(b) UAVS
(c) SATELLITES
(d) CITIZENS, ETC...
INFORMATION REDEPLOYED



- **THE ALGORITHM RAPIDLY HUNTS DOWN THE BEST MODEL “ON THE FLY”**
- **THE KEY: EACH SCENARIO-SIMULATION TAKES A FRACTION OF A SECOND**
- **CAN RAPIDLY TEST THOUSANDS OF SCENARIOS/PARAMETER SETS QUICKLY!**


REGIONAL POWER CELLS
REGIONAL FOOD PRODUCTION CELLS
REGIONAL WATER CELLS
REGIONAL SATELLITE CELLS
REGIONAL TRAFFIC CELLS
REGIONAL INTERNET CELLS

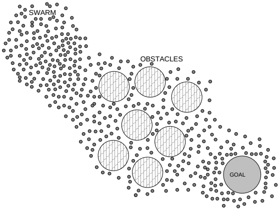
THE RISE OF QUADCOPTERS AND MAPPING STRATEGIES

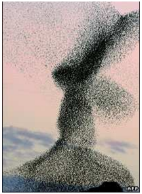


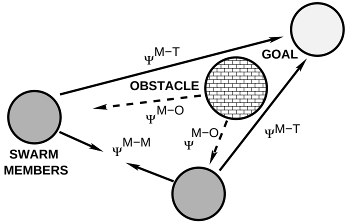




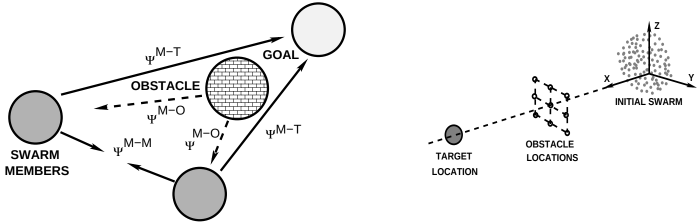
- **EASE OF USE OF DRONES HAS LED TO DEVELOPMENT OF MULTIDRONE STRATEGIES FOR MAPPING**







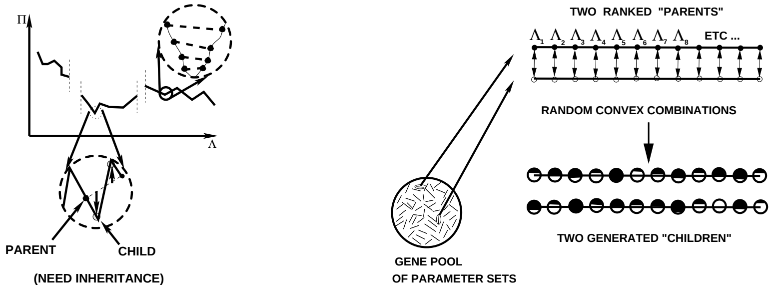
- **MODEL:** $m_i \ddot{\boldsymbol{r}}_i = \underbrace{\boldsymbol{\Psi}^{M-M}}_{member-member} + \underbrace{\boldsymbol{\Psi}^{M-T}}_{member-target} + \underbrace{\boldsymbol{\Psi}^{M-O}}_{member-obstacles}$
- **GOAL: USE ANIMAL BEHAVIOR TO CREATE SYNTHETIC SWARMS**



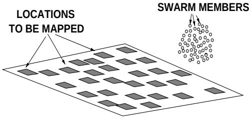
- *DYNAMICS* : $m_i \ddot{\boldsymbol{r}}_i = \boldsymbol{\Psi}(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_i, ..., \boldsymbol{r}_n) = \boldsymbol{\Psi}_i^{M-M} + \boldsymbol{\Psi}_i^{M-T} + \boldsymbol{\Psi}_i^{M-O}$
- *MEMBER* : $\boldsymbol{\Psi}_i^{M-M} =$

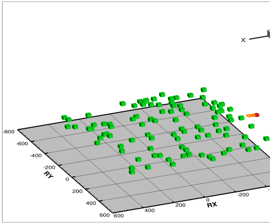
$$\sum_{k \neq i}^{n} \left(\left(\underbrace{\alpha_1^{M-M} ||\boldsymbol{r}_i - \boldsymbol{r}_k||^{\beta_1^{M-M}}}_{\text{attraction}} - \underbrace{\alpha_2^{M-M} ||\boldsymbol{r}_i - \boldsymbol{r}_k||^{-\beta_2^{M-M}}}_{\text{repulsion}} \right) \frac{\boldsymbol{r}_k - \boldsymbol{r}_i}{||\boldsymbol{r}_k - \boldsymbol{r}_i||} \right)$$

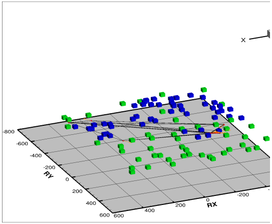
- *TARGET* : $\boldsymbol{\Psi}_i^{M-T} = \left(\alpha^{M-T} ||\boldsymbol{r}_* - \boldsymbol{r}_i||^{\beta^{M-T}} \right) \frac{\boldsymbol{r}_* - \boldsymbol{r}_i}{||\boldsymbol{r}_* - \boldsymbol{r}_i||}$
- *OBSTACLE* : $\boldsymbol{\Psi}_i^{M-O} = -\sum_{j=1}^{q} \left(\left(\alpha^{M-O} ||\boldsymbol{r}_{oj} - \boldsymbol{r}_i||^{-\beta^{M-O}} \right) \frac{\boldsymbol{r}_{oj} - \boldsymbol{r}_i}{||\boldsymbol{r}_{oj} - \boldsymbol{r}_i||} \right)$

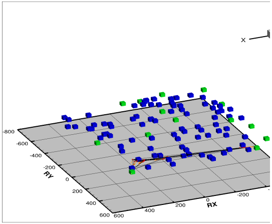


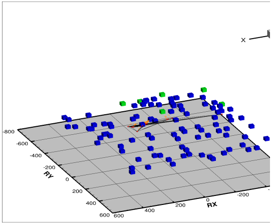
1. **USE CASES:** Well-suited for nonconvex, nonsmooth, multicomponent, multistage systems
2. **POPULATION:** Generate system population: $\boldsymbol{\Lambda}^i \stackrel{\text{def}}{=} \{\Lambda^i_1, \Lambda^i_2, \Lambda^i_3, \ldots, \Lambda^i_N\} \stackrel{\text{def}}{=} \{\alpha_i, \beta_i \ldots\}$
3. **PERFORMANCE:** Compute fitness/performance of each genetic string: $\Pi(\boldsymbol{\Lambda}^i)$ and rank them $(i = 1, \ldots)$
4. **MATING:** Mate pairs/produce offspring: $\boldsymbol{\lambda}^i \stackrel{\text{def}}{=} \Phi^{(I)}\boldsymbol{\Lambda}^i + (1 - \Phi^{(I)})\boldsymbol{\Lambda}^{i+1}$ where $0 \leq \Phi \leq 1$
5. **ELIMINATION:** Eliminate poorly performing genetic strings, keep top parents, top offspring
6. **NEXT GENERATION:** Repeat the process with the new gene pool and new random genetic strings
7. **POST-PROCESSING:** Employ gradient-based methods afterwards in the local "valleys"-if smooth enough

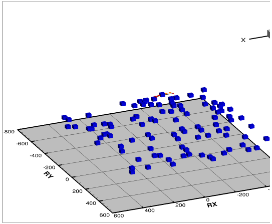

LOCATIONS
TO BE MAPPED
SWARM MEMBERS





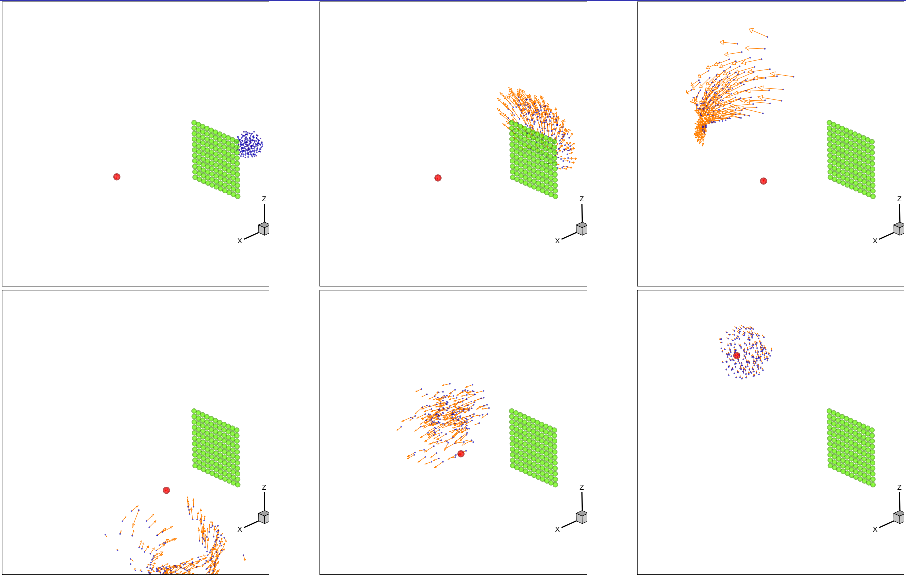






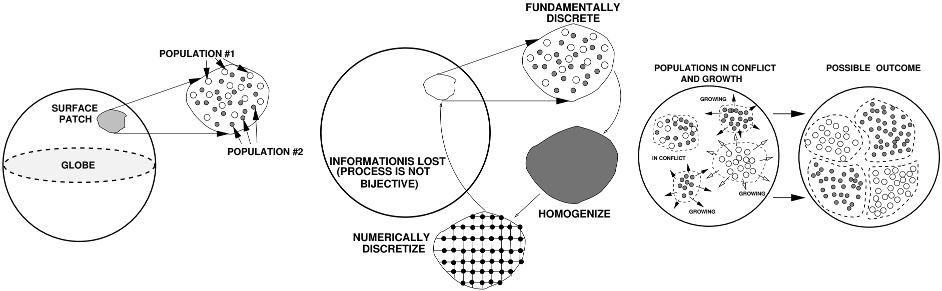
- **EXAMPLE-DESIGN VARIABLES: INTERACTION PARAMETERS=**α_i, β_i, $i = 1, \ldots, N$
- **STARLINGS (STURNUS VULGARIS): INTERACT WITH SPECIFIC MEMBERS**
- **ANOTHER CASE: INTERACTION WITH EVERY OTHER SWARM MEMBER**
- **ANOTHER CASE: INTERACTION WITHIN A COMMUNICATION RADIUS**
- **ANOTHER CASE: INTERACTION WITHIN A VISUAL FIELD**
- **THE KEY IS TO TRANSLATE BEHAVIOR INTO EQUATIONS**

MODEL PROBLEM: CHASING A MOVING TARGET

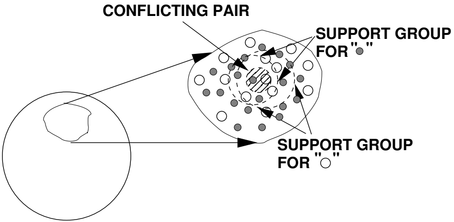


- $T_x = x_o + a_1 cos(a_2 t) + a_3 t, \quad T_y = y_o + b_1 sin(b_2 t) + b_3 t, \quad T_z = z_o + c_1 cos(c_2 t) + c_3 t$

AGENT-BASED COMPUTATION: POPULATION DYNAMICS

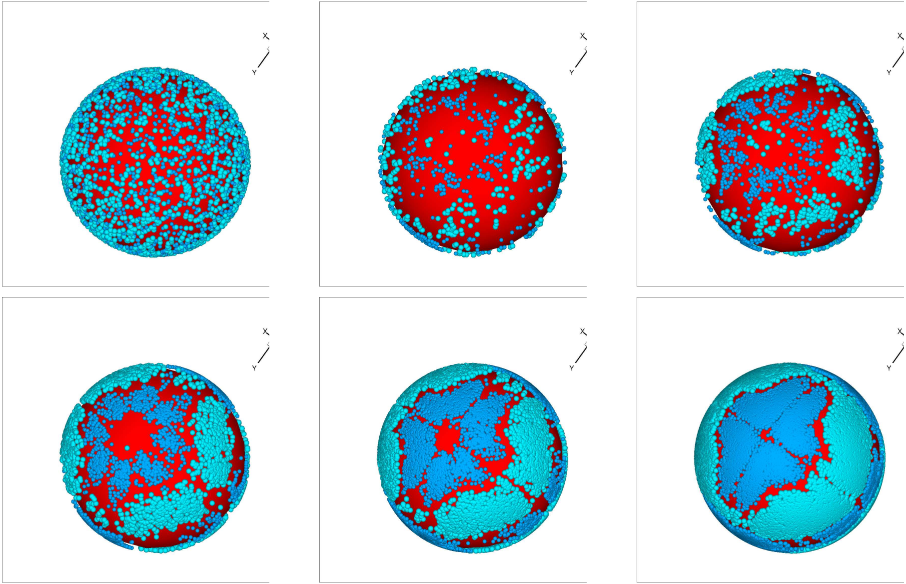


- **BASIC GROWTH:** $P(t+\Delta t) = \lambda P(t) \rightarrow P(t+\Delta t) - P(t) = (\lambda - 1)P(t) \rightarrow P(t) = P(0)e^{(\lambda-1)t} = P(0)e^{(b-d)t}$
- **PARAMETERS:** $\lambda = 1 + b - d$ **WHERE BIRTHRATE=**b **DEATH RATE=**d
- **COUPLED:** $\dot{P}_1 = rP_2 - \tau P_1$ **AND** $\dot{P}_2 = aP_1 - \gamma P_2$
- **OUTCOMES:** $\dot{P}_1 = rP_2 - \tau P_1 > 0$ **AND** $\dot{P}_2 = aP_1 - \gamma P_2 > 0$
- **LIKELY SCENARIO: (1) MASS FATALITIES (2) ENCLAVES (3) BOUNDARY EVOLUTION**
- **CHARACTERISTICS: (1) REPORODUCTIVE RATES (2) LIFESPANS (3) COMBAT SKILLS (4) MOBILITY**

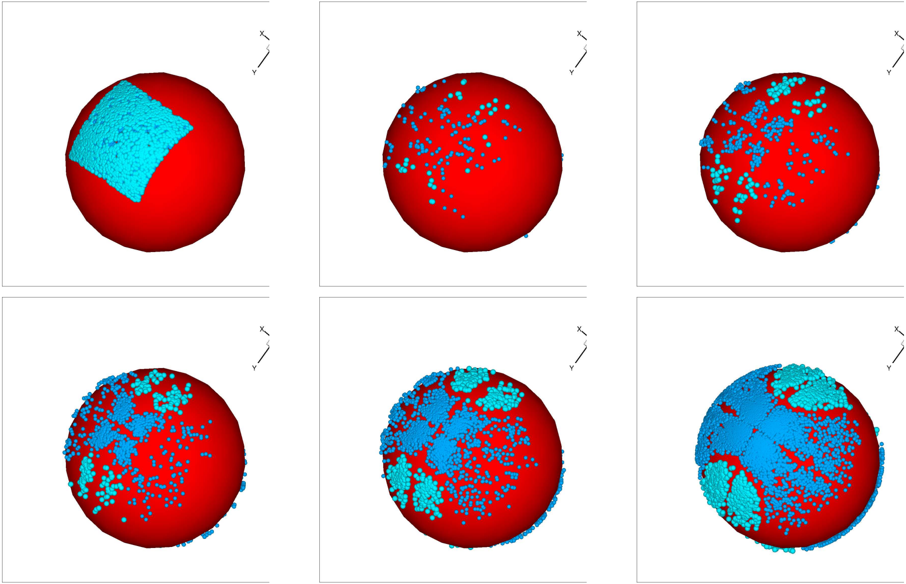


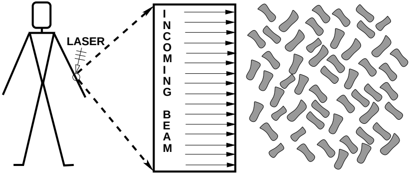
- **CONFLICT RADIUS:** $||\boldsymbol{r}_i^{(1)} - \boldsymbol{r}_j^{(2)}|| \leq d_{ij}^{(1-2)}$
- **SUPPORT-1:** $||\boldsymbol{r}_i^{(1)} - \boldsymbol{r}_j^{(1)}|| \leq s_{ij}^{(1-1)}$ **AND SUPPORT-2:** $||\boldsymbol{r}_i^{(2)} - \boldsymbol{r}_j^{(2)}|| \leq s_{ij}^{(2-2)}$
- **PROPORTIONS:** $\phi_1 = \frac{p_1}{p_1+p_2}$ AND $\phi_2 = \frac{p_2}{p_1+p_2}$
- **STEP 1: SET POPULATION PARAMETERS**
- **STEP 2: GENERATE INITIAL LOCATIONS**
- **STEP 3: CHECK FOR CONFLICTS**
- **STEP 4: COMPUTE SURVIVORS**
- **STEP 5: COMPUTE BIRTHS AND DEATHS**
- **STEP 6: UPDATE AGES**
- **STEP 7: REPEAT STEPS 2-6**

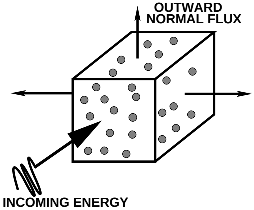
AGENT-BASED COMPUTATION: POPULATION DYNAMICS-GLOBALLY-DISPERSED

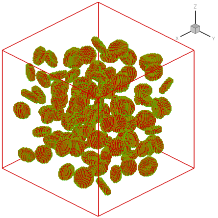


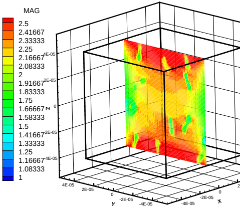
AGENT-BASED COMPUTATION: POPULATION DYNAMICS-INITIALLY ISOLATED





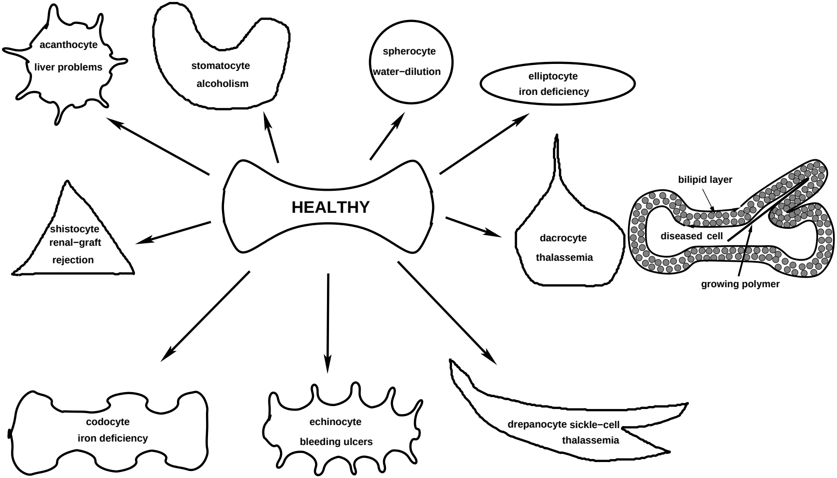




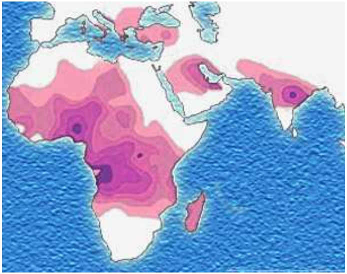


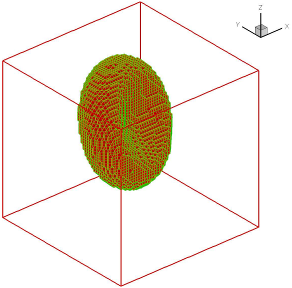
- **GOAL: RAPID NON-INVASIVE TESTING**
- **COLLABORATOR: F. KUYPERS (OAKLAND CHILDREN'S HOSPITAL)**

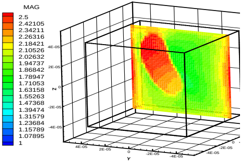
DISEASED RED BLOOD CELL GALLERY



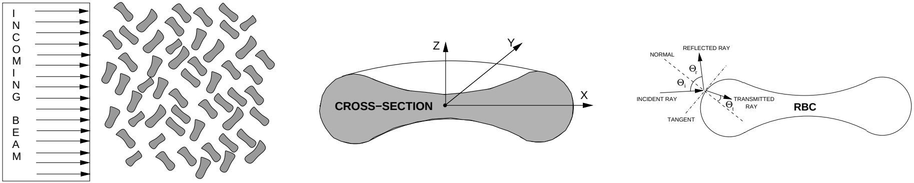
- **SHAPE-RELATED R-B CELL DISORDERS/IMPAIRED FUNCTION**
- **EXCESSIVE RED CELL DESTRUCTION OCCURS**
- **CELLS REMOVED PREMATURELY BY THE SPLEEN $\Rightarrow$ ANEMIA**



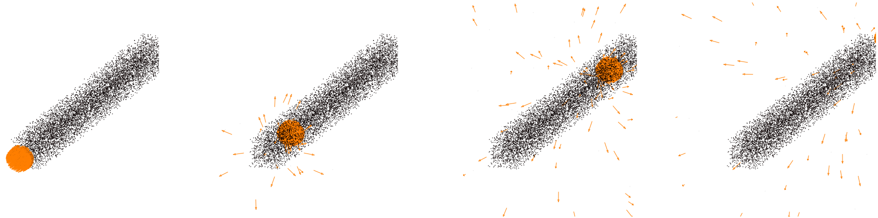




- **RED BLOOD CELLS TRANSPORT OXYGEN AND CARBON DIOXIDE**
- **SICKLE-CELL ANEMIA IS PREVALENT IN** $0.03 - 0.05\%$ **OF POPULATION**
- **HIGHER IN AFRICAN, MEDITERRANEAN AND ASIAN ANCESTRY POP.**
- **GOAL: RAPID NON-INVASIVE TEST TO DETERMINE DISEASED CELLS**

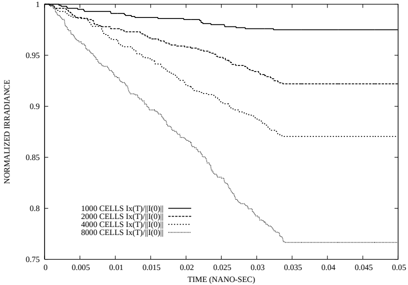


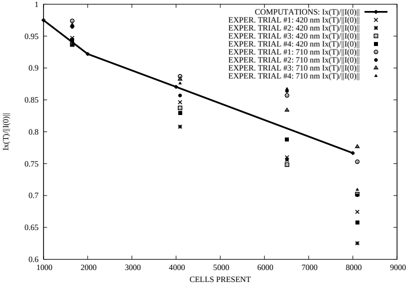
1. COMPUTE RAY REFLECTIONS (FRESNEL RELATIONS)
2. COMPUTE ABSORPTION BY CELLS
3. INCREMENT RAY POSITIONS FORWARD



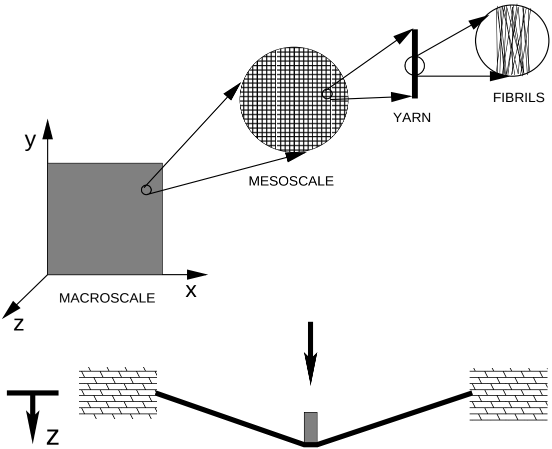
CELLS	ENERGY: # 1	ENERGY: # 2	ENERGY: # 3	ENERGY: # 4
1650	0.97390	0.96450	0.96700	0.96760
4090	0.88700	0.85700	0.88230	0.87580
6510	0.85700	0.86390	0.83370	0.86710
8100	0.75300	0.70050	0.77650	0.70900

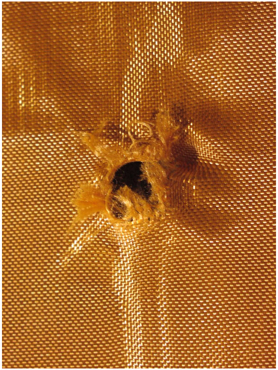
COMPUTATIONAL RESULTS: COMPARISON TO EXPERIMENTS



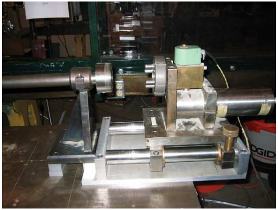


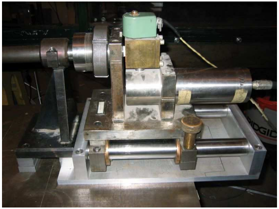
CELLS	ENERGY
1000	0.97501
2000	0.92201
4000	0.87046
8000	0.76656

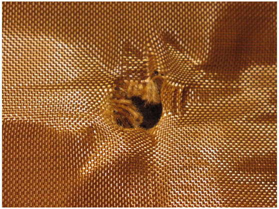




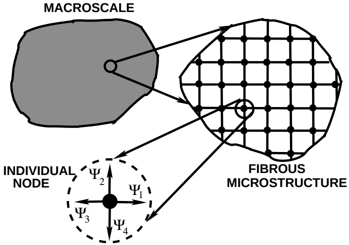
- **Applications: ballistic fabric such as KEVLAR, ZYLON and biological tissue**



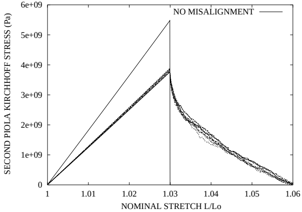


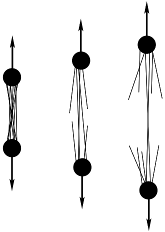
- **Pneumatic (nitrogen) gun, breech and barrel set up. ZYLON samples.**



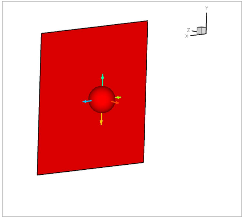
- **The yarn remain straight, undergoing a homogeneous stress state**
- **The forces only act along the length of the yarn**
- **The joint connections produce no bending or moments**
- **The yarn do not buckle**
- **The yarn do not slide relative to one another ("combing")**

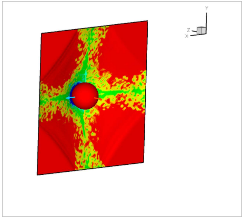
CONSTITUTIVE LAW: YARN CONTAINING HUNDREDS OF RANDOM FIBRILS

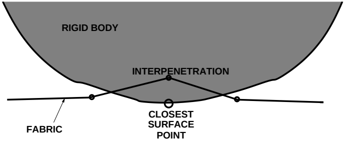




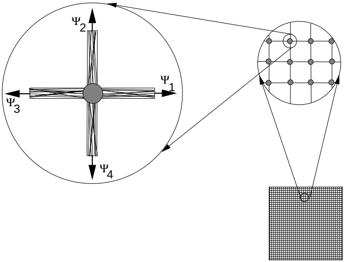
- **SECOND PIOLA-KIRCHHOFF STRESS:** $S = \mathcal{F}(U = \frac{L}{L_o}) = \alpha \boldsymbol{IE}^y E$
- **GREEN-LAGRANGE STRAIN:** $E = \frac{1}{2}(U^2 - 1)$
- **FORCE:** $\Psi = USA_o = \frac{L}{L_o} SA_o$
- **DAMAGE:** $\alpha(t) = min\left(1, \alpha(0 \leq t^* < t), \frac{(exp(-\lambda(U(t)-U_{crit}))-exp(-0.03\lambda))}{(1-exp(-0.03\lambda))}\right)$
- **DAMAGE PARAMETER RESTRICTION:** $0 \leq \alpha(t) \leq 1$





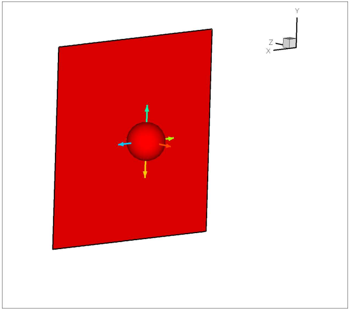


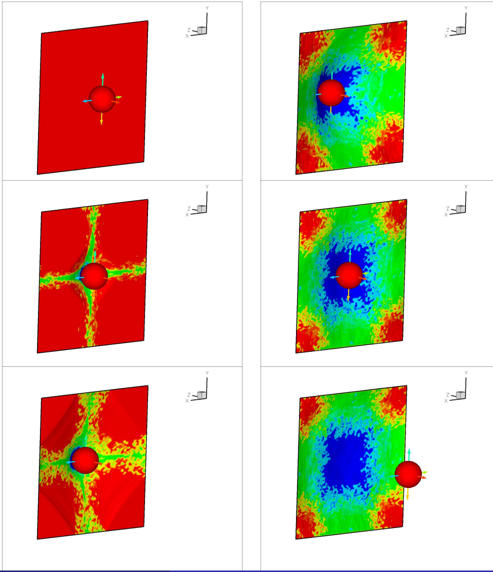
- **Move the fabric node to the closest point on the projectile's surface (there are a variety of algorithms to perform this operation).**
- **Compute contact forces from the interpenetrated (predictor) position and the corrected position (the difference is denoted the "gap").**
- **If there is friction, then a stick condition is assumed, then the friction force is checked against the static limit which, if violated, enacts a sliding friction force.**



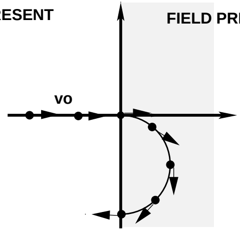
- **NODAL DYNAMICS:** $m_i \dot{\boldsymbol{v}}_i = \boldsymbol{\Psi}_i^{tot}$**=INTRA-YARN+EXTERNAL FORCES**
- **COUPLED SYSTEM:** $\boldsymbol{v}_i(t+\Delta t) = \boldsymbol{v}_i(t) + \frac{\Delta t}{m_i}\left(\phi \boldsymbol{\Psi}_i^{tot}(t+\Delta t) + (1-\phi)\boldsymbol{\Psi}_i^{tot}(t)\right)$
- $\Rightarrow \boldsymbol{r}_i(t+\Delta t) = \boldsymbol{r}_i(t) + \boldsymbol{v}_i(t+\phi\Delta t)\Delta t = \boldsymbol{r}_i(t) + \left(\phi \boldsymbol{v}_i(t+\Delta t) + (1-\phi)\boldsymbol{v}_i(t)\right)\Delta t$
- **SOLVED ITERATIVELY (IMPLICITLY) WITH TIME-STEP ADAPTATION**

AN IMPACT SEQUENCE FOR A SHEET-CONTACTOR PAIR





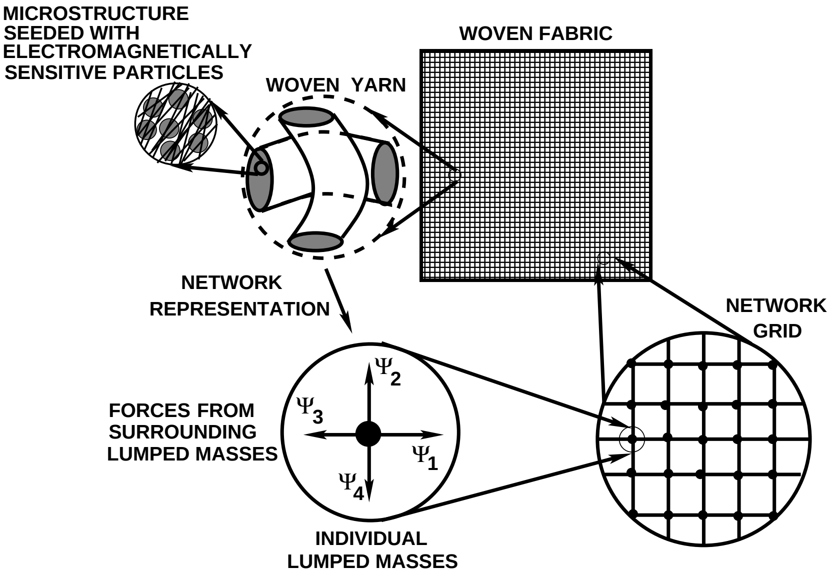
- COMPUTE DISPLACEMENTS/CONTACT
- COMPUTE YARN STRETCH
- COMPUTE FIBRIL RUPTURE
- COMPUTE CONTACTOR POSITION
- IF TOL MET, INCREMENT TIME
- IF TOL NOT MET, REDUCE TIME STEP

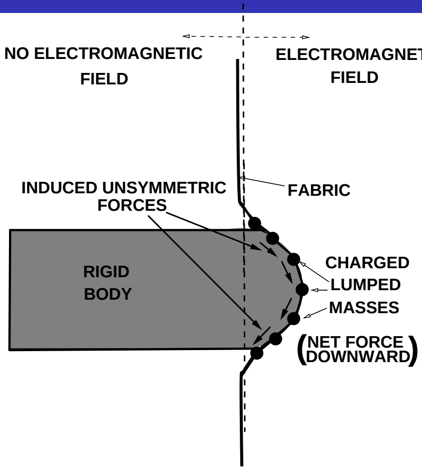


- $m\dot{\boldsymbol{v}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$
- **COMPONENT FORM:**

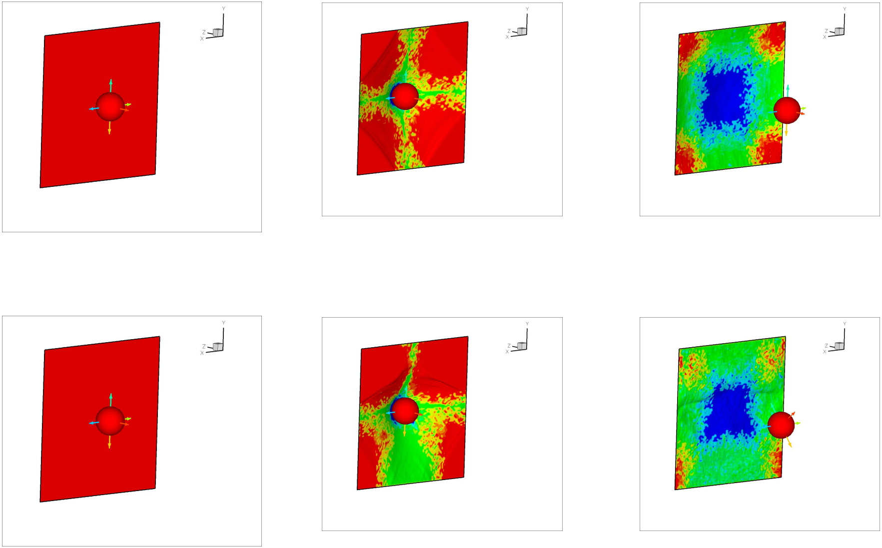
$$\dot{v}_1 = \frac{q}{m}(E_1 + (v_2 B_3 - v_3 B_2))$$
$$\dot{v}_2 = \frac{q}{m}(E_2 - (v_1 B_3 - v_3 B_1))$$
$$\dot{v}_3 = \frac{q}{m}(E_3 + (v_1 B_2 - v_2 B_1))$$

- CHOOSE THE COMPONENTS OF B FOR THE DESIRED EFFECT
- INDUCES HELICAL MOTION $\Rightarrow$ HARNESSED FOR TUMBLING
- MAGNETIC EFFECTS$\Rightarrow$ *TURNING RADIUS* $= R = \frac{m||\boldsymbol{v}||}{|q|||\boldsymbol{B}||}$
- $\star$KEY EFFECT: ROTATION TIME$=\frac{R\theta}{||\boldsymbol{v}||} = \frac{m\theta}{|q|||\boldsymbol{B}||}$=<u>VELOCITY-INDEPENDENT</u>


MICROSTRUCTURE
SEEDED WITH
ELECTROMAGNETICALLY
SENSITIVE PARTICLES
WOVEN YARN
WOVEN FABRIC
NETWORK
REPRESENTATION
NETWORK
GRID
FORCES FROM
SURROUNDING
LUMPED MASSES
Ψ_2
Ψ_3
Ψ_1
Ψ_4
INDIVIDUAL
LUMPED MASSES



- **PROJECTILE PUSHES CHARGED FABRIC INTO MAGNETIC FIELD**
- **THIS INDUCING ROTATION VIA THE CONTACT FORCES**
- **FABRIC DYNAMICS:** $m\ddot{\boldsymbol{r}}_i = \underbrace{\boldsymbol{\Psi}_i^{tot}}_{total} = \underbrace{\boldsymbol{\Psi}_i^{nn}}_{\text{yarn}} + \underbrace{\boldsymbol{\Psi}_i^{con}}_{\text{contact}} + \underbrace{\boldsymbol{\Psi}_i^{fric}}_{\text{friction}} + \underbrace{q_i(\boldsymbol{E}_i + \boldsymbol{v}_i \times \boldsymbol{B}_i)}_{\text{electromagnetic forces}}$



- **PATENT: T. I. Zohdi. US Application No. 61/313,058**