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An Adaptive Pattern Recognition Methodology for Damage Classification in Composite Laminates

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Introduction

- Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to reduce life-cycle costs and improve reliability
- Essentially involves integrating non-destructive evaluation (NDE) devices into a vehicle to collect prognostic data
  - SHM could reduces inspection/maintenance costs by 33% through CBM
  - can catch damage that may have occurred between scheduled intervals
  - integrate SHM systems into new vehicles or retrofit for ageing vehicles
- Applicable to any field – highest payoff in air/spacecraft






Problem Statement

- SHM algorithms are susceptible to rising false positive rates
  - materials age due to environmental and mechanical fatigue
  - maintenance and repairs can tighten bolts, replace ribs or add patches
- Differences between aircraft in a fleet could affect accuracy
  - sensor tolerances, placement, installation and bond preparation
  - manufacturing tolerances for individual aircraft
- Can compensate by revising or retraining algorithms over time
  - logistically impractical, time consuming, negates SHM economic benefits
  - tailored changes invalidate/complicate certification of an SHM system
- Adaptive pattern recognition-based methodology proposed
  - accommodate perturbations in structural response not due to damage
  - goal of maintaining or accounting for algorithm accuracy

Damage Detection Fundamentals

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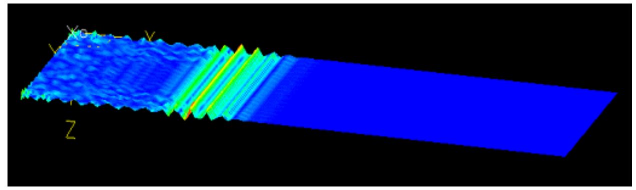
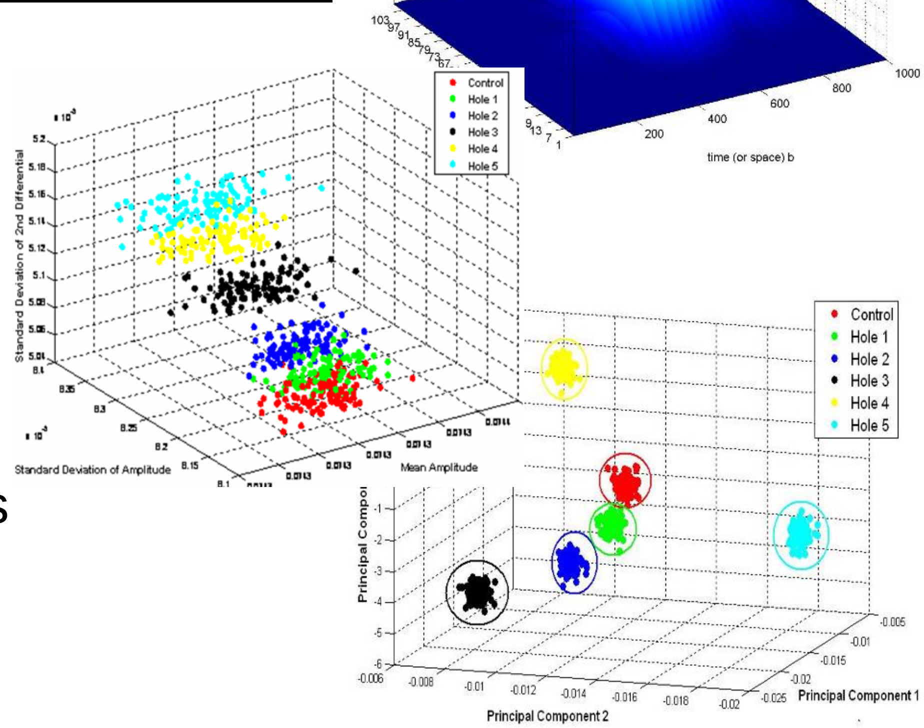
- Several challenges involved in detecting damage in composites
  - delamination and impact (below visible surface) dominate
  - modes may not be discrete (can interact)
- Ideally top-level binary categorization of pristine or damaged
  - taking micromechanics view materials inherently have flaws
  - microscopic flaws grow slowly, accelerated overload or impacts events
  - damage threshold must be defined for some detectable flaw size level
- Would like further classification beyond presence of damage
  - must extract many separate features for detailed classification
  - pattern recognition methods trained to recognize multiple damage states
  - large feature set may lead to redundancy and computational inefficiency
  - feature reduction techniques can be employed to reduce dimensionality

Standard Methodology Steps

- Signal Conditioning
  - denoise raw signal
  - remove unwanted artifacts





- Feature Extraction
  - discriminative features for analysis
  - time, frequency & energy domains
- Feature Selection
  - repeatable features unique to class
  - can reduce dimensionality (PCA)
- Algorithms
  - Pattern Recognition (PR) to identify damage presence, type and severity
  - localization performed with convention single or multi-sensor methods
  - confusion matrix can be used to calculate confidence levels

Standard Training Flowchart

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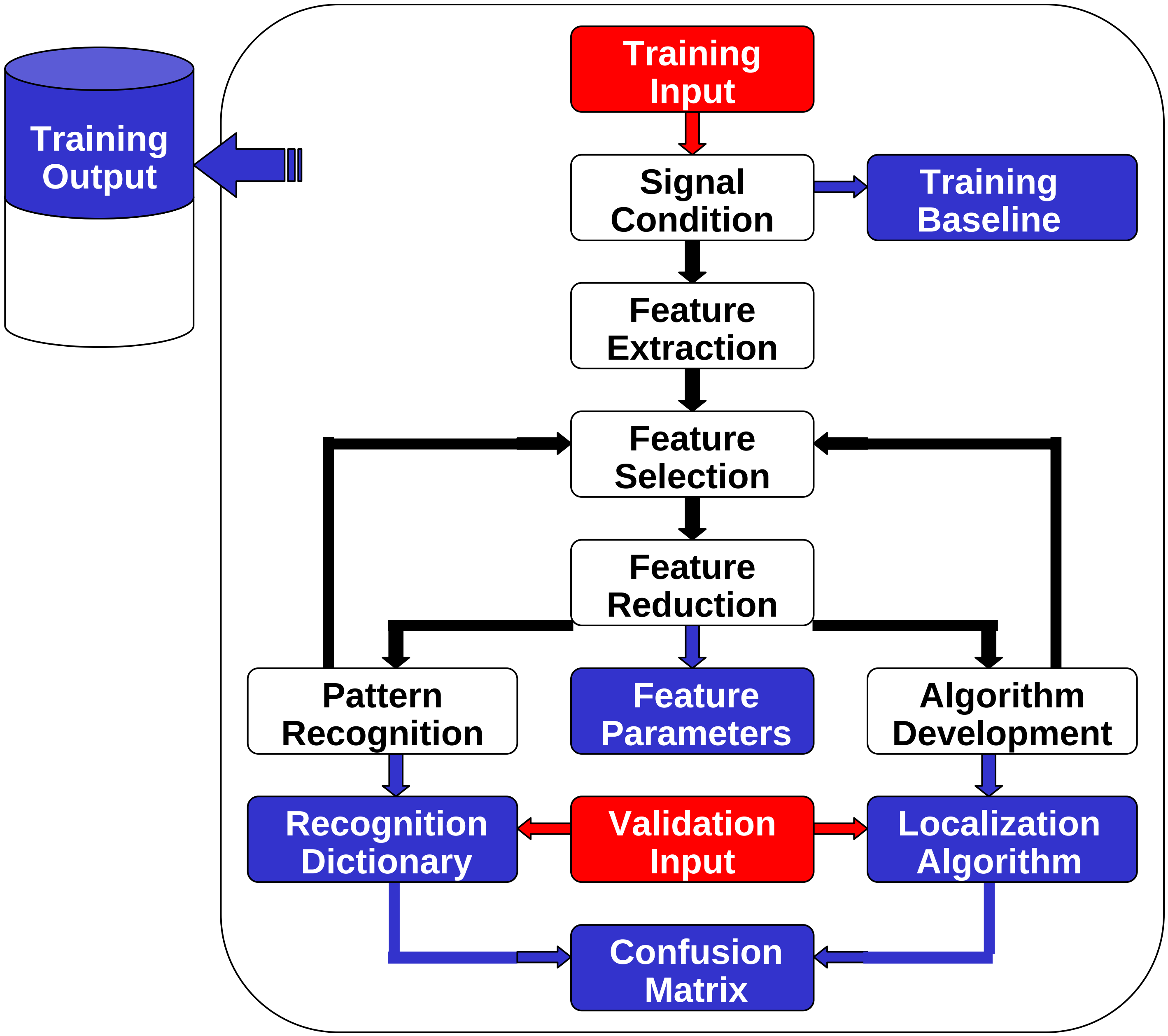
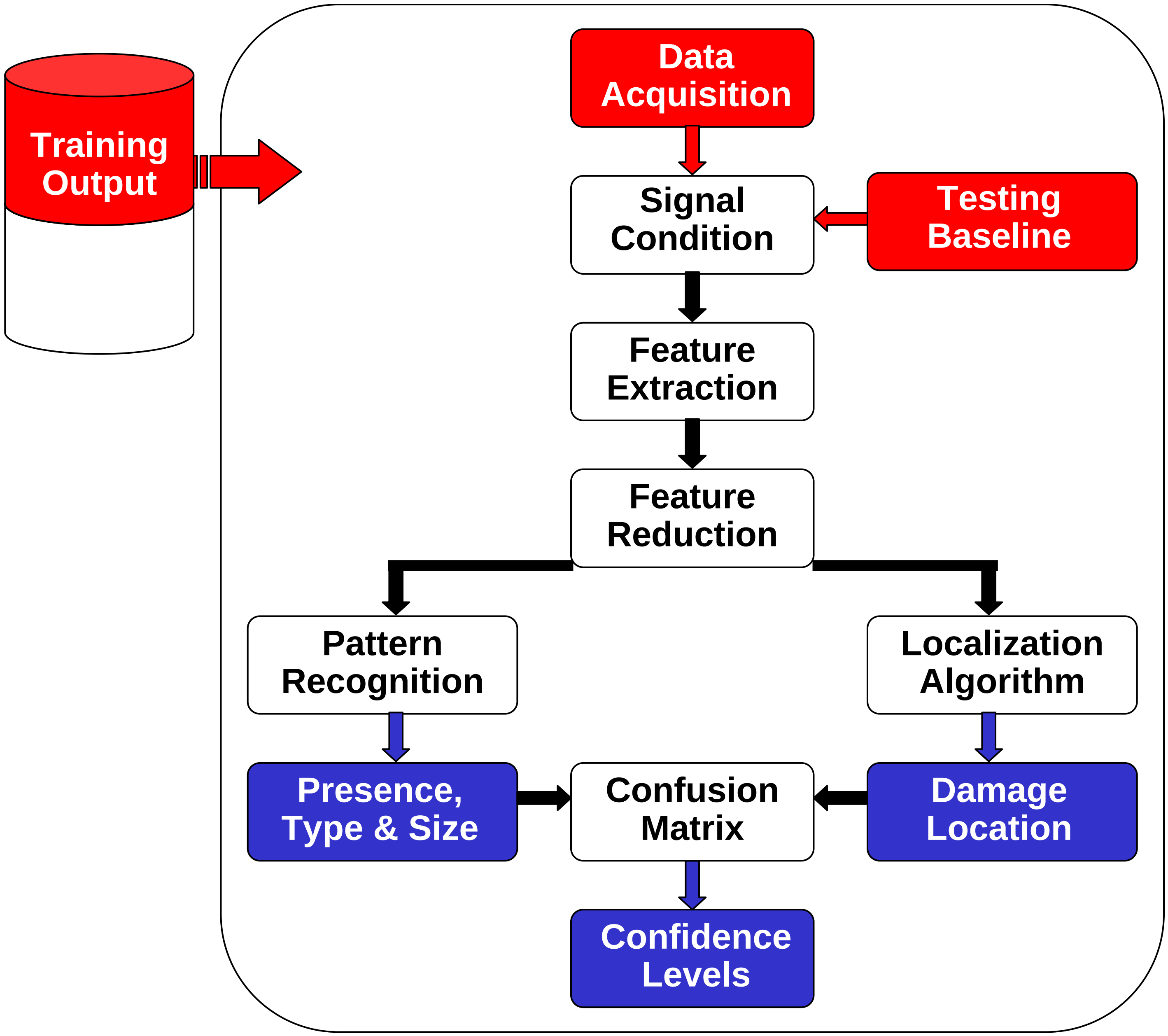
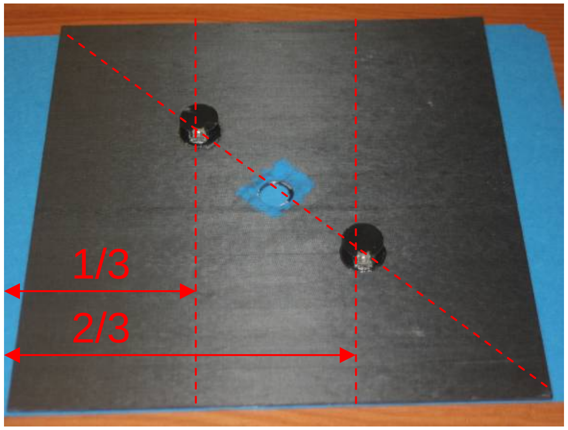


Standard Testing Flowchart



Experimental Setup



Plates	Damage Type	Damage Severity
3	Impact (5 lbs dropped weight)	4”, 8”, 16”, 32”
3	Hole (center drilled)	$^{1}/_{32}$”, $^{1}/_{8}$”, ¼”, ½”
3	Delamination (corner cut)	¼”, ½”, 1”, 1.5”

- 11.75” x 0.1” square quasi-isotropic CFRP laminates, 2 nodes
- Lamb wave tests at 100kHz using M.E.T.I.-Disk 3 SHM nodes
- 3 damage modes investigated with 4 levels of severity for each
- 100 tests per node for each configuration, total 9000 data sets
  - 1 node for each damage type was designated as the “training node” and all data collected was used to train PR algorithm
  - other nodes on same and all separate plates were “testing nodes” used to collect experimental data for subsequent predictions

Pattern Recognition Results

PREDICTED		No Damage	Drilled Hole				Delamination				Impact			
ACTUAL		ND	1/32"	1/8"	¼"	½"	¼"	½"	1"	1.5"	4"	8"	16"	32"
No Damage	ND	**100%**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Drilled Hole	1/32"	0%	**86%**	14%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	1/8"	0%	53%	**47%**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	¼"	0%	0%	0%	**44%**	56%	0%	0%	0%	0%	0%	0%	0%	0%
	½"	0%	0%	0%	0%	**100%**	0%	0%	0%	0%	0%	0%	0%	0%
Delamination	¼"	0%	0%	0%	0%	0%	**99%**	1%	0%	0%	0%	0%	0%	0%
	½"	0%	0%	0%	0%	0%	58%	**30%**	12%	0%	0%	0%	0%	0%
	1"	0%	0%	0%	0%	0%	1%	9%	**58%**	32%	0%	0%	0%	0%
	1.5"	0%	0%	0%	0%	0%	0%	0%	0%	**100%**	0%	0%	0%	0%
Impact	4"	0%	0%	0%	0%	0%	0%	0%	0%	0%	**76%**	23%	1%	0%
	8"	0%	0%	0%	0%	0%	0%	0%	0%	0%	6%	**33%**	61%	0%
	16"	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	**98%**	0%
	32"	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	14%	**86%**

- K-Nearest Neighbor (KNN) pattern recognition code employed
  - supervised learning algorithm
  - state based on majority category of optimized "K" nearest data sets
- Confusion matrix shows statistical accuracy of KNN predictions

Pattern Recognition Discussion

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- Results of PR-based methodology have been very successful
  - obtained using an optimized K-Nearest Neighbor code
  - **100%** presence accuracy without any false positives or missed damage
  - **100%** type of damage accuracy without any mis-classifications
  - **99.9%** severity prediction including adjacent levels (77% without)
- Sufficient results for technician to make a repair decision
  - achieve “adjacent” results by intelligently selecting severity boundaries
  - accuracy would improve with additional training data
- Achieved using separate plates for training and testing
  - broad implications for feasibility of eventual commercial implementation
  - single validated training data set needs to be deployed for entire fleet
  - can account for variability in sensor fabrication and placement
  - accommodate “real” damage types such as delamination and impact

Adaptive Compensation for PR

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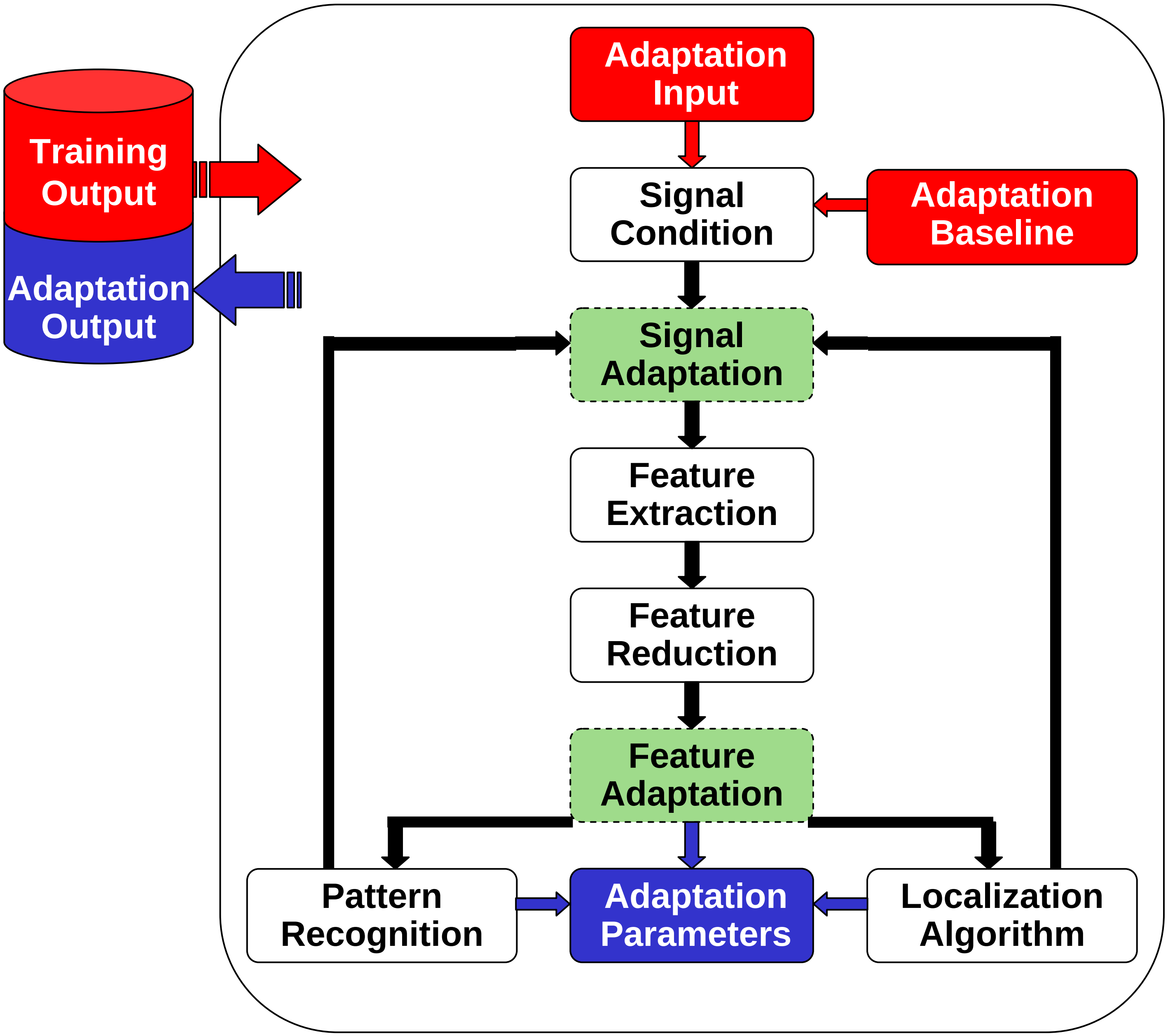
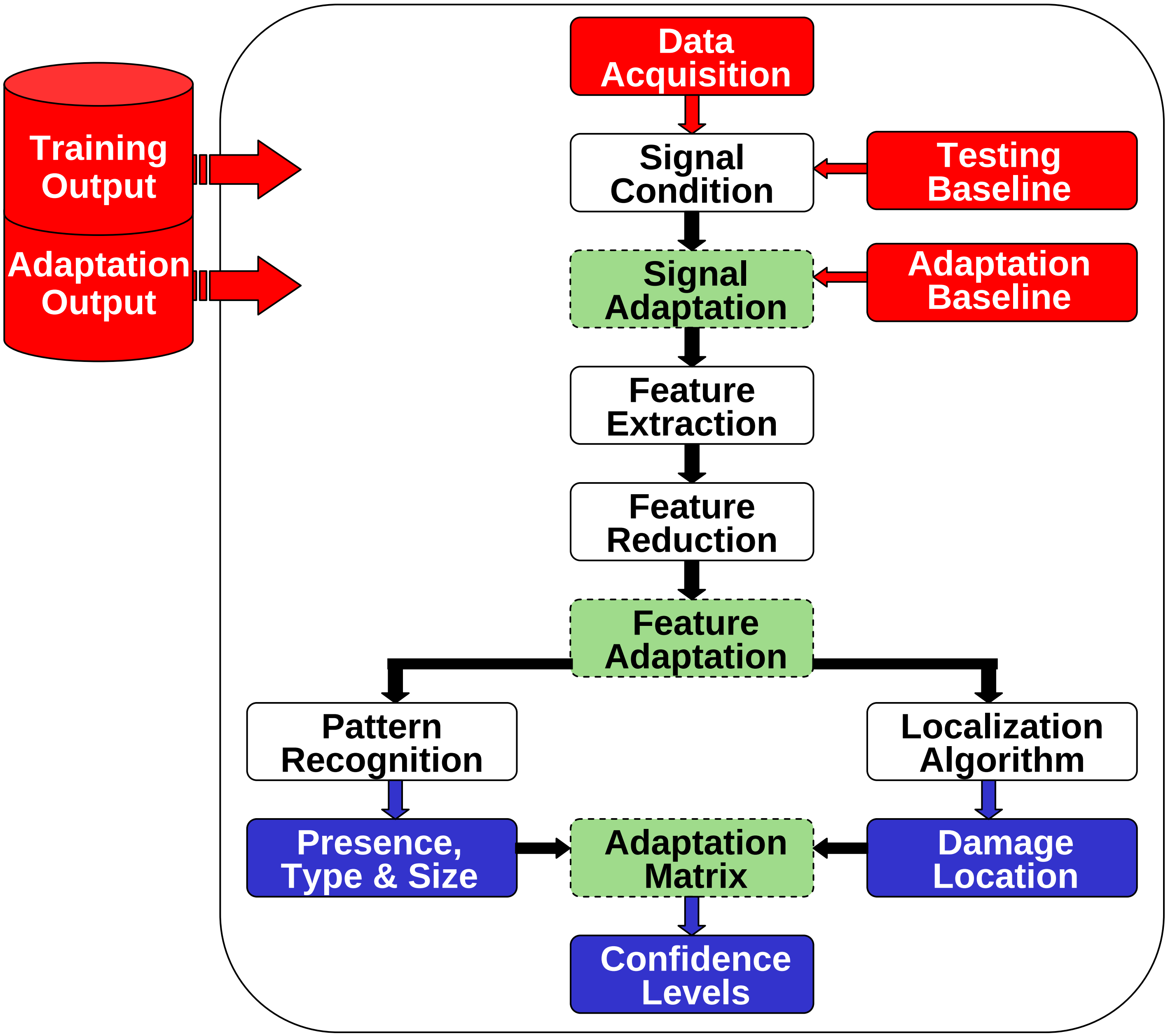
- Adaptation modules inserted at the signal and feature levels
  - transformation vectors for addition/subtraction, scaling and translating
  - operations performed in multiple domains (time, frequency, wavelet, etc)
- Adaptive testing executed similarly to standard test procedure
  - baseline from "known good state" used to accommodate perturbation
  - assumes that baseline is collected within a known no-damage condition
  - assumes difference between baselines are within tolerable threshold
- Methodology to compensate for small perturbations in signals
  - uses perturbed training input from simulated and/or experimental data
  - goal of minimizing impact on the algorithm accuracy
  - confidence levels for each state as a function of perturbation level
  - simulated perturbations were introduced into baseline and test signals

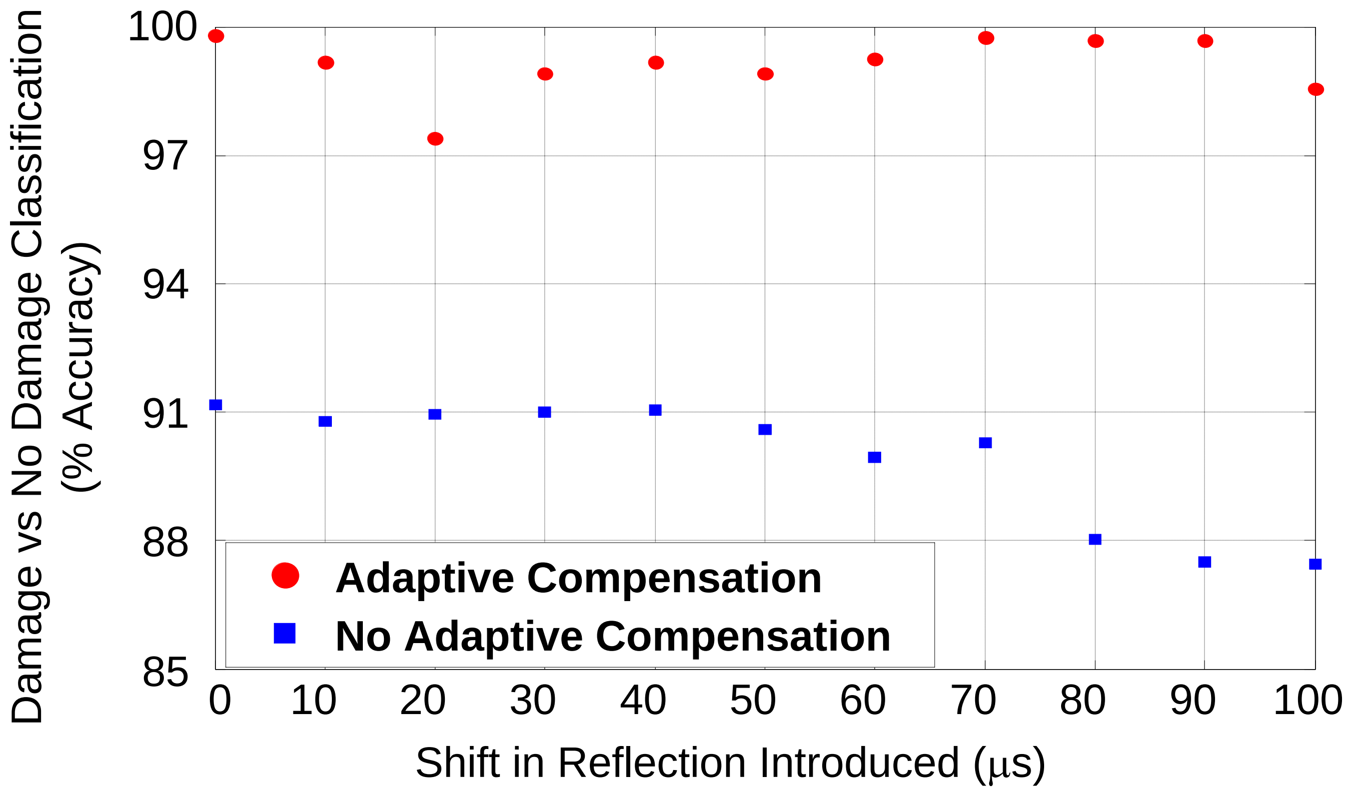
Adaptive Training Flowchart



Adaptive Testing Flowchart

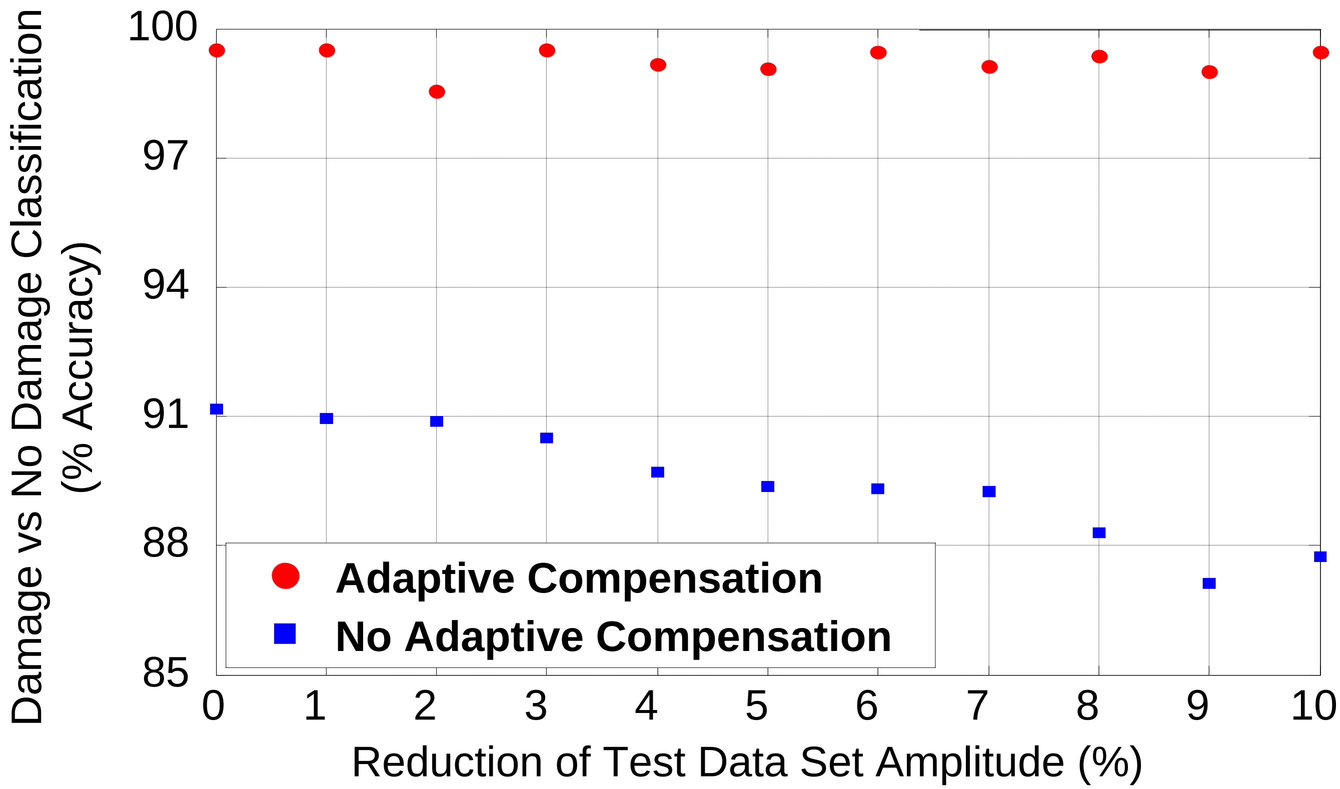


Time Domain Perturbation



- Time delay between 0-100μs was introduced
- Represents change from repair moving a boundary condition
- Adaptation methodology is able to maintain >97% accuracy
- Traditional PR methodology accuracy degrades to <87%

Energy Domain Perturbation



- Uniform amplitude attenuation between 0-10% was introduced
- Replicates a degraded sensor bondline
- Adaptation methodology is able to maintain >98% accuracy
- Traditional PR methodology accuracy degrades to <87%

Frequency Domain Perturbation

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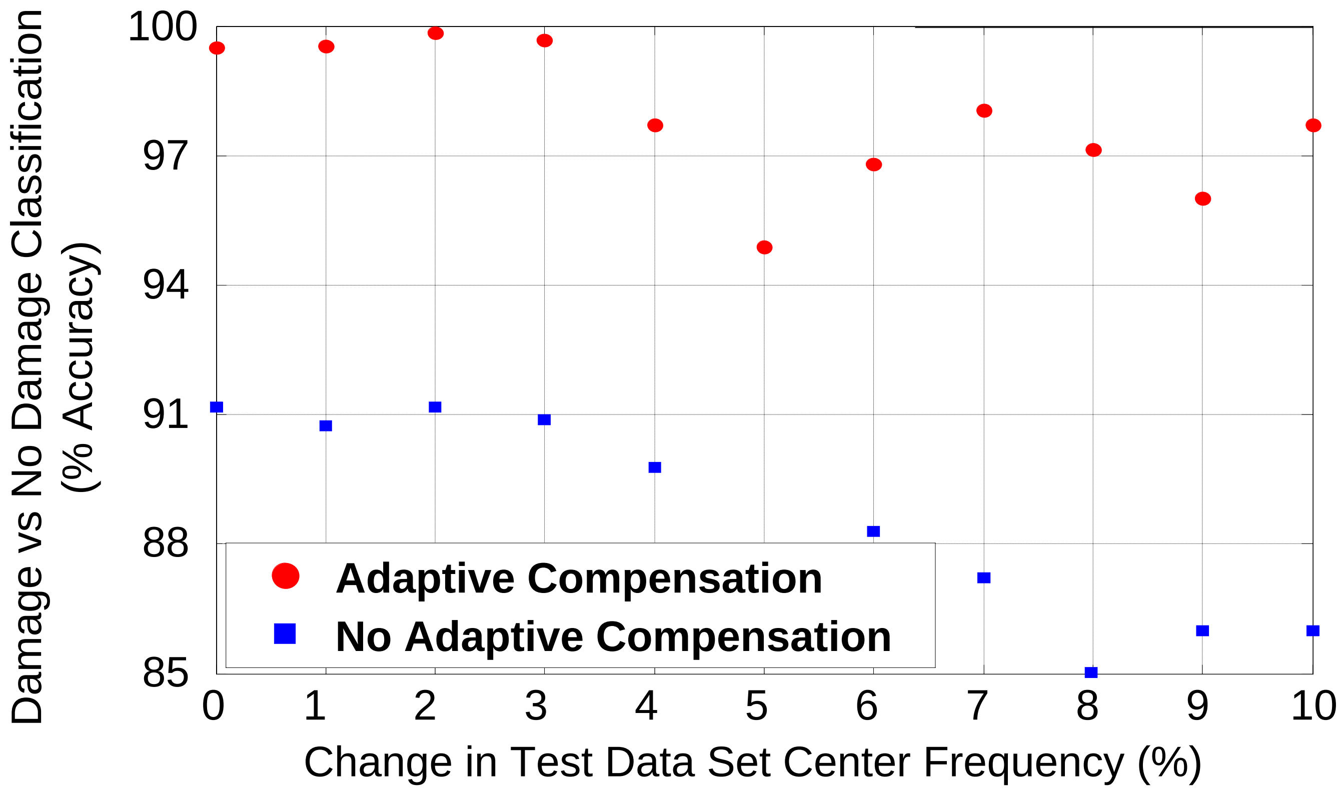

- Central frequency shift between 0-10% was introduced
- Seen in ageing from microcracks reducing material modulus
- Adaptation methodology is able to maintain >95% accuracy
- Traditional PR methodology accuracy degrades to <85%

Conclusions

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- Adaptive compensation SHM methodology presented
  - accommodates perturbations caused by ageing, maintenance & repairs
  - designed to maintain/account for damage detection algorithm accuracy
  - flowcharts given for training algorithm and adaptation modules, testing
  - adaptation modules are inserted at both the signal and feature level
  - transforms based upon differences between original and new baseline
- Damage detection results presented with simulated ageing
  - perturbations up to 10% in signal time, energy and frequency domains
  - standard algorithm exhibits decreasing accuracy with more variability
  - adaptive algorithm maintains accuracy by incorporating new baselines
- Successfully demonstrates feasibility of adaptive modules to compensate for signal perturbations not attributable to damage
  - work remains to fully develop methodology for commercial applications
  - extend investigation to damage type, severity and location
  - experimental validation beyond pure simulation
  - using analytical and/or finite element models to train for perturbations

Acknowledgments

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