Physics-informed Markov chains for remaining useful life prediction of power electronic modules

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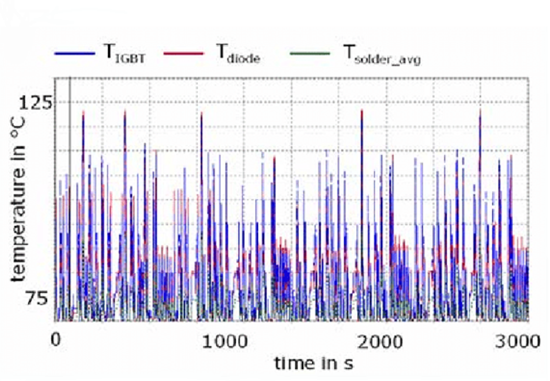
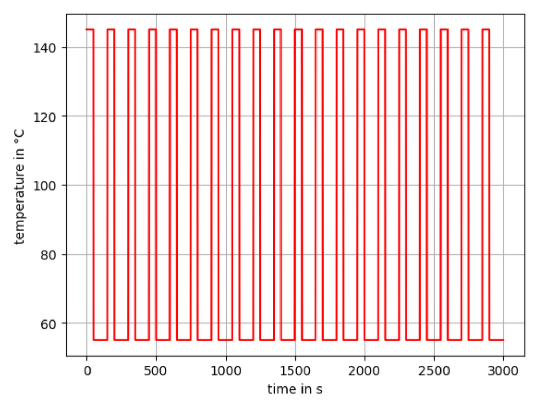
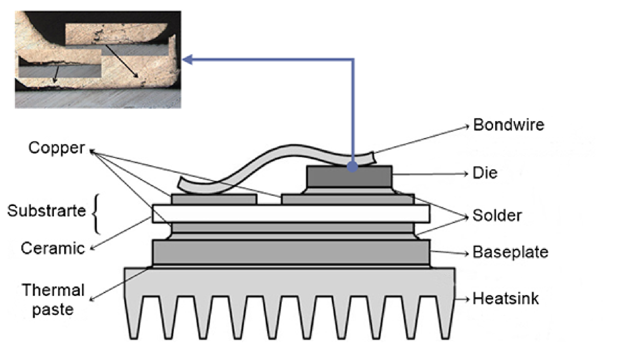
1. Context

- Remaining useful life estimation of power electronic modules is difficult to assess due to their long lifespan and the difficulty of modeling loading profiles.
- Working conditions are amplified and simple uncomprehensive loading profiles are used.
- ***Extrapolation*** and ***expressivity*** problems occur due to such approximations.
- The sole failure mechanism considered is degradation in the contact area between the chip, the metallization and the bondwire.

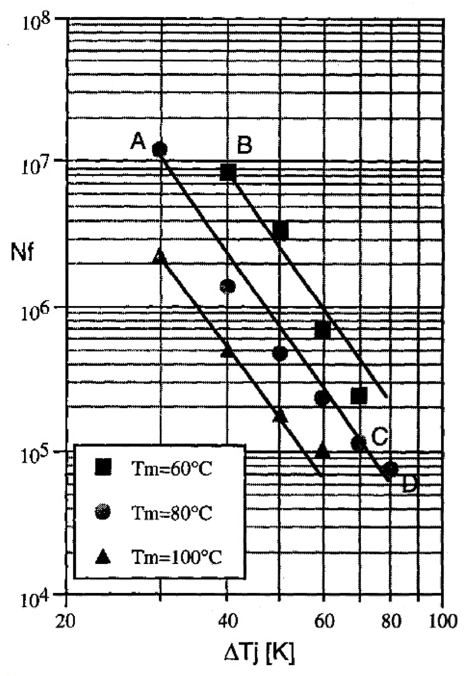


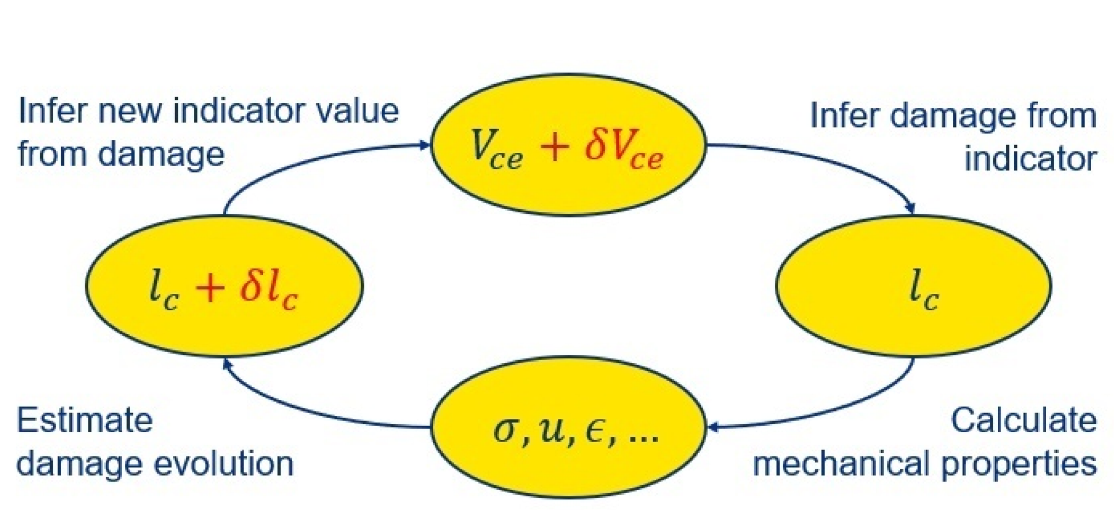




2. Approach

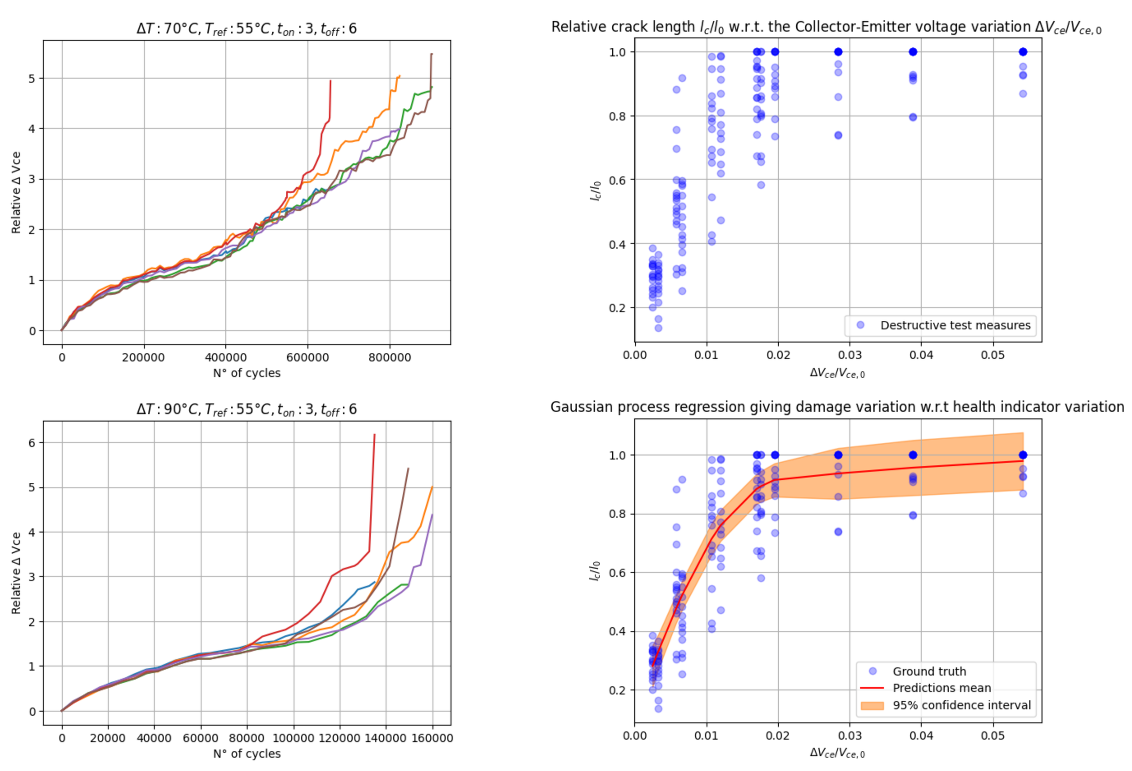
- Classical approaches approximate the number of cycles to failure N_f, assuming a fixed temperature variation ΔT.
- We present a recursive remaing useful life estiamtion per cycle by :
  1. Inferring the current damage value l_c from the health indicator value V_{ce}, using experimental data.
  2. Using simulations to apply loadings according to the loading profile, and calculating corresponding mechanical quantities.
  3. Using physics-informed Markov chains to predict damage evolution from mechanical quantities, coupled with experimental data.





3. Experimental data

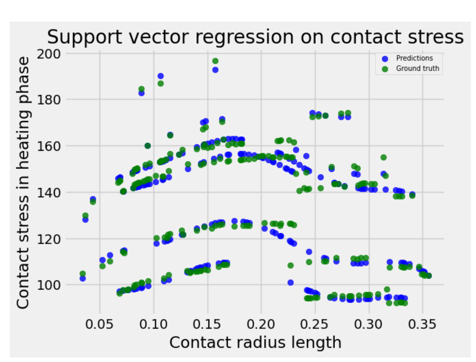
- Runs to failure giving V_{ce} w.r.t. N, as well as destructive tests giving l_c w.r.t. V_{ce} were carried out in a previous research.
- We use a total of 898 data points giving V_{ce} with respect to N, for $\Delta T = 70°C, 90°C$ and $110°C$, with an average step size of 5339.
- Gaussian process regression was used to estimate l_c from V_{ce} on 175 data points.

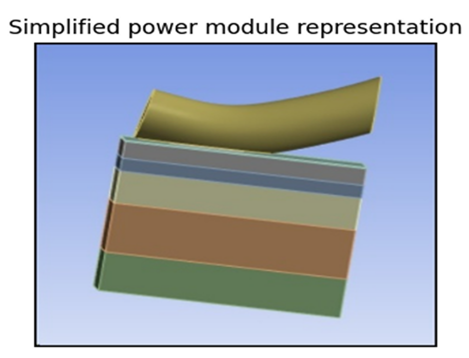


4. Simulated data

- A reduced geometric model was used to infer mechanical properties, given l_c and ΔT.
- Average stress σ, strain ϵ and deformation u are calculated for heating and cooling phases in both metallization and contact.
- Data-driven models are trained on simulated data to obtain surrogate models.

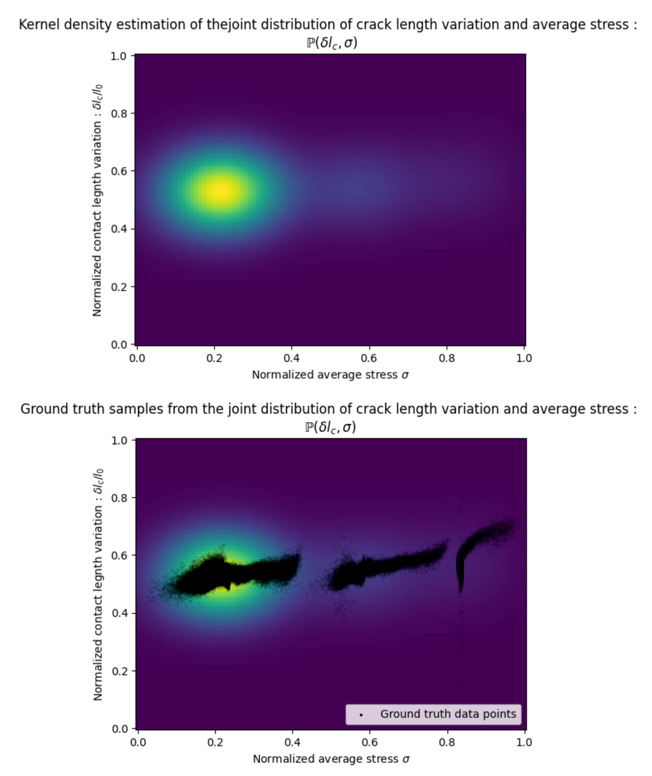
Algorithm	MSE	R^2
Bayesian neural network	0,261	0,733
Linear regression	0,274	0,719
Support vector regression	**0,247**	**0,746**
Order 4 polynomial regression	0,257	0,736



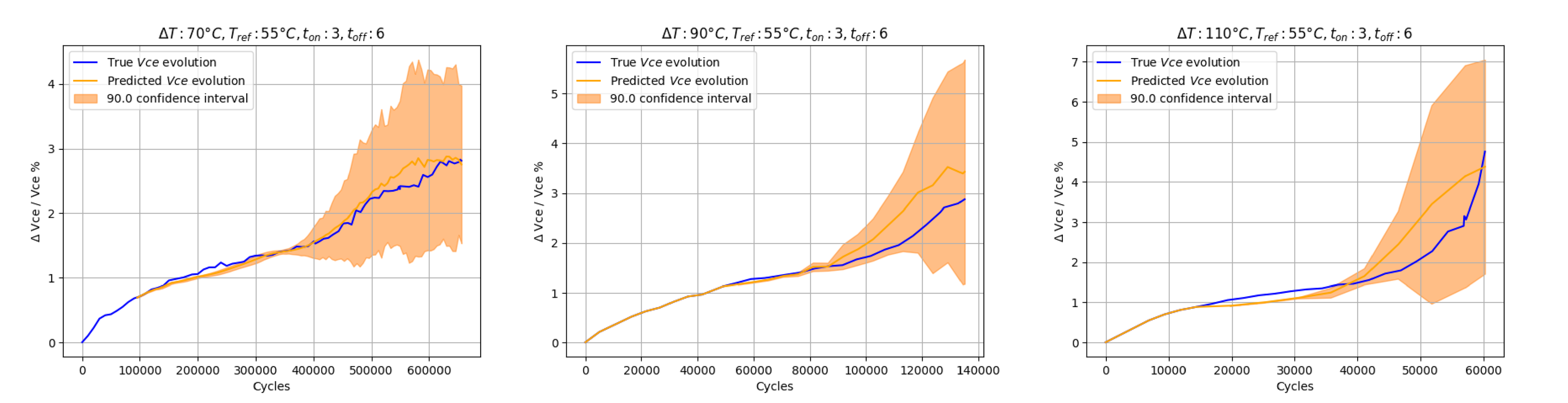


5. Markov chain predictions

- Estimate damage variation $\delta l_{c,i}$ at time i given the vectors $M_{i-1}, M_{i-2}, \ldots$ of previous mechanical values; a high order markov chain.
- Find the probability of each possible variation $\mathbb{P}(\delta l_{c,i} | M_{i-1}, M_{i-2}, \ldots)$ using Kernel density estimation.
- Sample from said probability distribution to predict damage evolution.



6. Results



Metric [Ghr+24] / Temperature variation	$70°C$	$90°C$	$110°C$
RBT	0.702	0.802	0.509
RMSBT	0.637	0.802	0.509

7. Conclusions

- A remaining useful life prediction per cycle was presented, as opposed to classical point estimations, which accounts for a variable loading profile.
- The prediction scheme uses physical quantities measured numerically based on the loading profile to tackle the extrapolation issue.
- Data-driven methods were used to substitute inherently slow numerical simulations.
- The probabilistic nature of Markov chains makes predictions robust to variance.

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