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The Language of Deformation

Semantic Failure Analysis as a Prerequisite for Dexterous Manipulation of Deformable Objects


Ignacio Cuiral-Zueco
Clermont Auvergne INP


David Hardman
Univ. of Cambridge


Michele Pierallini
Università di Pisa


Erfan Shahriari
RAI Institute, Zurich

CONTEXT AND MOTIVATION

Why do robots need to *understand* deformation failures?

- **Deformable Object Manipulation (DOM)** = handling soft, flexible, or fragile objects = industry, healthcare, home...
- Robots detect *that* something failed, but not *how and why*
- Different failures need **different (sometimes opposite)** corrective actions

Rigid objects	Deformable/fragile objects
Few failure modes (slip, drop)	**Many** failure modes (buckling, tearing, plastic deformation...)
Physics well-understood	Non-linear, history-dependent, material-specific
Recovery strategies generalize	Each failure needs a *different* corrective response

Example: Squeezing clay vs. compressing a thin rod = same reading ("force rising"), but **opposite** required action.

WE PROPOSE

Semantic Failure Analysis for Deformable Object Manipulation (SFA-DOM)

We propose **SFA-DOM** as a new paradigm: robots must move beyond detecting failure to *semantically classifying* its physical cause and responding accordingly.

MAIN CHALLENGES

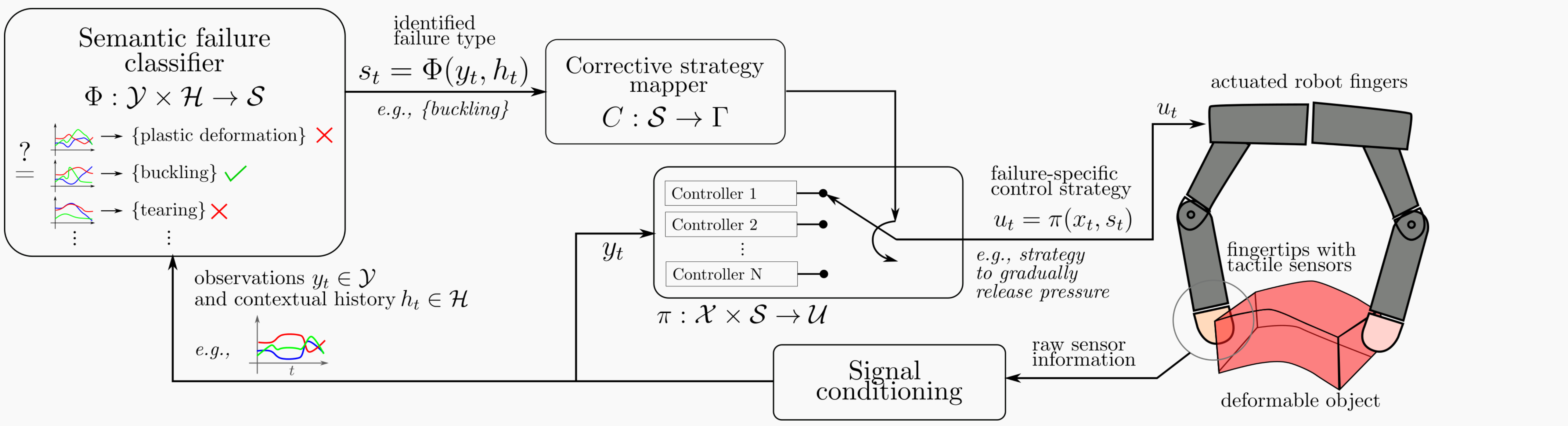
Sensing
Events at ~0.2–0.7 N (near wrist F/T noise floor)
→ Contact-proximal tactile sensing

Actuation
Sub-newton modulation needed
→ Low-inertia, back-drivable actuators

Modelling
FEM/Cosserat gap ~1.5 N RMSE (too coarse)
→ Data-driven models on real contact data

Control
Different failures → opposite strategies
→ Policies conditioned on failure label

FRAMEWORK

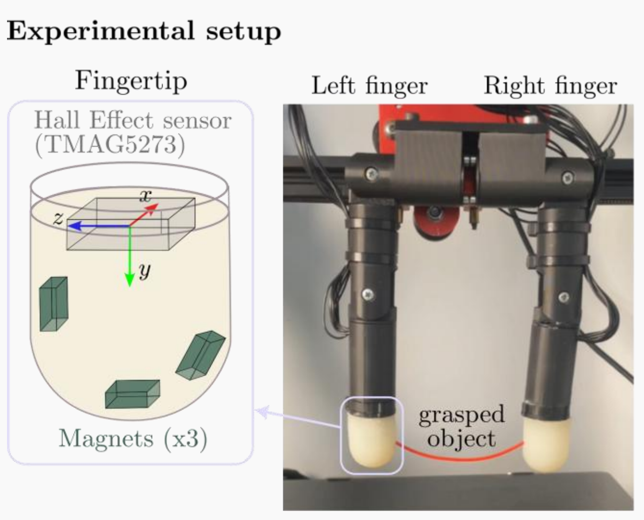


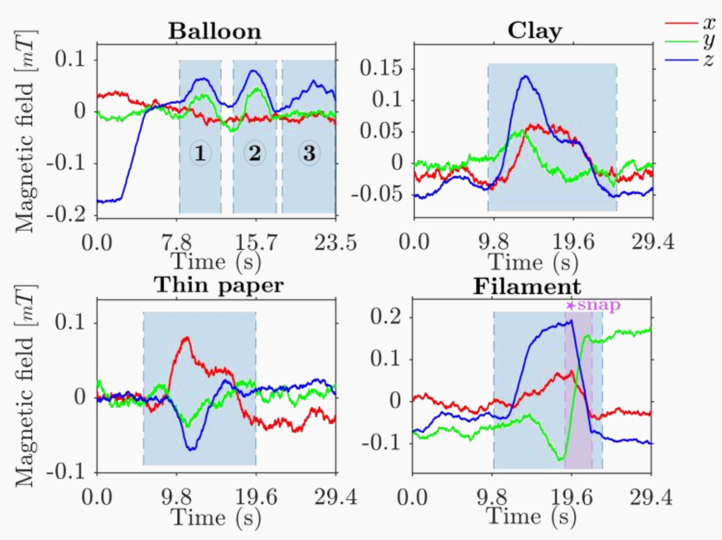
Classifier Φ
$\Phi: \mathcal{Y} \times \mathcal{H} \to \mathcal{S}$
Sensor data + history → failure label
(buckling, tearing, plastic def. ...)

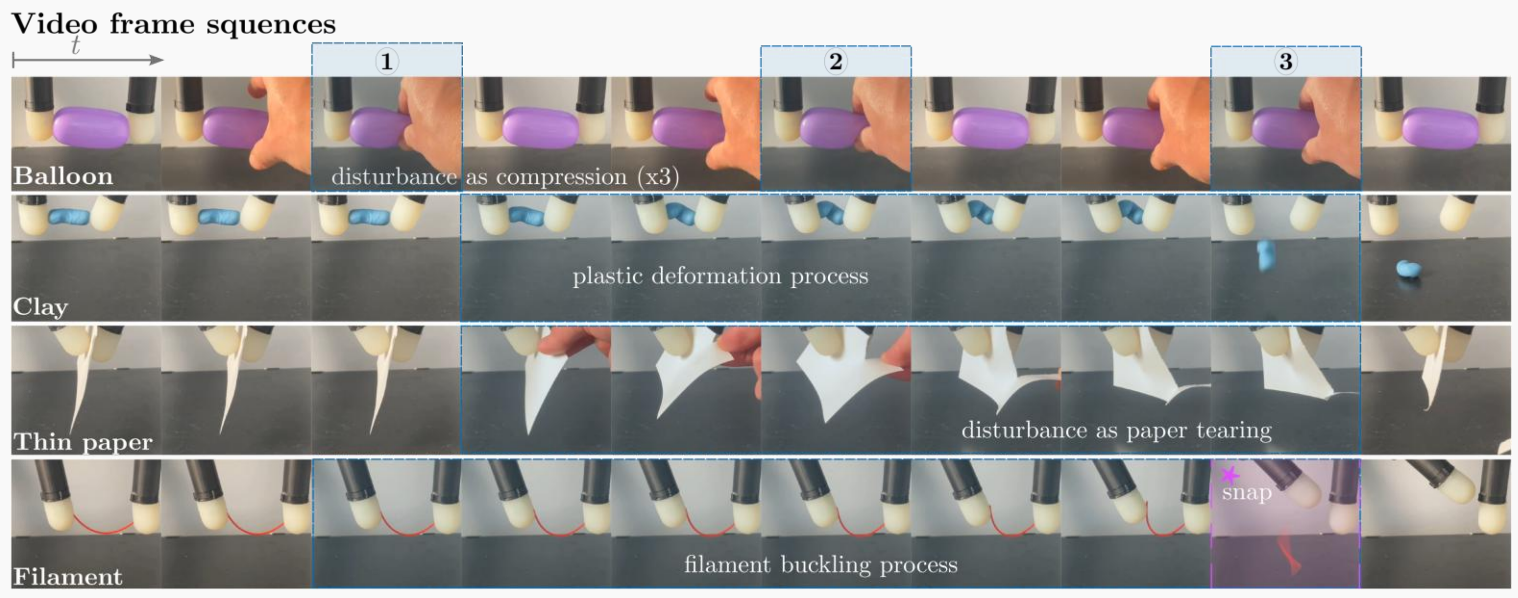
Corrective Mapper C
$C: \mathcal{S} \to \Gamma$
Failure type → corrective strategy

Control Policy π
$\pi: \mathcal{X} \times \mathcal{S} \to \mathcal{U}$
Actions conditioned on state + failure label

EXPERIMENTS Distinct failures → distinct tactile *signatures*







Object	Failure case	Signature
Balloon	Pressure coupling	Periodic pulses (non-local force)
Clay	Plastic deformation	Non-linear 2-phase decay
Paper	Tearing	Antisymmetric signal decay
Filament	Buckling / snap	Linear rise → sudden drop

WE PROPOSED

Semantic Failure Analysis as a necessary block for robust **DOM**
Framework: failure classifier Φ, corrective mapper C, failure-aware policy π
PoC validation: distinct failures produce classifiable signatures

WE IDENTIFIED

Hardware bottleneck: sub-newton events for sensing and actuation
Modeling bottleneck: first-principles models are too coarse for control
SFA-DOM is achievable but requires advances = relevant research line

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