

Predictive Digital Twins

for unmanned aerial vehicles

Michael Kapteyn, Karen Willcox

Concept

Design

Manufacturing

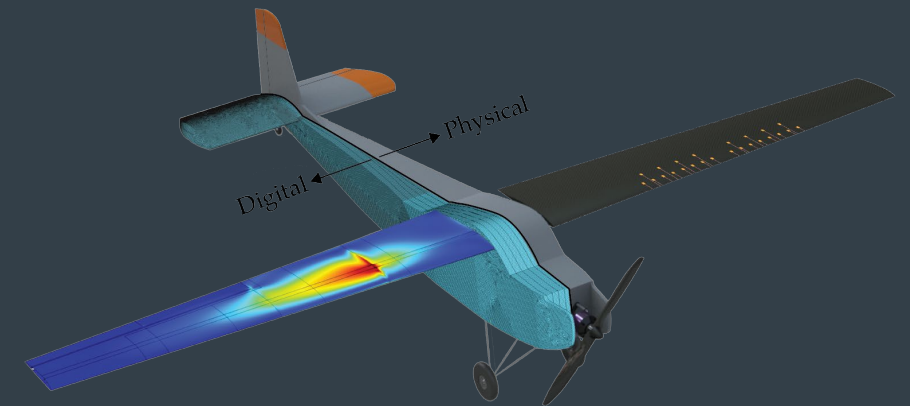
Operation

Post Life

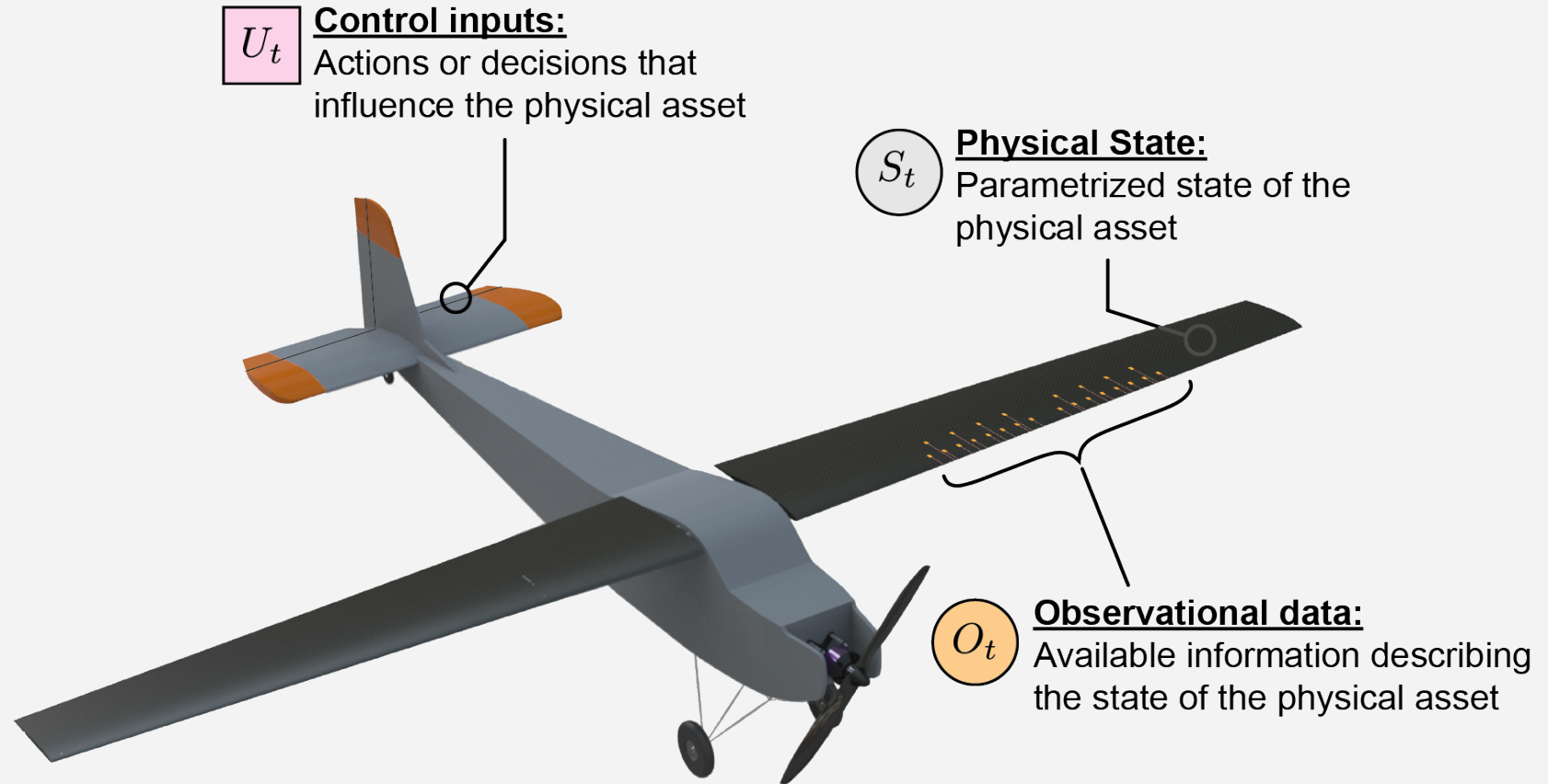
Retirement

“A Digital Twin is a set of **virtual information constructs** that **mimics the structure, context, and behavior** of an **individual/unique physical asset**, is **dynamically updated** with data from its physical twin **throughout its lifecycle**, and **informs decisions that realize value**”

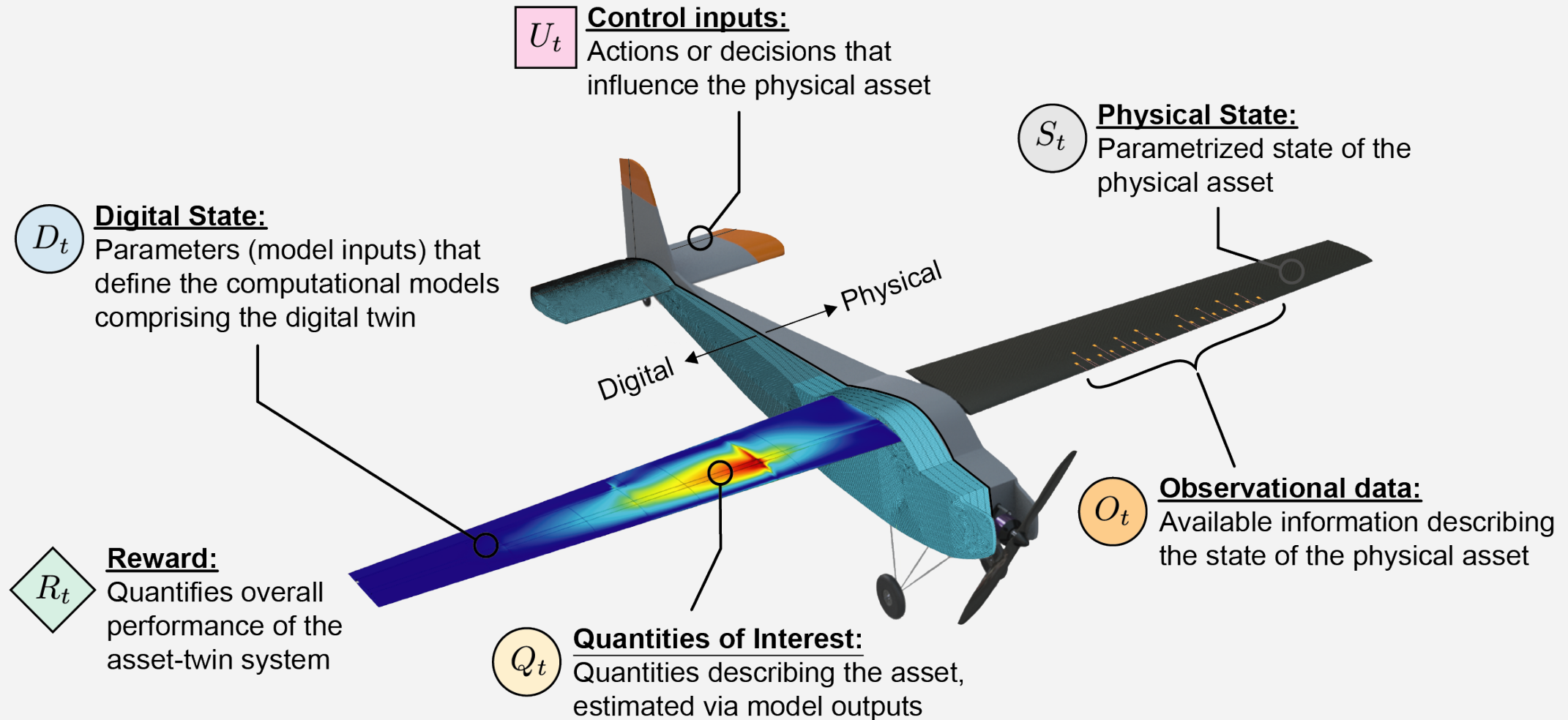
- AIAA Institute Position Paper, 2020

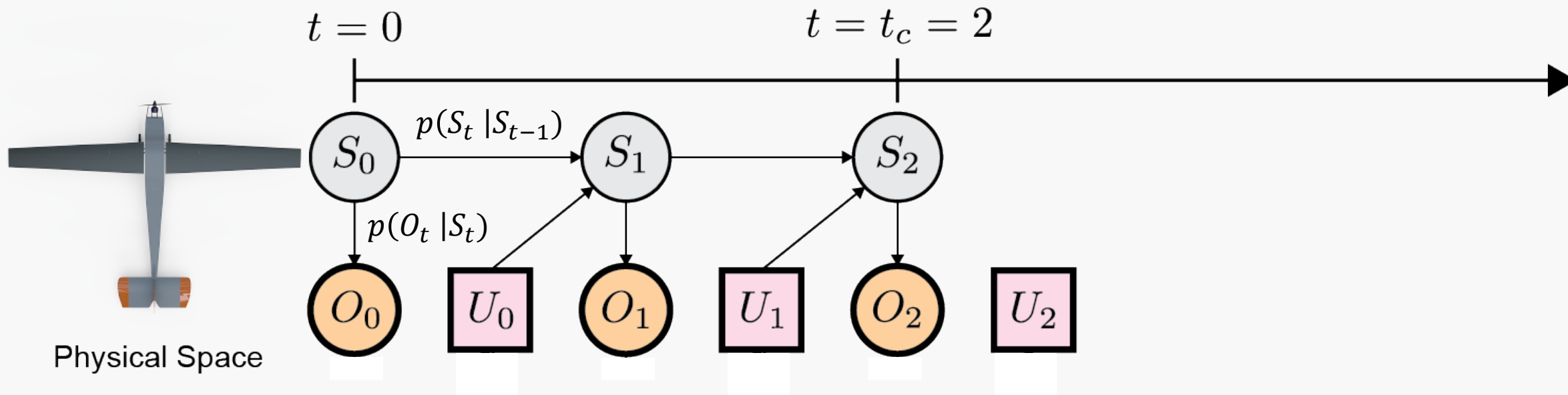


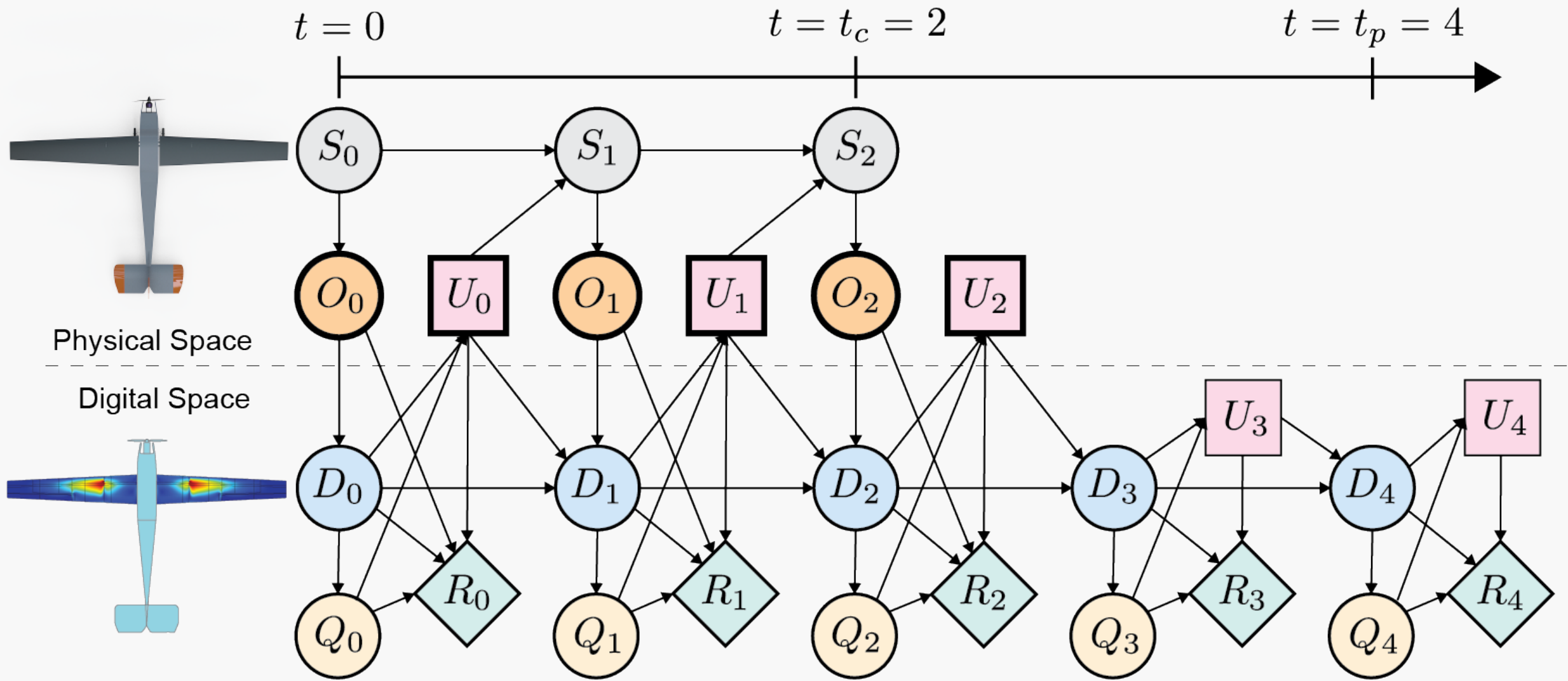
Mathematical abstraction of an asset-twin system



Mathematical abstraction of an asset-twin system







Graph represents joint probability distribution: $p \left(D_0, \dots, D_{t_p}, Q_0, \dots, Q_{t_p}, R_0, \dots, R_{t_p}, U_{t_c+1}, \dots, U_{t_p} \mid o_0, \dots, o_{t_c}, u_0, \dots, u_{t_c} \right)$

Representing a Digital Twin as a probabilistic graphical model gives an integrated framework for calibration, data assimilation, planning and control [Kapteyn, Pretorius, W. *Nature Comp. Sci.* 2021]

Predictive Digital Twin Use-case

Automatic monitoring, virtual inspections, simulation-based certification

Forecasting, predictive maintenance, planning

Operations: Tradeoff between

- Favorable asset state
- Digital twin accuracy
- Required control effort
- Observation acquisition cost

Learn from historical data,
transfer insights to similar assets

Mathematical Formulation via Probabilistic Graphical Model

Data assimilation: $p(D_{t_c}, Q_{t_c}, R_{t_c} \mid u_0, \dots, u_{t_c}, o_0, \dots, o_{t_c})$

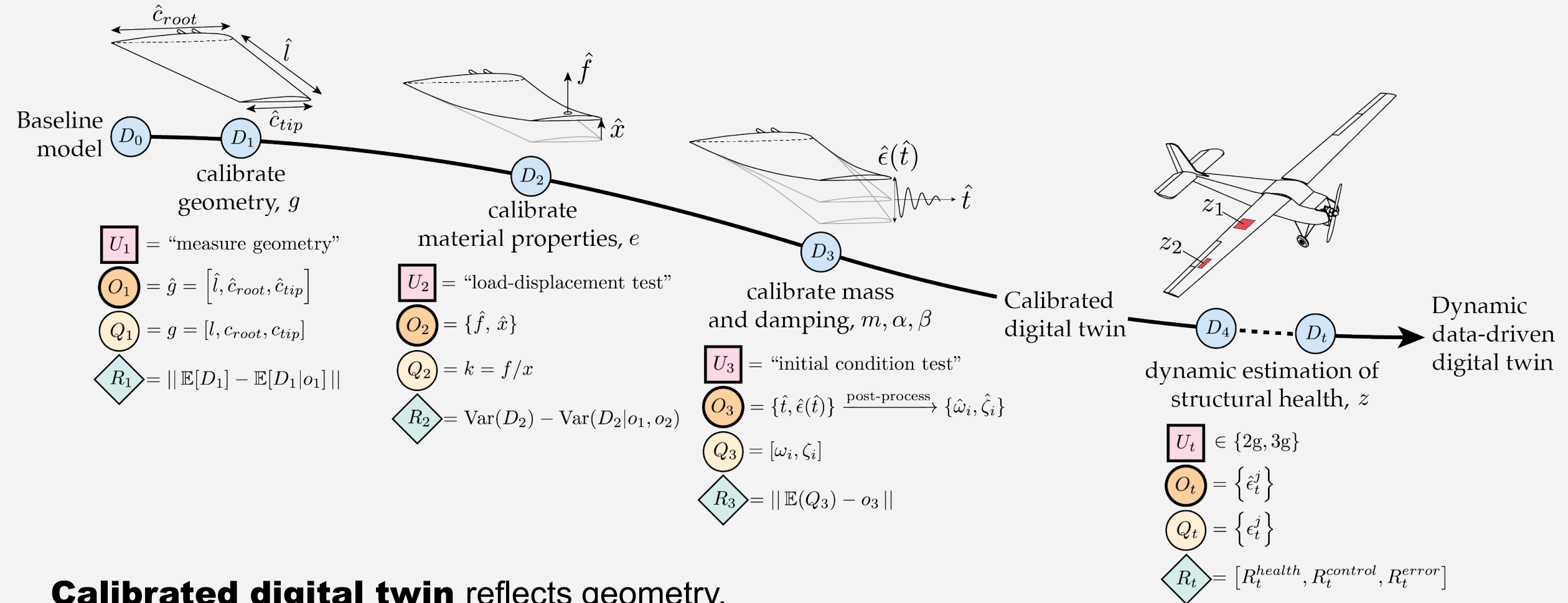
Prediction: $p(D_{t_p}, Q_{t_p}, R_{t_p} \mid u_0, \dots, u_{t_c}, o_0, \dots, o_{t_c})$

Multi-objective optimization: $\phi_t^{\text{evaluation}} = p(R_t \mid D_t, Q_t, U_t, O_t)$
$$\max_{U_{t_c}, \dots, U_{t_p}} \sum_{\tau=t_c}^{t_p} \mathbb{E}[R_\tau]$$

Learning: $\phi_t^{\text{dynamics}} = p(D_t \mid D_{t-1}, U_t)$
 $\phi_t^{\text{assimilation}} = p(O_t \mid D_t)$

Creating and evolving a structural digital twin for an unmanned aerial vehicle

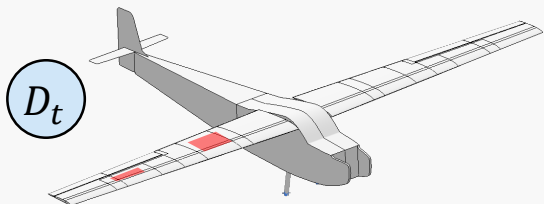
[Kapteyn, Pretorius, W. *Nature Comp. Sci.* 2021]



Calibrated digital twin reflects geometry, material properties, and structural properties of the physical UAV, along with estimates of our uncertainty



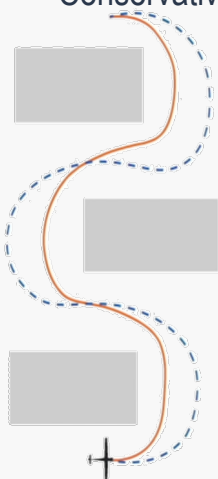
S_t



D_t

— Aggressive flight path
— Conservative flight path

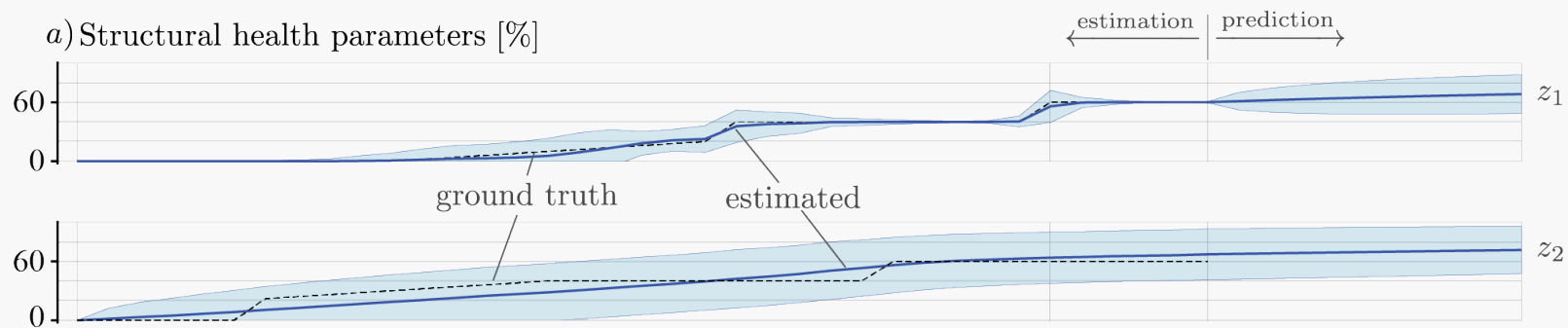
U_t



O_0

a) Structural health parameters [%]

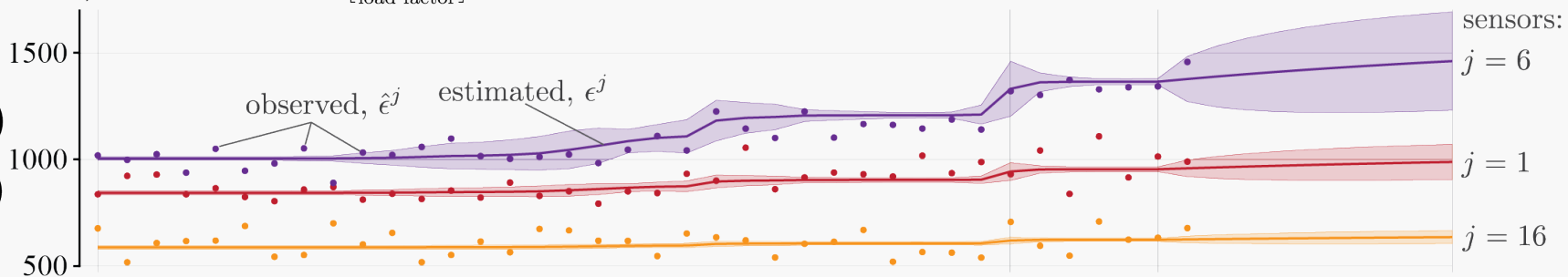
D_t



b) Normalized strain $\left[\frac{\mu\epsilon}{\text{load factor}} \right]$

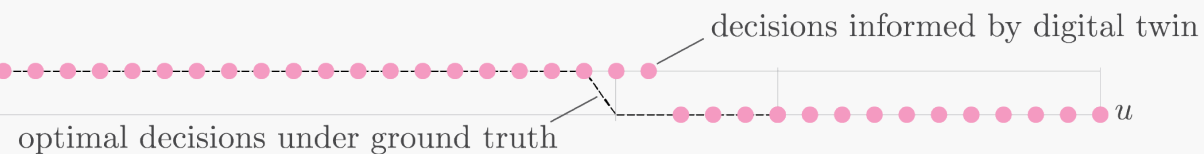
O_t

Q_t



c) Control inputs [-]

U_t



d) Reward functions [-]

R_t

