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A REVIEW OF EMERGING APPLICATIONS AND FUTURE RESEARCH DIRECTIONS OF ARTIFICIAL INTELLIGENCE IN DIGITAL TWINS

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Overview

- Digital twins connect physical assets, models, and measurements.
- Artificial intelligence can extend twins beyond monitoring and prediction.
- This narrative review examines eight emerging application areas.
- Focus: engineering contributions, representative evidence, limitations, and future research.

Eight Emerging Applications

Model and data development

- Test scenario generation
- Cybersecurity and recovery
- Mutual calibration
- Synthetic fault data

Decision-making and autonomy

- Policy learning and transfer
- Adaptive fidelity and autonomy
- Knowledge-based reasoning
- Symbolic planning and replanning

Review Scope and Method

- Focused narrative review of representative studies; not a systematic literature search.
- Compare each method by input, output, engineering purpose, and limitations.
- Includes machine learning, generative models, reinforcement learning, AI agents, ontologies, and symbolic planning.
- Distinguishes reported achievements from combinations proposed as future work.

1. Test Scenario Generation

- Digital twins permit repeatable testing of demanding operating conditions.
- ScenGE couples language-model reasoning with adversarial trajectory optimization [18].
- The output is an executable scenario, not merely an abstract description.
- Future opportunity: use challenging scenarios to direct active sampling and model refinement [6,18].

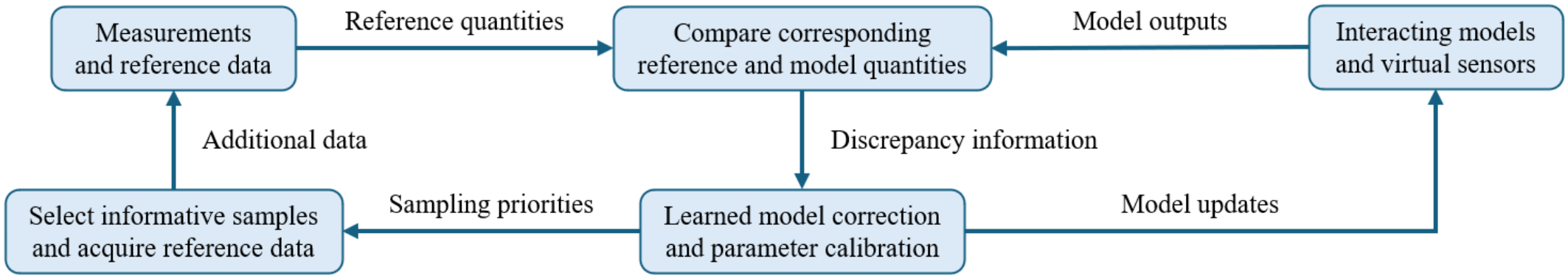
2. Cybersecurity and Recovery

- A twin can generate labeled process data for intrusion detection [19].
- Distributed/federated learning is vulnerable to poisoned updates [22].
- FL-TWIN uses filtering, model history, and rollback of global-model checkpoints [20].
- Challenge: distinguish attacks from legitimate changes and avoid false-positive interventions.

3. Mutual Calibration

- Coordinate corrections of sensors and virtual models, rather than correcting each independently.
- Physical–virtual sensor calibration [23] and neural correction of indirectly observed targets [7].
- AI agents can coordinate tools and calibration workflows [13].
- Proposed connection: share discrepancy information with active sampling to select informative new evaluations [6–8,13,23].

Concept: Calibration and Active Sampling



Conceptual workflow from paper Figure 1; proposed integration, not an experimentally demonstrated system.

4. Synthetic Fault Data

- Physical failure measurements are scarce; simulations and generative AI can supply training examples.
- GAN-based augmentation for structural damage [9].
- Virtual-to-real fault-distribution mapping for reducer diagnosis [3].
- Uncertainty-aware training distinguishes uncertain examples from exact measurements [15].
- Limitation: synthetic data cannot repair incorrect physical fault assumptions.

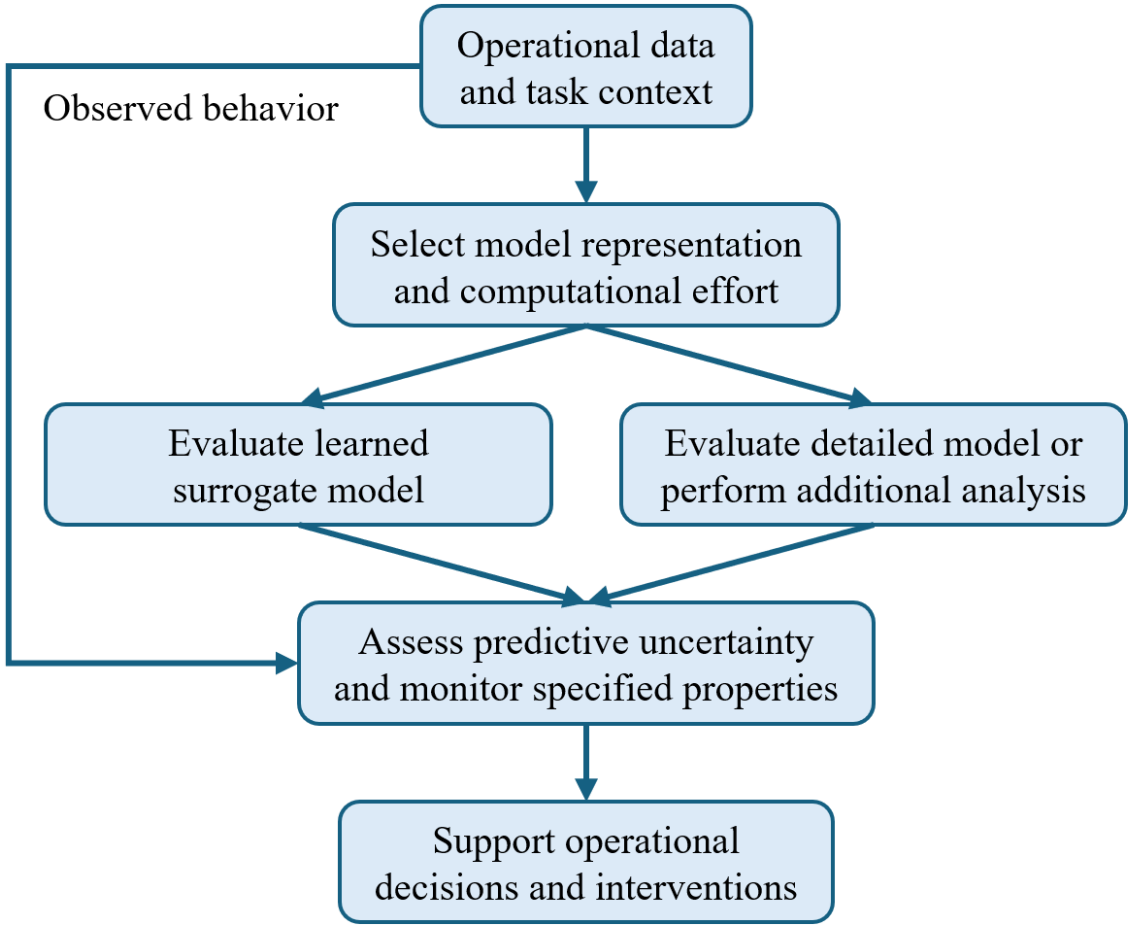
5. Policy Learning and Transfer

- Reinforcement learning trains candidate control policies through virtual interactions [4,5].
- Linked robot-arm digital twins support training and evaluation [4].
- RialTo reconstructs environments from observations and uses simulation plus demonstrations [5].
- Future work: connect policy refinement to model synchronization and uncertainty [5,8].

6. Adaptive Fidelity and Autonomy

- Match computational effort and model fidelity to the current prediction or control task.
- Surrogate models speed recurring evaluations; model profiling compares accuracy and cost [14,17,26].
- Manufacturing twins can activate more detailed simulation when anomalies occur [16].
- Runtime verification can monitor operational requirements and support intervention [27].

Concept: Model Selection and Monitoring



Conceptual architecture from paper Figure 2; combinations require further evaluation.

7. Knowledge-Based Reasoning

- Ontologies and knowledge graphs represent assets, capabilities, and relationships [28].
- Manufacturing study uses capability requirements and rules to rank replacement tools [29].
- A language model provides a natural-language explanation, while selection rules remain explicit.
- Research direction: encode dependencies between sensors, model estimates, and calibration targets.

8. Symbolic Planning and Replanning

- PDDL action models specify available operations, preconditions, and effects [30].
- A DT-supported manufacturing system can generate executable plans.
- Speculative replanning improves a plan while production is underway [30].
- Potential integration: knowledge-based resource selection + planning + physical simulation.

Cross-Application Research Connections

Connections motivated by the literature

- Scenario generation ↔ active learning
- Mutual calibration ↔ sampling
- Synthetic faults ↔ uncertainty-aware diagnosis
- Model synchronization ↔ policy learning

Integration challenges

- Physical and semantic consistency
- Uncertainty and reliable decisions
- Computational cost and fidelity
- Transfer to real-world operation

Critical Limitations

- Different studies provide different evidence: simulation, operational records, demonstrations, or theoretical methods.
- Offline simulation does not automatically constitute a continuously synchronized digital twin.
- Some cited studies concern workflows relevant to DT development rather than deployed twins.
- Proposed combinations in this review should not be mistaken for validated integrated solutions.

Conclusions

- AI can make digital twins more adaptive, reliable, and autonomous.
- The eight areas span data generation, calibration, diagnosis, control, fidelity selection, reasoning, and planning.
- Research opportunities lie in useful connections between these capabilities.
- Future evaluations must demonstrate physical consistency, transferability, uncertainty handling, and real operational benefit.