Simulation-Based Uncertainty Propagation in Geometric Networks for Surgical Robotics

X.M. Christine Zhu

Mentors: Dr. Russell H. Taylor
Dr. Adnan Munawar

JOHNS HOPKINS UNIVERSITY

MOTIVATION

- Surgical robotic systems rely on **multiple geometric components**:
  - Robots, tracking systems, anatomy, sensors, etc.
- Each component introduces **uncertainty**:
  - Calibration error
  - Measurement noise
  - Kinematic modeling error
- These uncertainties **interact** through geometric composition

Core problem

There is no unified, general framework to **model and query uncertainty propagation across an arbitrary geometric network**.

This project bridges **geometry, probability, and simulation**, providing a principled way to understand uncertainty in complex robotic systems.

SYSTEM ABSTRACTION: NETWORK VIEW

System Representation

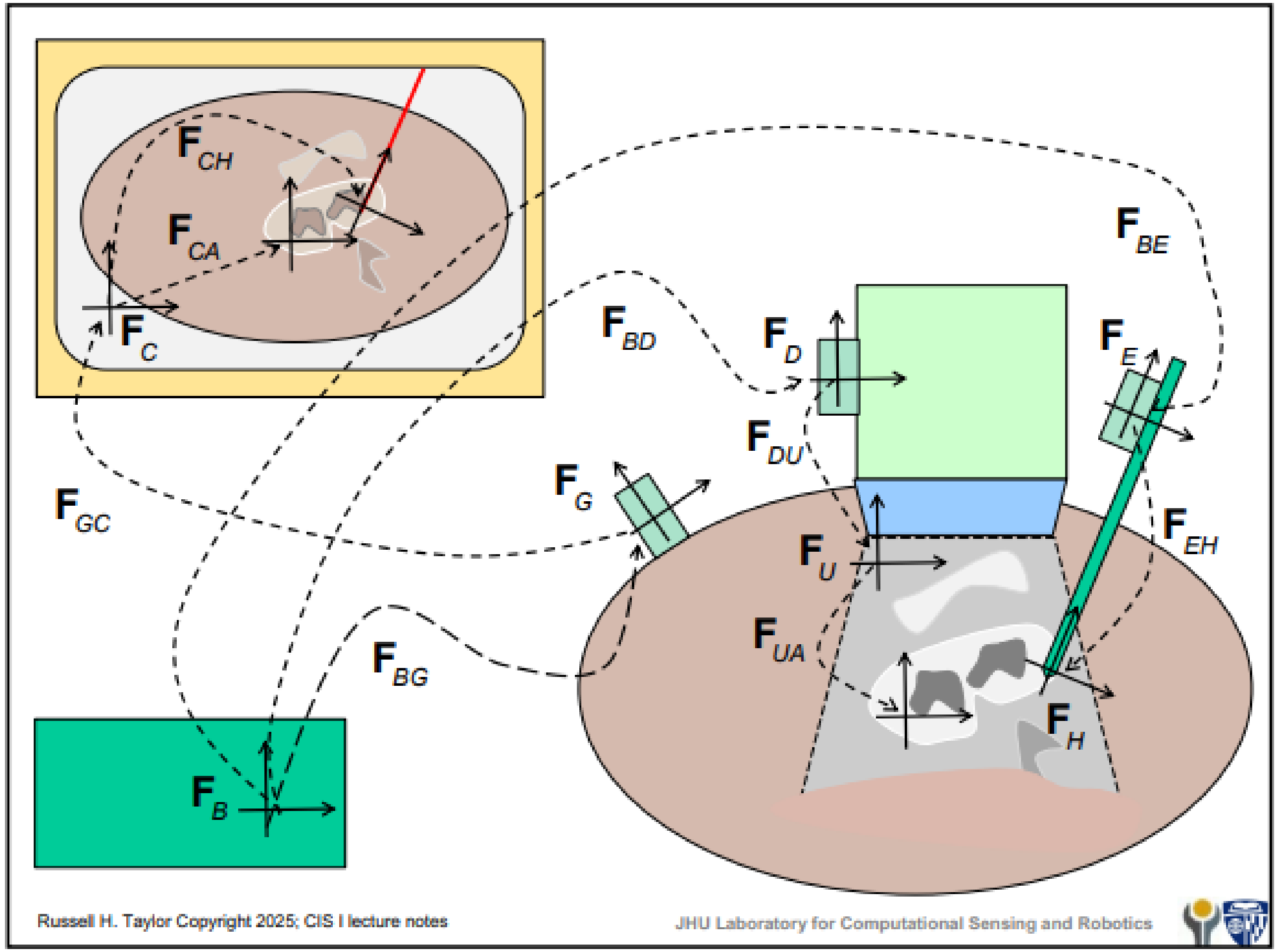
- System modeled as a **graph**:
  - **Nodes**: frames or points
  - **Edges**: geometric relationships with uncertainty

Examples of Nodes

- Robot base, links
- Optical tracker, EM tracker
- Ultrasound Sensors
- Video Cameras
- Anatomy
- Fiducial or tool to tip points, 3-DOF points

Examples of Edges

- Rigid transformations
- Kinematic chains
- Sensor measurements



GOALS & SIGNIFICANCE

Project Goal:

Develop a **general simulation framework** that models and propagates uncertainty through a network of geometric relationships, enabling uncertainty queries between any two nodes.

Significance:

- Enables **quantitative uncertainty reasoning** in:
  - Surgical navigation
  - Registration
  - Tracking–robot fusion
- Models systems as **networks of uncertain frames and points**
- Treats uncertainty as a **first-class geometric quantity**
- Enables **end-to-end uncertainty queries** between any two nodes
- Supports Monte Carlo validation
- Supports both 1-time uncertainty (e.g. tolerance) and multiple time uncertainty (e.g. noise)

TECHNICAL APPROACH & DEVELOPMENT PLAN

Technical approach summary

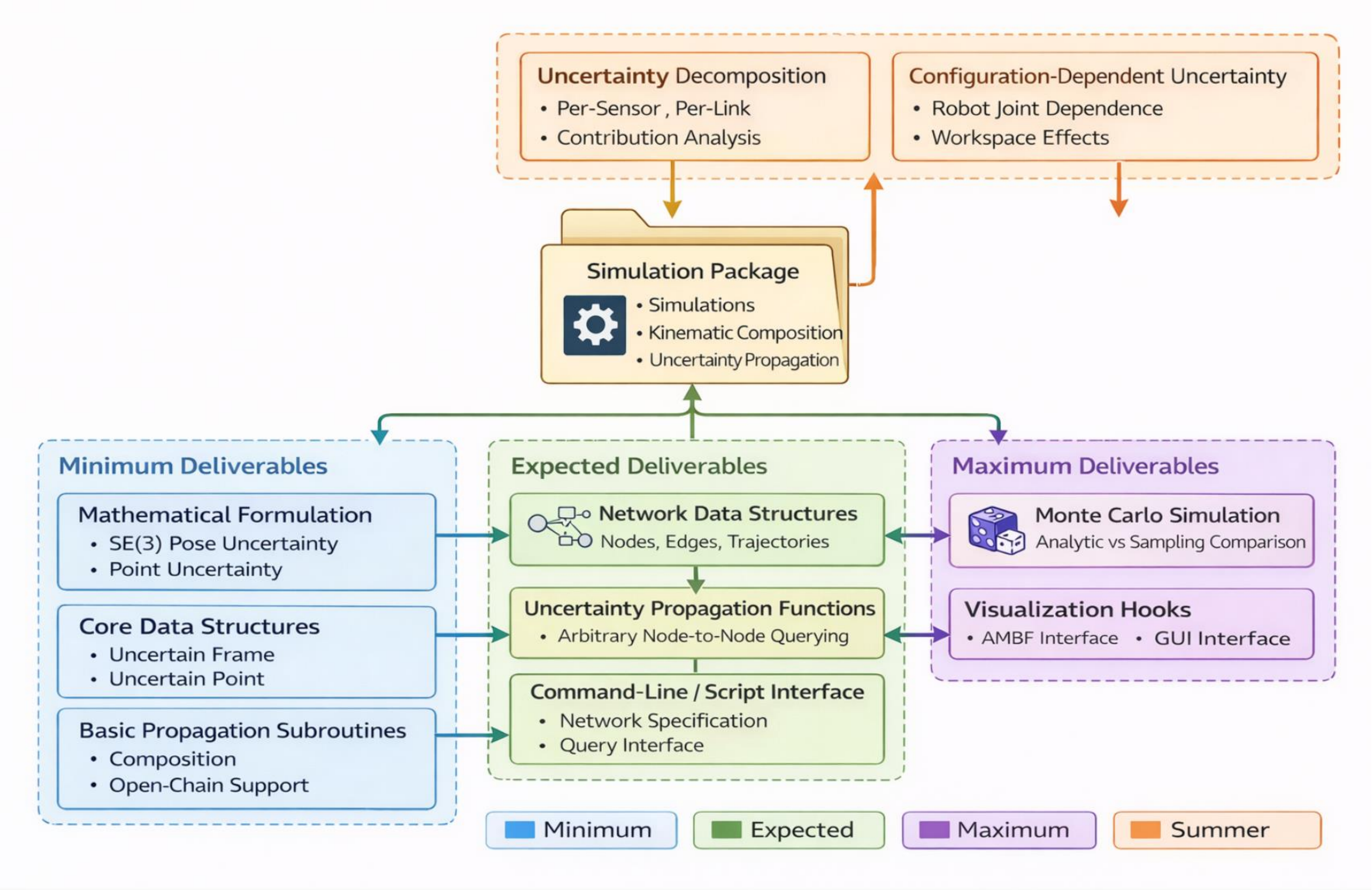
- Define uncertainty-aware geometric primitives
- Build composable operators
- Represent system as a graph
- Support Monte Carlo propagation
- Validate and visualize in AMBF

Development Plan

- Phase 1: Mathematical & Software Foundations
- Phase 2: Network & Simulation
- Phase 3: AMBF & Visualization

Figure: Illustration of Uncertainty Propagation

SYSTEM BLOCK DIAGRAM



DELIVERABLES

Minimum

- Mathematical formulation for uncertainty propagation
- Core data structures
  - Uncertain **Frame**
  - Uncertain **Point**
- Basic subroutines for composing and propagating uncertainty
- Open-chain network support
- Simple test cases demonstrating correctness

Expected

- Fully functional **network system** for uncertainty propagation
- Support for querying uncertainty between arbitrary nodes
- Command-line or script-based network specification
- Documentation and examples

Maximum

- Monte Carlo simulation for validation and comparison
- AMBF-based visualization
- GUI for interactive network specification and querying

TIMELINE & MILESTONES

WEEKS	GOALS	MILESTONES
Weeks 1-2	• Establish correct uncertainty modeling. • Define covariance representations. • Validate with simple example.	Documents for math framework and implementation plan. Expected: 02/15/2026
Weeks 3-4	• Implement uncertainty-aware geometric primitives. • Working uncertainty propagation for kinematic chains.	Core function library validated on basic examples. Expected: 03/01/2026
Weeks 5-6	• Support general geometric networks. • Enable uncertainty queries between any two nodes.	General geometric network support implemented. Expected: 03/15/2026
Weeks 7-8	• Validate propagation. • Implement Monte Carlo sampling.	Monte Carlo validation completed. Expected: 03/29/2026
Weeks 9-10	• Usable interface. • Implement GUI.	User workflow validated on representative examples. Expected: 04/05/2026
Weeks 11-12	• Prepare evaluation-ready output. • Integrate to AMBF for visualization. • Finalize documentation.	Visualization integrated. Finalize documentation. Expected: 04/19/2026

MANAGEMENT

Meeting Schedule

- Regular standing meetings will be used to review progress, discuss modeling assumptions, and adjust scope as needed
  - Every Friday, 1:30-2:30 p.m. with Dr. Taylor
- Extra meetings may be scheduled if clarification or design decisions are required

Data Management

- All simulated data, configuration files, and experiment results will be stored in a structured project repository
- Intermediate results (e.g., Monte Carlo samples, uncertainty outputs) will be saved in reproducible formats for analysis and validation
- Version control will be used to track code and data evolution

Dependencies

- Access to computing – resolved
- Consultation from Dr. Munawar for AMBF – resolved

Background Reading

Uncertainty Propagation

https://en.wikipedia.org/wiki/Propagation_of_uncertainty

Uncertainty Modeling

https://en.wikipedia.org/wiki/Uncertainty_quantification

Kalman Filter

https://en.wikipedia.org/wiki/Kalman_filter

Measurement Theory

https://en.wikipedia.org/wiki/Measure_(mathematics)

Thank You!

X.M. Christine Zhu

xzhu83@jhu.edu