VirtuCath™ Software Verification Report

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1.0 Purpose

The purpose of this document is to provide verification for the VirtuCath™ simulation software. This report formally documents the physical accuracy of the software's core mechanical simulation by benchmarking its performance against an established, state-of-the-art analytical model from the academic literature.

2.0 Scope

This verification study applies to the core physics engine of VirtuCath™. While the VirtuCath™ software is capable of simulating complex catheters with multiple flexible sections and multi-pullwire actuation, this study focuses on a simplified, foundational case to specifically verify the underlying physics model. The scope is therefore limited to the quasi-static analysis of a single-segment, single-pullwire flexible catheter, without considering external loads or friction. While a full-fidelity verification would include all complexities, this foundational study is a necessary decoupling of variables to isolate and verify the mathematical accuracy of the core elastic rod solver.

3.0 Referenced Documents

- Rao, P., Peyron, Q., Lilge, S., & Burgner-Kahrs, J. (2021). How to Model Tendon-Driven Continuum Robots and Benchmark Modelling Performance. *Frontiers in Robotics and AI*, 7. DOI: 10.3389/frobt.2020.630245

4.0 Code Availability

The C++ code used to generate the benchmark data for this verification study is a modified fork of the original open-source library provided by Rao et al. (2021). The modified code, which was adapted to be interactive and solve for the specific parameters of this verification task, is available for review at the following repository:

- **URL:** https://github.com/MishaTikh/VirtuCathVerification/

5.0 Verification Methodology

The verification process utilizes a parametric Sweep approach. An automated script generates permutations of catheter parameters (Length, EI, Offset) and actuation inputs (Displacement). For every permutation, the system:

1. Calculates the "Reference" equilibrium state (Tip Angle and Actuation Force) using the semi-analytical Cosserat Rod model (Rao et al.).
2. Instantiates the specific catheter definition in the VirtuCath™ engine.
3. Solves for the equilibrium state using VirtuCath™.
4. Compares the simulation outputs against the reference values.

5.1 Benchmark Standard: State-of-the-Art Continuum Robot Models

The benchmark for this study was the Cosserat Rod Model. This is considered the highest-fidelity approach. It treats the catheter backbone as a continuous, elastic rod with six degrees of freedom at every point along its length. It makes no geometric assumptions about the final shape and directly solves the differential equations governing forces and moments.

5.2 Test Configuration

A virtual catheter with a single flexible segment was defined with a sweep of 72 catheter permutations with the following parameters:

- **Flexible Section Lengths:** 30 to 90 mm
- **Tendon (Pullwire) Offset:** 0.5 to 8 mm from the centerline
- **Input Actuation:** .5 to 5 mm of pullwire displacement
- **Catheter Stiffness:** 0.00010 to 0.01000 $N{\cdot}m^2$

5.3 Comparison Metrics

Two primary outputs were recorded to measure the correlation between the platforms. These metrics are considered sufficient as they represent the fundamental engineering input and output of the system:

1. **Required Tendon Force (N):** This metric represents the actuation **input**. Verifying the force confirms that the simulation's **statics** are correct, as the relationship between force and displacement defines the system's stiffness (EI).
2. **Final Tip Deflection Angle (°):** This metric represents the primary functional **output**. Verifying the angle confirms that the simulation's overall **kinematic** behavior and final shape are correct, which is the most direct measure of catheter performance.

6.0 Results

The validation suite executed a total of 280 simulations covering the full parameter space defined in Section 2.0.

Geometric Accuracy Results (Deflection Angle)

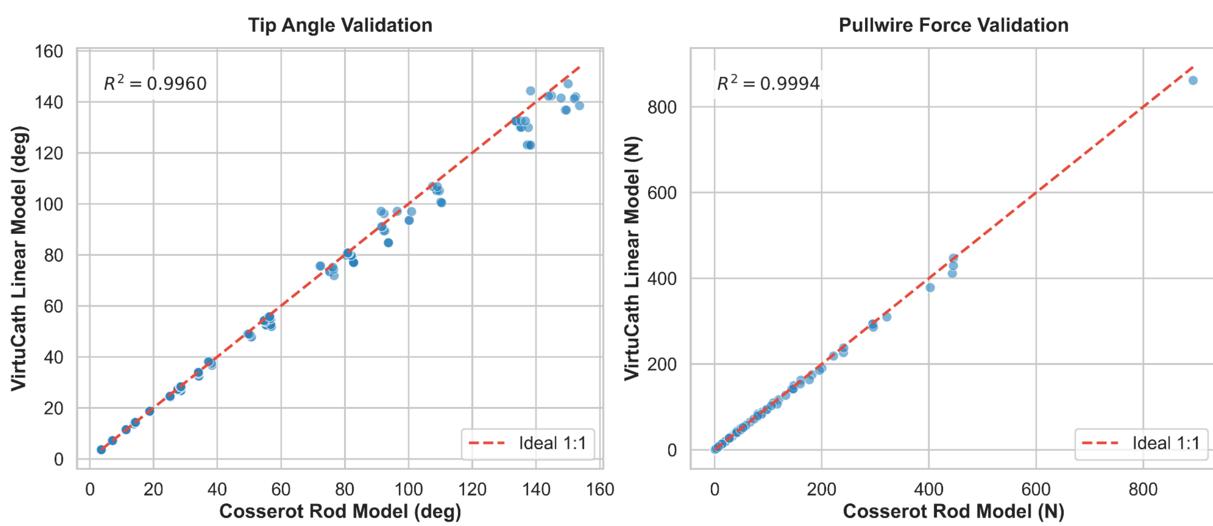
- **Maximum Absolute Error (MaxAE):** 13.28%
- **Mean Absolute Error (MAE):** 2.95%
- **Median Absolute Error:** 2.03%
- **Standard Deviation:** 2.77%

Force Accuracy Results

- **Maximum Absolute Error (MaxAE):** 11.27%
- **Mean Absolute Error (MAE):** 2.30%
- **Median Absolute Error:** 1.65%
- **Standard Deviation:** 2.06%

6.1 Visual Verification (Geometric)

The plot below illustrates the correlation between the Cosserot values (X-axis) and the VirtuCath values (Y-axis) for the entire batch.

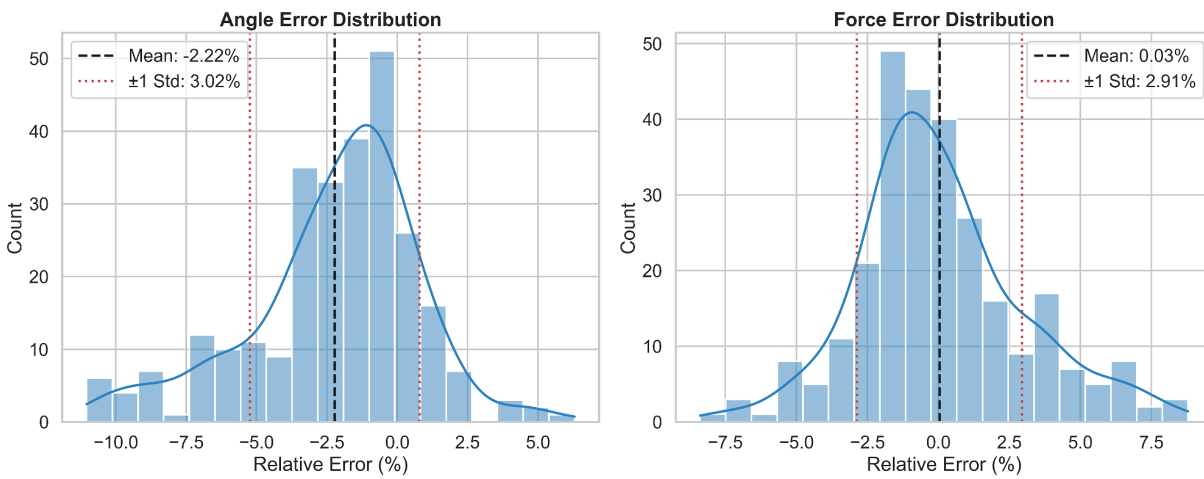


6.2 Error Frequency Distribution

The peak frequency occurs at the lowest error magnitudes, demonstrating that the solver achieves high fidelity for the bulk of the parameter space. The distribution's tail confirms that larger deviations are rare statistical outliers associated with specific edge cases, rather than a systemic inaccuracy in the core physics engine. The maximum percentage errors occur at two distinct boundaries of the parameter space:

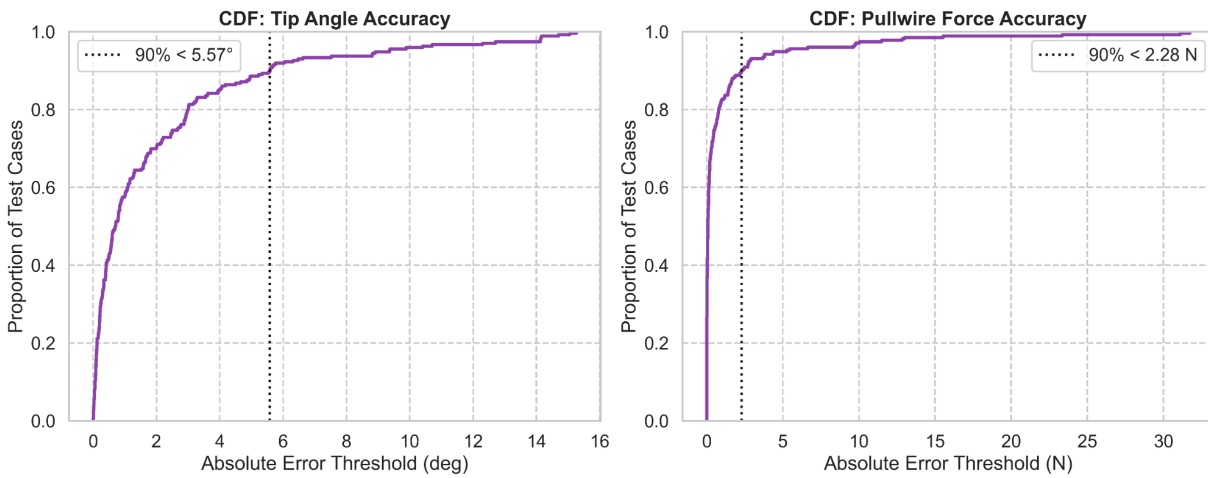
- The highest angle error is associated with the stiffest catheters (EI = 0.01 N·m²).
- The highest force error is associated with the softest catheters (EI = 0.0001 N·m²).

This dual-metric deviation analysis confirms that the solver's worst-case behavior is contained at the extreme edges of the tested parameter range.



6.3 Cumulative Probability Analysis

The cumulative distribution function (CDF) aggregates the error statistics to quantify the solver's reliability confidence. The steep initial ascent of the curve illustrates that a dominant percentage of the design space is resolved within a negligible error margin. This metric confirms that while outliers exist, the probability of encountering significant deviation during standard operation is statistically minimal.



7.0 Analysis and Conclusion

The VirtuCath™ core physics engine has been successfully verified against the Rao et al. (2021) benchmark. The solver demonstrates high accuracy in both geometric deformation and force estimation across a wide range of catheter lengths, stiffnesses, and tendon offsets. The detailed analysis confirms that the solver remains robust across orders of magnitude in force and maintains acceptable accuracy even in highly flexible, non-linear regimes.

While this report successfully verifies the mathematical accuracy of the core physics engine, a complete software validation involving a comparison against physical catheter prototypes remains the necessary subsequent step. This full physical validation is an extensive undertaking and is therefore beyond the scope of this verification report (VR-VC-001).