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A Novel, Realistic Mobility Model for Deep Space Network Simulations Under ns-3

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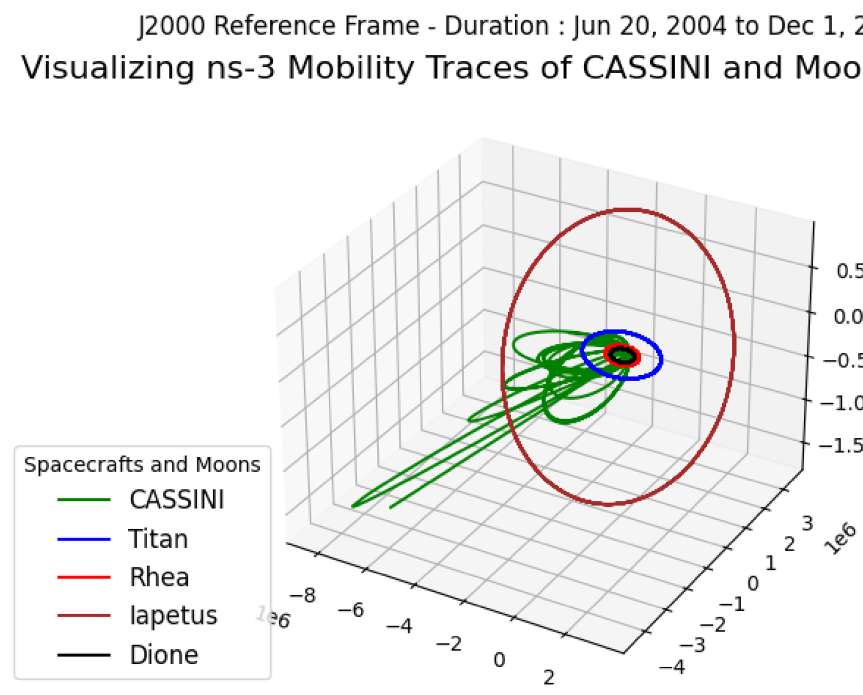

1. Introduction

In scenarios involving Deep Space Network (DSN) simulations, achieving precise network mobility and communication is challenging. This paper proposes a novel method for integrating the Spacecraft, Planet, Instrument, Camera-matrix, Events (SPICE) toolkit to achieve highly precise DSN simulations. As an initial step, this paper integrates the SPICE framework with ns-3 and develops a SPICE-enhanced mobility model for simulating the spacecraft and planets. This approach differs from conventional simulation platforms such as Satellite Network Simulator 3 (SNS3) and Network Simulator 3 with Low Earth Orbiting (LEO) satellites (ns-3-leo). The integration of SPICE with ns-3 expands networking opportunities beyond Low Earth network simulations.

2. NASA/NAIF's SPICE

SPICE is a space related ancillary data system[3] that serves as a scientific tool for space mission planning and analysis. It provides a standardized framework for incorporating critical data related to spacecraft, celestial bodies, instruments, camera matrices, and events.

In **Astrodynamic computations**, The SPICE system employs sophisticated methods to approximate the interpolation in the positions of celestial bodies over time. One prominent technique used by NASA's Jet Propulsion Laboratory (JPL) is the deployment of Chebyshev polynomials in the creation of Development Ephemeris (DE). Particularly efficient for interpolating planetary positions, Chebyshev polynomials play a crucial role in capturing celestial body vibrations between discrete time steps within the Ephemeris.

The fundamental form of the Chebyshev polynomial approximation is given by the expression:

$$f(t) = \sum_{n=0}^{N} a_n T_n(x) \tag{1}$$

Here, $f(t)$ represents the approximation function of astrodynamic oscillations concerning the position or velocity of spatial objects under the time t. The parameter N denotes the degree of the polynomial used in the approximation, and a_n are the coefficients associated with the Chebyshev polynomials. The term $T_n(x)$ signifies the n-th Chebyshev polynomial evaluated at x.

The Chebyshev polynomials $T_n(x)$ are defined over the time interval $[-1, 1]$ and are expressed recursively as:

$$T_0(x) = 1, \quad T_1(x) = x, \quad T_{n+1}(x) = 2x \cdot T_n(x) - T_{n-1}(x)$$

The variable x is intricately linked to the normalized time t, given by $x = \frac{2t-(a+b)}{(b-a)}$, where a and b delineate the time interval within which the Chebyshev polynomial approximation holds true.

During the fitting process, the coefficients a_n are meticulously determined to optimize the approximation of the given function over the specified time interval. This meticulous approach ensures accurate representations of celestial dynamics within the realm of astrodynamics.

3. SPICE-ns Mobility Model

A generic SPICE-ns mobility model simulation involves the following components:

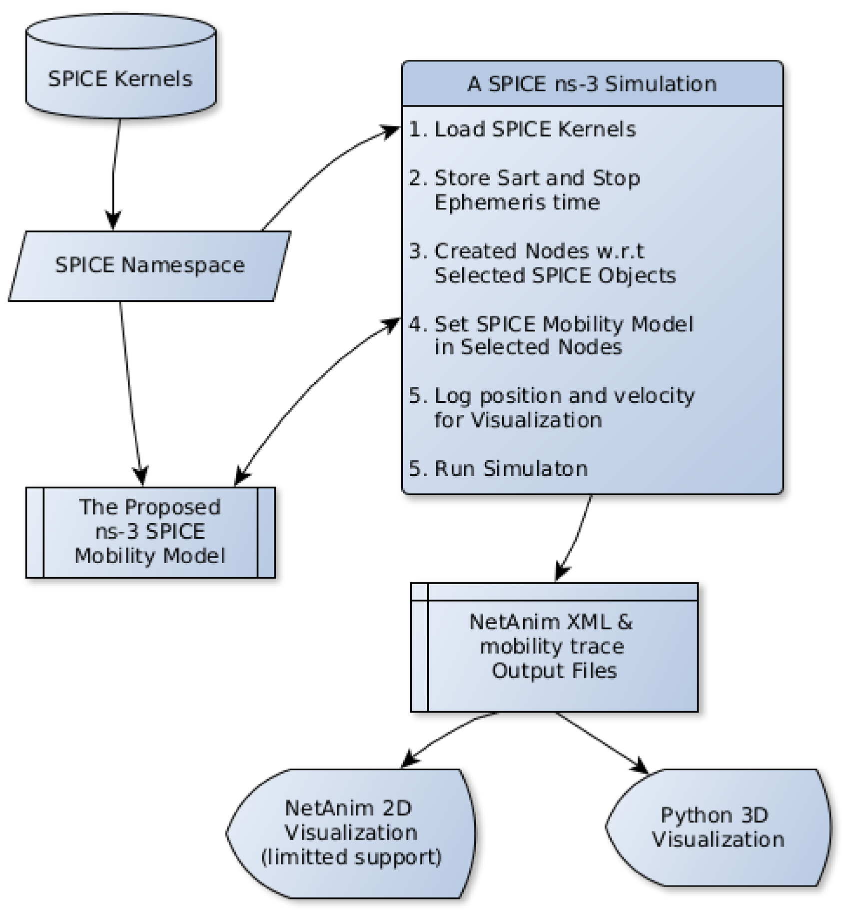

Figure 1: The SPICE Mobility Model

- **SPICE-ns**: This is the overall framework built within ns3 using NAIF's CSPICE for DSN Mobility and DTN Simulations.
- **SPICE Kernels**: SPICE Kernels are integrated into ns3 and loaded into memory at the simulation time(compile-time and run-time).
- **SPICE Namespace**: The SPICE Namespace is part of the SPICE-ns framework, similar to the ns3 Namespace but with CSPICE API and SPICE Kernel support. SPICE API functions kernel pools are kept under this separate namespace called"NASA_SPICE".
- **SPICE Mobility Model**: The SPICE Mobility Model is a generic celestial mobility model based on SPICE Ephemeris, providing high accuracy in astrodynamics(velocity, position and oscillations).
- **Output/Visualization**: A successful SPICE ns-3 simulation will generate NetAnim XML files, mobility trace files, and output files. Currently, NetAnim 2D Visualization has limited support, but the simulation can produce a comprehensive SPICE ns-3 Python 3D Visualization.

4. The Mobility Results

In our simulations, we performed DSN ns3 mobility with J2000 Reference frame ("J2000" - Julian year 2000 celestial reference system), Saturn and its moon with CASSINI spacecraft. The visual output results in a ns3 mobility model with SPICE-ns trajectories.

The proposed model provides high-precision scientific numerical data for the positions and velocities of celestial bodies over space-time. In the above figure , we used JPL DE Ephemeris of the moons of the planet Saturn. It is a 3D plot made using the ASCII mobility trace file that was logged during the ns-3 simulation run. If you are familiar with the SpiceyPy examples, you can verify the accuracy of this ns-3-generated mobility path of CASSINI.

5. Conclusions

In this simulation we're approximately simulating 4.57056e+07 seconds (528.6 days or 17.37months) of movements of CASSINI spacecraft in its trajectory and the orbital movements of 4 moons of the planet Saturn. Even at a short Ephemeris step time of 125 seconds, it only took around 45 seconds of simulation time to simulate the whole 17.37 months of such complex movements. Even for simulating 528.6 days of mobility of 5 objects, only around 400 MB of system memory is consumed.

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