Simulation Interoperability Standards Organization

"Simulation Interoperability & Reuse through Standards"

A Discussion of Time Management Concepts and Time Constraint Equations for Multi-Rate Federation Executions

2025-SIW-Presentation-010

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Introduction

- High Level Architecture (HLA) IEEE 1516 Time Management Services [1, 3] are critical to technical simulations like those created for space systems using the Space Reference Federation Object Model (SpaceFOM) [2].
- Time Management can be used to ensure data coherence and execution repeatability in distributed simulations. When combined with real time execution policies, Time Management is being used to support real time execution of mixed software and hardware in the loop integration, verification, and validation simulations for active space systems development.
- The associated challenges with Time Management and its use is discussed, starting with simple common rate frame scheduled simulations, then simple multi-rate simulations, and ending with complex mixed rate simulations.
- The authors then formulate the significant time constraint relationships between identified frame scheduling parameters.
- The intent is to provide a concise discussion of how to use Time Management in both simple cases and in more complex mixed frame rate federation executions.

High Level Architecture - Time Management Services

- **HLA Logical Time Representation**
  - Two principal standard types that are used: 64-bit integer time and 64-bit float time.
  - Only the HLAInteger64Time time representation will be considered.
  - SpaceFOM does provide a mapping between HLA Logical Time (HLT) and the federate time scale as a 64-bit integer representing microseconds.
- **Time Advance Request (TAR) and Time Advance Grant (TAG)**
  - TAR is a federate service call used to request the HLA Runtime Infrastructure (RTI) to advance HLT to a desired time.
  - TAG is a coordinated service callback from the RTI that tells a federate that a coordinated advancement in time has happened for the entire federation execution.
- **Time Constrained versus Time Regulating**
  - A Time Regulating federate assumes a responsibility in a federation execution that requires it to advance time using the TAR service calls. A time managed federation execution can only advance HLT once all Time Regulating federates have issued a TAR.
  - A Time Constrained federate is constrained in its ability to advance its local HLT subject to a TAG. A Time Constrained federate will only receive a TAG for a specified time once all time regulating federates have issued a TAR for that specified time.

SpaceFOM

- **Time-Lines**

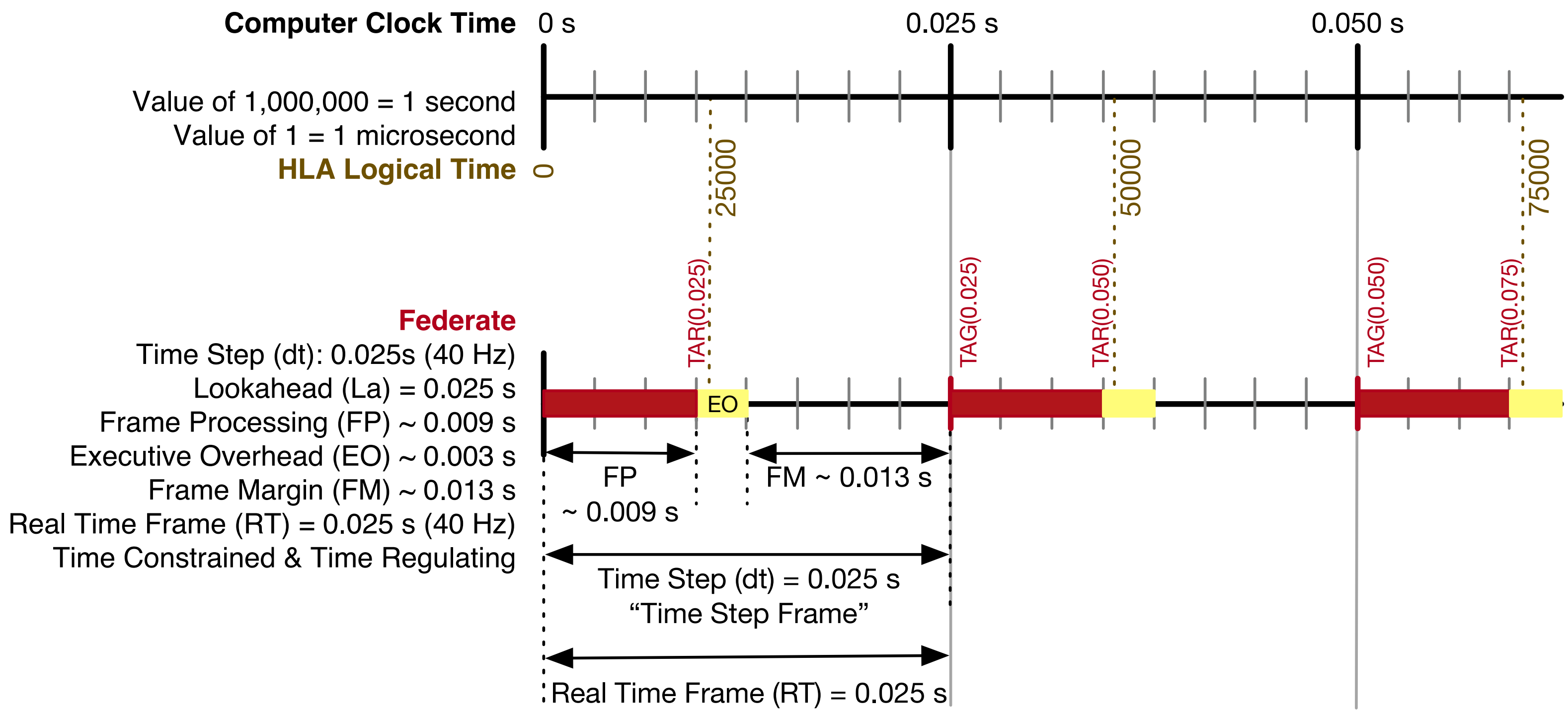
  The SpaceFOM defines the following 6 distinct time lines associated with a SpaceFOM-based federation execution:
  - **Physical Time (PT):** the non-spatial dimension associated with our spacetime continuum in which events are ordered in irreversible succession from the past to the present to the future.
  - **Computer Clock Time (CCT):** the representation of time maintained and managed by the computer usually using some form of oscillator counting oscillations from a known epoch. Mapped into an approximation of PT.
  - **Simulation Elapsed Time (SET):** the time measure associated with an individual simulation starting at zero and advancing monotonically in quantifiable steps.
  - **Simulation Scenario Time (SST):** a model within a simulation that associates the Simulation Elapsed Time with a representation of the problem's Physical Time.
  - **HLA Logical Time (HLT):** the time line used by HLA to order messages, regulate execution time advance (TAR & TAG), and enable deterministic behavior in distributed simulation.
  - **Federation Scenario Time (FST):** a time associated with the physical systems being modeled in the participating federates in the federation execution.

- **Roles and Responsibilities**
  - **Master:** Manages the overall execution of the federation execution. Also manages the time synchronization by providing the scenario time epoch, mode transition times, central timing equipment times, and the least common time step for the current federation execution.
  - **Pacing:** Provides the time regulating clock for the overall federation execution. The Pacing federate uses the native HLA Time Management services to regulate the advance of HLT in coordination with the Simulation Scenario Time.
  - **Root Reference Frame Publisher:** Provides the federation execution with the name of the root reference frame for the federation execution reference frame tree.

- **Time Management Options**
  - The SpaceFOM standard supports time stepped simulation based on fixed uniform time steps. Specifically, it relies on the use of the HLA Time Management services to coordinate the time-based progression of participating federates using uniform fixed increments of HLT. This includes support for Time Constrained and Time Regulating federates.

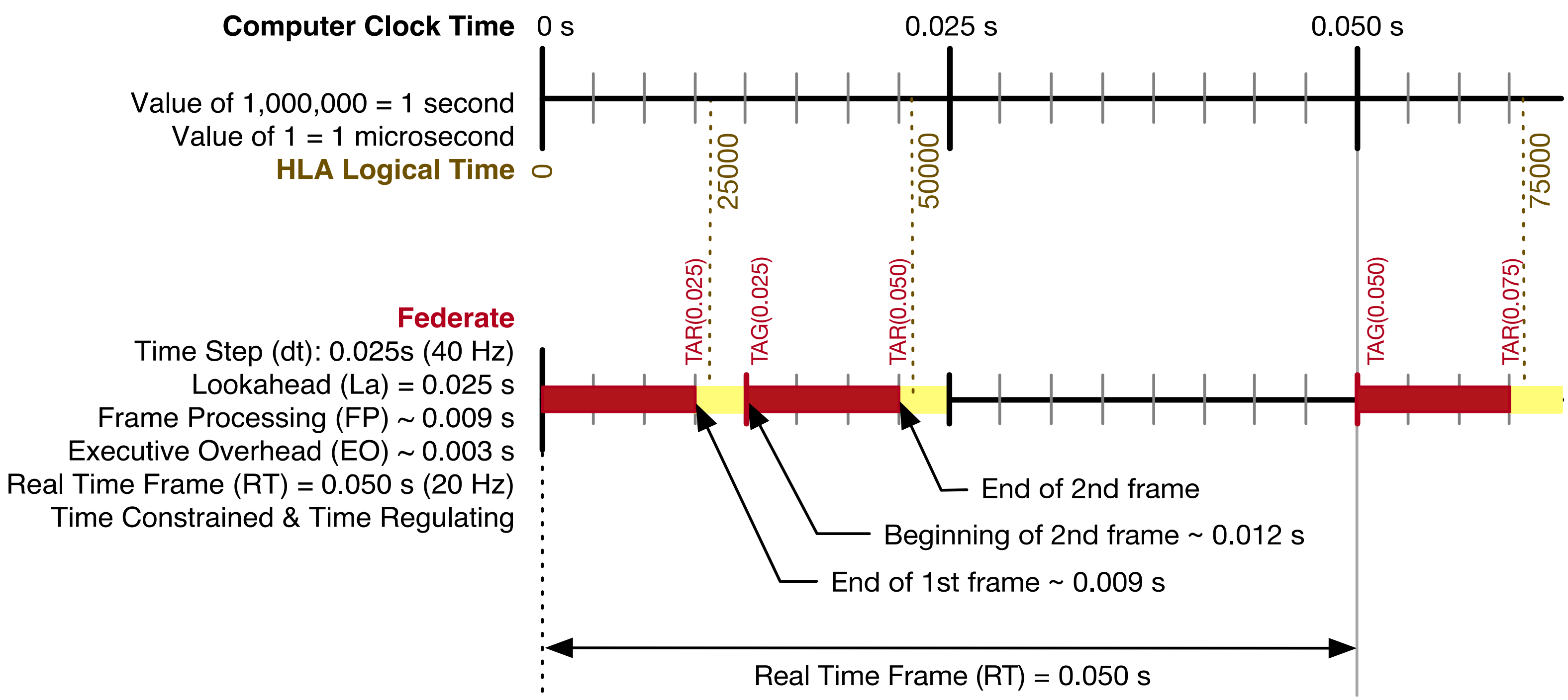
The Challenges of Time Synchronization - Basic Simulation Execution Frame Concepts

- **Simplified case where the principal federate time step (dt) is the same as the real time frame (RT), in this case 0.025 seconds or 40 cycles per second (Hz). This helps to show the relationship between the frame processing time (FP), executive overhead (EO), and principal time step (dt).**



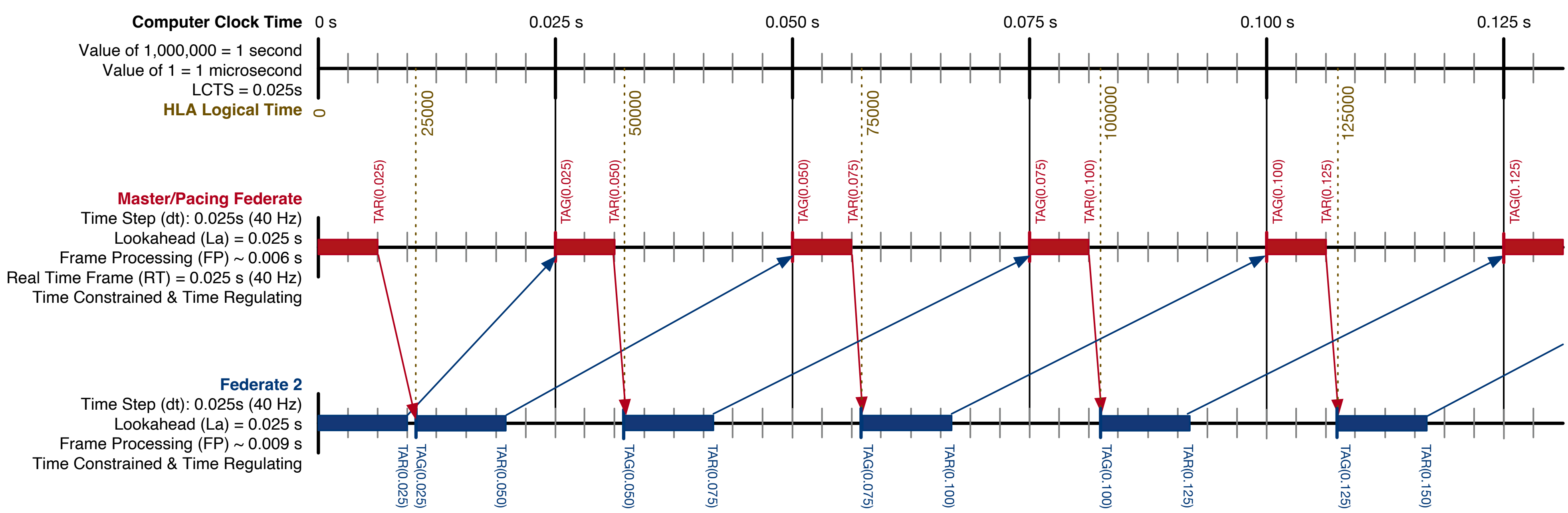
The Challenges of Time Synchronization - The Effects of Real Time

- What happens if the federate time step is not the same as the real time frame?
- The figure shows a slightly more complex case where the real time frame is twice the federate time step. In this case, the federate time step is still 0.025 seconds (40 Hz). However, the real time frame is now 0.050 seconds (20 Hz). The real time frame is twice the federate time step.



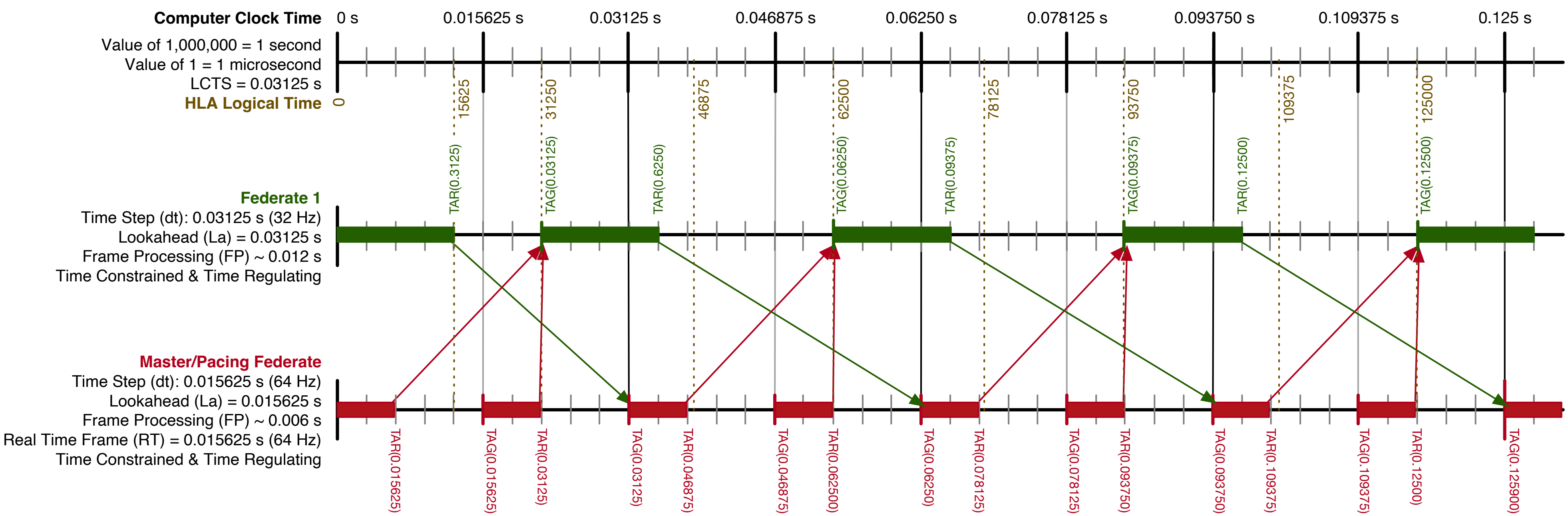
The Challenges of Time Synchronization - Simple Matched Rate Multi-Federate Case

- The figure shows the case where there are two federates in the federation execution with matching frame scheduling: Master/Pacing Federate (MPF) and Federate 2 (F2). Both federates have a federate time step of 0.025 seconds (40 Hz). The MPF has a real time frame of 0.025 seconds (40 Hz). Federate 2 does not have a real time frame and runs as fast as possible.



The Challenges of Time Synchronization - Simple Multi-Rate Multi-Federate Case

- **What if the time steps (dt) for federates do not match?**
- **This figure is like the previous one, but where the federate time steps do not match. Here, the MPF dt is 0.015625 seconds (64 Hz) with a matching real time frame (RT). Unlike the previous case, the additional federate, Federate 1 (F1), has a dt of 0.031250 seconds (32 Hz), $dt_1 = 2 \times dt_{MPF}$. Specifically, F1 takes on a single time step for every two time steps in the MPF. In addition, $FP_1 \approx 0.013$ seconds while $FP_{MPF} \approx 0.006$ seconds.**



The Challenges of Time Synchronization - Least Common Time Step

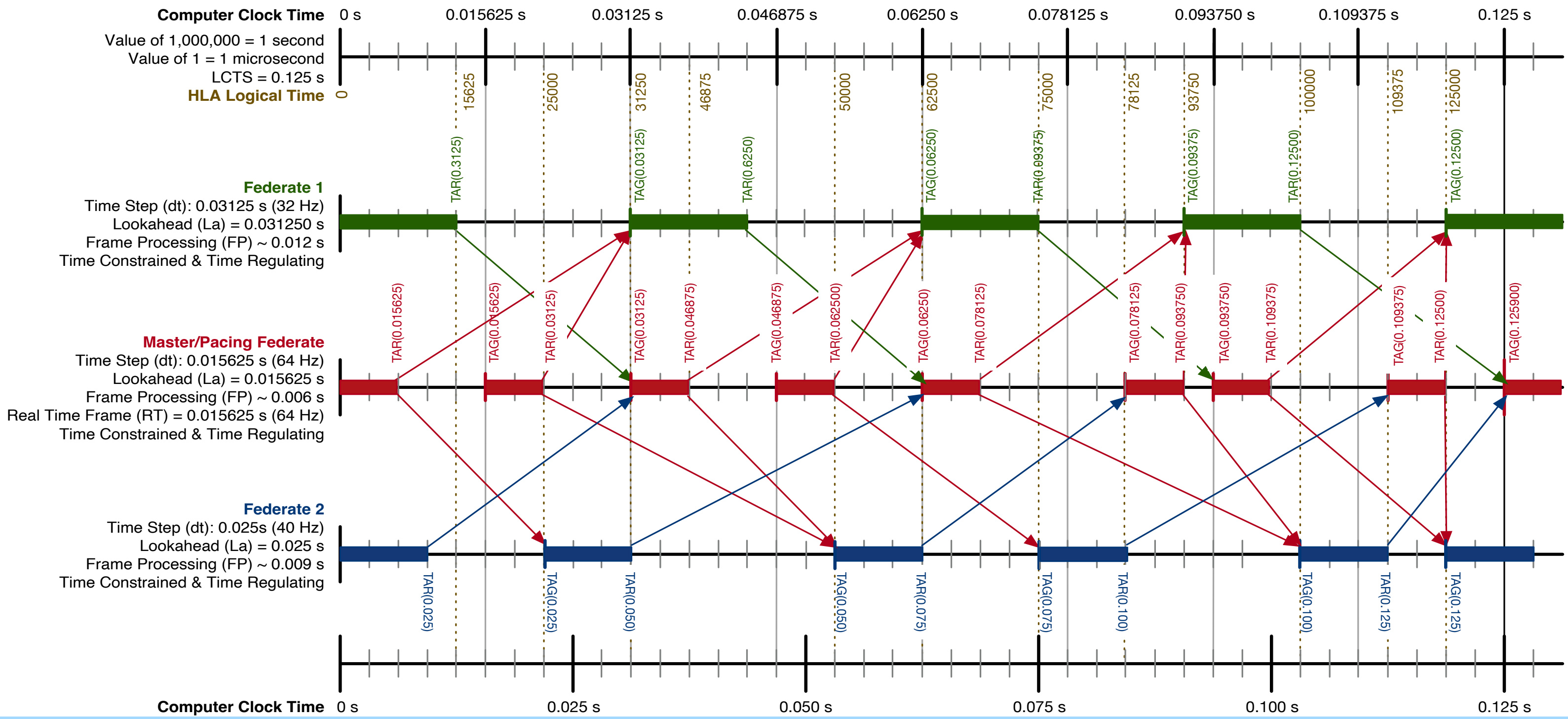
- **This is a good point to introduce another important concept called the Least Common Time Step (LCTS).**
- **The LCTS is the least common value of all the federate time steps for the time regulating and/or time constrained federates in a federation execution. The LCTS can be computed by finding the Least Common Multiple (LCM) of the set of time steps (dt_i) of the time regulating and/or time constrained federates joined to the federation execution [6, 7, 8].**

$$LCTS = LCM(HLT(dt_1),HLT(dt_2), \ldots,HLT(dt_N)) \tag{3}$$

- **The LCTS is used in the computation to find the next HLT boundary available to all federates in the federation execution. For the preceding example, MPF and F1 federates share common frame boundaries at integer multiples of the LCTS; in this case LCTS = 31250 (0.03125 s).**

The Challenges of Time Synchronization - Complex Multi-Rate Mult-Federate Case

- The final case explored here is a more complex multi-rate multi-federate case where the federate time steps are not as simply related as shown for the Simple Multi-Rate Multi-Federate case. This case starts with the MPF and F1 federates shown in the previous figure, but adds an additional federate, F2, that has a time step of 0.025 seconds. The LCTS for this collection is no longer 0.03125 seconds but increases to 0.125 seconds. As can be seen in Figure 5, this leads to a HLT common frame boundary every 8-time steps for the MPF, every 4-time steps for F1, and every 5-time steps for F2.



Time Constraint Equations

- **Individual Federate Constraints**
  - These equations deal with the individual federate Lookahead (La_i) and time step (dt_i) values in association with the federation wide Least Common Time Step (LCTS).
    - *The first relationship is the federate time step (dt_i) must be strictly greater than zero so that federate time will advance.*

$$dt_i > 0 \tag{4}$$

    - *The second relationship is between La_i and the federate time step (dt_i); dt_i must be greater than or equal to La_i.*

$$dt_i \geq La_i \tag{5}$$

  - A time step (dt_i) less then the Lookahead time (La_i) will result in an invalid requested HLT because the minimum allowable requested time will be the granted HLT plus the La_i.
  - The next two equations deal with LCTS and the federate time step (dt_i).
    - *First, LCTS must be greater than or equal to dt_i.*

$$LCTS \geq dt_i \tag{6}$$

    - *The second is that the LCTS must be an integer multiple of dt_i.*

$$LCTS \,\%\, dt_i = 0 \tag{7}$$

  - These relationships are already a consequence of the way LCTS is computed but are stated here explicitly as additional checks on timing computations and constraints.

Time Constraint Equations

- **Federation Wide Constraints**
  - Federation wide timing constraints result from the analysis of the collection of all participating time regulating and/or time constrained federated joined to the federation execution.
  - These deal with the relationships between the LCTS and the Real Time frame (RT).
  - First, the LCTS must be greater than or equal to RT.

$$\text{LCTS} \geq \text{RT} \tag{8}$$

  - In addition, LCTS needs to be an integer multiple of RT.

$$\text{LCTS} \,\%\, \text{RT} = 0 \tag{9}$$

- **Complete Set of Time Constraints as a Boolean Algebra Equations**

$$(LCTS \geq RT) \wedge (LCTS \,\%\, RT = 0) \tag{10}$$

$$\wedge_{i=1}^{N}\big((dt_i > 0) \wedge (dt_i \geq La_i) \wedge (LCTS \geq dt_i) \wedge (LCTS \,\%\, dt_i = 0)\big) \tag{11}$$

Conclusions

- It is important that HLA/SpaceFOM federate, and federation developers understand the time synchronization fundamentals of multi-rate, multi-federate, time managed, and real time federation executions along with the associated time constraints involved.
- Developers should consider generating timing diagrams like those presented when designing a federation execution and checking the time constraint equations with the federate startup and initialization routines to ensure timing consistency.
- Timing diagrams are useful in understanding the relationship between various fundamental timing parameters associated with time synchronized federation executions using the HLA Time Management services. They also illustrate the nonintuitive nature of time synchronization, time advance, real time execution, and timestamp ordered data delivery.
- The complex multi-rate multi-federate design should be avoided in preference for simple matched rate multi-federate and simple multi-rate multi-federate designs if possible.

Future Work

- The time constraint checks are being incorporated into the HLA/SpaceFOM middleware package developed by the Software, Robotics, and Simulation Division (ER) at NASA's Johnson Space Center called TrickHLA [10] to ensure time synchronization consistency.
- The timing diagram techniques will be used to help design a distributed simulation architecture for NASA's Artemis program.
- The time constraint equations could be updated to account for latencies arising from the physical distances between federates and the data transmission latencies coming from the data sizes and network speeds.
- Real time constraints could be derived from the federate frame processing times and federate time step sizes.
- The impact of complex multi-rate multi-federate designs on simulation fidelity could be expound upon.

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Q&A / Discussion

References

[1] Simulation Interoperability Standards Organization/ Standards Activities Committee (SISO/SAC). IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA) - Framework and Rules. Technical Report IEEE-1516-2010, The Institute of Electrical and Electronics Engineers, 2 Park Avenue, New York, NY 10016-5997, August 2010.

[2] E. Crues, D. Dexter, A. Falcone, A. Garro, M. Madden, B. Möller, and D. Ronnfeldt. Standard for Space Reference Federation Object Model (SpaceFOM). Number SISO-STD-018-2020. Simulation Interoperability Standards Organization (SISO), P.O. Box 781238, Orlando, FL 32878-1238, USA, October 2019.

[3] Simulation Interoperability Standards Organization/ Standards Activities Committee (SISO/SAC). IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA) - Federate Interface Specification. Technical Report IEEE-1516.1-2010, The Institute of Electrical and Electronics Engineers, 3 Park Avenue, New York, NY 10016-5997, August 2010.

[6] Eric W. Weisstein. Least common multiple. MathWorld: https://mathworld.wolfram.com/ LeastCommonMultiple.html, December 2024.

[7] Eric W. Weisstein. Greatest common divisor. MathWorld: https://mathworld.wolfram.com/ GreatestCommonDivisor.html, December 2024.

[8] Eric W. Weisstein. Prime factorization. MathWorld: https://mathworld.wolfram.com/ PrimeFactorization.html, December 2024.

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