Aerospace, Programming Languages, and Information Technology Co-Development: Aerospace Simulation and Real-Time Systems

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This fifth article of the twelve-part series treats aerospace simulation and real-time systems as a thread of the co-development arc. Flight simulation supplied one of the earliest sustained demands for real-time computing, from the Link Trainer of the 1920s and 1930s through the digital simulators of the postwar period and into the distributed simulation networks of the contemporary era. The real-time operating systems that emerged from aerospace simulation and control applications later became a distinct engineering discipline whose vocabulary and techniques diffused through essentially all safety-critical and time-sensitive computing. This article walks the simulation thread from its mechanical origins through its digital maturation, treating each transition as an instance of the aerospace-computing coupling formalized in A237 operating under the pressure of training, testing, and development requirements that could not be met by flight operations alone.

The framing established in A237 identified simulation as one of the load-bearing applications through which computing capability entered aerospace. The Whirlwind computer treated in A240 originated as a flight-simulator engine before its Cold War air defense pivot, illustrating that the flight simulation and air defense threads shared common technical requirements for real-time computation. This article picks up the simulation thread and traces its development into training simulators, engineering simulators, hardware-in-the-loop test facilities, and eventually distributed interactive simulation networks that support contemporary aerospace development and operations.

Pre-Digital Flight Simulation

The Link Trainer was the first widely deployed flight simulator. Edwin Link, a pipe-organ builder from Binghamton, New York, patented the Link Trainer in 1930 using pneumatic bellows and a rotating platform to reproduce aircraft attitude changes in response to control-stick inputs, per the biographical treatment in Kelly 1970. The initial Link Trainer had no visual display and no analog-computed aerodynamics. Its value was in reproducing the tactile and vestibular sensations of instrument flight without visual reference, which allowed instrument-flight training under controlled conditions on the ground rather than in weather that would be dangerous for novice pilots. The Link Trainer entered military service in substantial numbers during the Second World War, with approximately 10,000 units delivered to the United States Army Air Forces alone. The training value was directly attributable to the reduction in weather-related training accidents and to the skill development that instrument-flight training required.

The postwar period brought analog computers into the flight simulation loop. Reeves Instrument Corporation, Electronic Associates Incorporated hereafter EAI, and other analog-computer manufacturers built general-purpose analog computers that could be programmed

to solve aircraft equations of motion in real time. A typical postwar analog flight simulator used the analog computer to solve the six-degree-of-freedom equations of aircraft motion, transformed control-stick and rudder inputs into force and moment inputs to the equations, and drove the motion platform and instrument displays from the computed aircraft state. The general form of the aircraft dynamics equations, treated as standard material in the textbook by Etkin 1996, is

$$m\dot{\mathbf{v}} = \mathbf{F}(\mathbf{v}, \omega, \delta)$$

$$I\dot{\omega} = \mathbf{M}(\mathbf{v}, \omega, \delta)$$

where $\mathbf{v}$ is the aircraft velocity vector, ω is the angular velocity vector, δ is the vector of control-surface deflections, m is the aircraft mass, I is the inertia tensor, and $\mathbf{F}$ and $\mathbf{M}$ are the aerodynamic and propulsive force and moment functions that depend nonlinearly on aircraft state and control inputs. Analog computers of the 1950s solved these six coupled ordinary differential equations continuously in real time, updating the motion platform and instruments at rates limited only by the analog-mechanical bandwidth of the output actuators.

The value of analog simulation was that it could reproduce the closed-loop pilot-aircraft dynamics in a way that trained the pilot’s control-response habits for the aircraft being simulated. This required accurate aerodynamic force and moment functions, which were obtained from flight test of the actual aircraft and encoded in the analog simulator as pre-cut function-generator cams or diode-function-generator networks. Programming an analog simulator for a new aircraft therefore required physical rework of the machine rather than software modification.

The fundamental accuracy limit of analog simulation was set by drift and noise in the operational amplifiers and function generators. For a chain of n integrators each contributing per-second error ϵ_0, the accumulated error over simulation time T scales as

$$\epsilon_{\text{analog}}(T) \approx \epsilon_0 \sqrt{n} \cdot T$$

under the same uncorrelated-error assumption used in the analog differential analyzer treatment in A238. For typical simulator integrator counts of order 10 and per-integrator error of order 0.01 percent per second, the accumulated error reaches one percent within roughly 30 seconds of simulated flight, which limited analog simulator utility for long-duration missions and drove the digital transition of the late 1950s.

Digital Flight Simulation

The transition from analog to digital flight simulation began in the late 1950s with the availability of digital computers fast enough to solve the aircraft equations of motion at rates matching the pilot’s perceptual and control bandwidth. The pilot control-input bandwidth is approximately 2 to 5 Hertz, and smooth motion perception requires simulator updates at approximately

$$f_{\text{sim}} \gtrsim 20 \text{ Hz}$$

with instrument display updates at 20 to 30 Hertz and visual system updates that later became the constraint at 30 to 60 Hertz. The digital computer had to solve the aircraft equations of motion, transform coordinates for display generation, and drive the motion platform within a

computational budget of approximately 30 to 50 milliseconds per update cycle. The total end-to-end transport delay from pilot control input to perceived response summed the dynamics computation, display generation, and motion platform actuation delays as

$$T_{\text{transport}} = T_{\text{dynamics}} + T_{\text{display}} + T_{\text{motion}} \lesssim T_{\text{pilot tolerance}}$$

with $T_{\text{pilot tolerance}}$ of order 100 to 150 milliseconds above which pilot control quality degrades noticeably and above which pilot-induced oscillation risk rises. Meeting this budget across all components was the engineering discipline that distinguished production flight simulators from research prototypes. The Whirlwind computer treated in A240 met this budget for the case of the Cape Cod System air defense demonstration, and subsequent digital computers of the late 1950s and 1960s met it for progressively more sophisticated flight simulations.

The Link Company, later renamed Singer-Link and then CAE-Link after successive acquisitions, produced digital flight simulators throughout the 1960s and 1970s using dedicated digital computers built specifically for the flight-simulation application. Later generations used general-purpose minicomputers from Digital Equipment Corporation hereafter DEC and mainframes from International Business Machines Corporation hereafter IBM. The commercial airline industry adopted digital flight simulators aggressively in the 1970s and 1980s as regulatory authorities began to accept simulator training hours as credit toward flight-time requirements for pilot licensing, which produced a substantial commercial market that further accelerated simulator technology development.

Visual system technology developed in parallel with computational technology. Early digital simulators used camera-and-model systems in which a physical scale model of the airport and terrain was viewed by a servo-driven camera whose position and attitude corresponded to the simulated aircraft position. Camera-model systems were displaced in the 1970s and 1980s by computer-generated imagery systems built around specialized visual computers by companies including Evans and Sutherland, General Electric, and later Silicon Graphics. Contemporary flight simulators use commercial graphics processors adapted for the requirements of low-latency high-fidelity aerospace visuals. The comprehensive review of flight simulation techniques in Baarspul 1990 in Progress in Aerospace Sciences documents the state of the discipline at the transition point between camera-model and computer-generated imagery visual systems and remains a standard reference on the engineering trade-offs across simulation subsystems.

Hardware-in-the-Loop Testing

Flight simulation for pilot training addresses the human element of the aviation system. Hardware-in-the-loop testing addresses the equipment element by substituting simulated environments for physical flight conditions during aircraft development and integration. In a hardware-in-the-loop configuration, actual flight-hardware components are connected to a simulation of the surrounding environment that would exercise them in flight. Sensors receive simulated inputs. Actuators drive simulated loads. Computers execute their actual flight software against a simulated aircraft dynamics model rather than a real aircraft.

The value of hardware-in-the-loop testing is that it exercises the actual flight equipment under repeatable conditions that flight test cannot economically or safely provide. Fault conditions that occur once per million operating hours in flight can be induced deliberately in the laboratory. Edge cases in the flight envelope can be exercised without risk to aircraft or crew. Software changes can be validated against exhaustive input sequences before flight test approval. The economics of hardware-in-the-loop testing favor its use for every flight software change on modern aerospace platforms, with flight test reserved for cases where the physical aerodynamics or engine behavior cannot be adequately simulated. The engineering methodology for hardware-in-the-loop testing as a general control-system development technique is

treated in Isermann Schaffnit Sinsel 1999 in Control Engineering Practice, focused on engine-control applications but with methodology transferable to essentially all closed-loop control validation.

The hardware-in-the-loop configuration imposes strict real-time constraints on the simulation. The simulated dynamics must be updated at rates matching or exceeding the actual sensor and actuator bandwidths, typically hundreds to thousands of Hertz. The Nyquist-Shannon sampling theorem sets a lower bound on the simulation update rate as

$$f_{\text{sim}} \geq 2 \cdot f_{\text{bandwidth}}$$

for the highest-frequency dynamic content $f_{\text{bandwidth}}$ that the simulation must reproduce with fidelity, with practical implementations targeting factors of 5 to 10 above the Nyquist minimum to avoid aliasing artifacts in reconstructed signals. The end-to-end loop timing budget is

$$T_{\text{loop}} = T_{\text{sensor sim}} + T_{\text{signal path}} + T_{\text{controller}} + T_{\text{actuator sim}} + T_{\text{dynamics}}$$

which must fit within the actual flight-loop period for the simulated system to behave equivalently to the physical system. Meeting this budget for high-bandwidth flight control loops on modern combat aircraft requires simulation computers that are substantially faster than the flight computers they simulate against. The “iron bird” test rigs used by aircraft manufacturers combine hardware-in-the-loop flight computer testing with actual physical actuators, hydraulic systems, and flight-control linkages to exercise the aircraft’s mechanical response together with its computational response.

Real-Time Operating Systems

Real-time operating systems emerged as a distinct discipline in the 1970s and 1980s from the requirements of aerospace and industrial control applications. The rate monotonic scheduling analysis by Liu and Layland formalized in A237, the response time analysis of Joseph and Pandya also cited in that article, and the priority inheritance protocols of Sha Rajkumar and Lehoczky together supplied the theoretical foundation. Commercial and open-source real-time operating systems that implemented these techniques include several examples. VxWorks from Wind River Systems first shipped in 1987. VRTX from Ready Systems first shipped in 1980. pSOS from Software Components Group first shipped in 1982. RTEMS from the United States Army Missile Command was first released to the public in 1988 and later maintained by OAR Corporation. The ARINC 653 standard, named for the Aeronautical Radio, Incorporated document series in which it was published in 1996 and widely adopted for commercial avionics, specifies a partitioned real-time operating system architecture that isolates safety-critical applications from each other using time and space partitioning.

The engineering distinction between a real-time operating system and a general-purpose operating system is captured by the response-time distribution. A general-purpose operating system optimizes for average throughput and permits arbitrary latency in individual tasks under load. A real-time operating system provides bounded worst-case response time even under overload conditions. Formally, if the response time of a task under some workload has probability distribution $P(T)$, then a real-time operating system guarantees

$$T_{\text{worst-case}} = \sup\{T : P(T) > 0\} \leq T_{\text{deadline}}$$

for all admissible workloads, whereas a general-purpose operating system provides only a bound on the mean or a quantile response time. A closely related property is jitter, the variation in response time across successive invocations of the same task, bounded by

$$J = \sup T - \inf T \leq J_{\max}$$

with $J_{\max}$ set by the application requirement. Low jitter is essential for control loops where periodic sampling must occur at consistent intervals to preserve the mathematical assumptions of the discrete-time control design. Real-time operating systems for aerospace applications typically target jitter bounds in the range of microseconds to tens of microseconds against periodic tasks with periods in the range of milliseconds to hundreds of milliseconds. The engineering difference between average-case and worst-case response guarantees is what makes real-time operating systems suitable for safety-critical aerospace applications where deadline miss can cause catastrophic outcomes.

The real-time operating systems used in production aerospace applications are typically qualified against industry consensus standards including the ARINC 653 partitioning standard and the process-based standards treated in a later article of this series. The design principles for partitioning kernels including ARINC 653 are treated in Rushby 1999, a NASA-published foundational analysis of partitioning requirements, mechanisms, and assurance approaches. Real-time operating system selection for an aerospace program depends on the reliability requirements applicable to the safety-critical partition, the processor family supported, and the vendor’s long-term support commitment for the product configuration. The comprehensive engineering treatment of real-time systems as a design discipline is Kopetz 2011, which remains the standard textbook for distributed embedded systems design.

Distributed Interactive Simulation

Distributed interactive simulation extended the flight-simulator concept from single-cockpit training to multi-participant exercises across geographically distributed simulators connected by a network. The SIMNET program of the United States Defense Advanced Research Projects Agency hereafter DARPA, initiated in 1983 and operational by 1987, was the first large-scale distributed simulation system, providing networked M1 tank and other ground-combat simulators for combined-arms training exercises at multiple sites, per the account in Miller and Thorpe 1995 published in the Proceedings of the IEEE.

The technical innovation that made SIMNET feasible was the dead-reckoning protocol that reduced network bandwidth requirements. Rather than transmitting simulator state at every update, each simulator transmitted its state only when its position or attitude deviated from a mutually agreed extrapolation by more than a threshold value. The bandwidth required for N_{entities} simulated entities updating at maximum rate f_{update} with per-update packet size S_{packet} scales as

$$B_{\text{network}} \leq N_{\text{entities}} \cdot f_{\text{update}} \cdot S_{\text{packet}} \cdot (1 - \eta_{\text{dead-reckoning}})$$

where $\eta_{\text{dead-reckoning}}$ is the fraction of updates suppressed by successful extrapolation. Typical dead-reckoning efficiency exceeds 90 percent for ground-combat entities and 70 percent for aircraft, giving network bandwidth reductions of one to two orders of magnitude compared with naive full-state transmission. For constant-velocity extrapolation of an entity with actual acceleration a over update interval Δt, the extrapolation position error grows quadratically as

$$\epsilon_{\text{DR}}(\Delta t) = \frac{1}{2} a \, (\Delta t)^2$$

which sets the maximum time between full-state updates for a given position-error threshold. For an aircraft under 1 g maneuver acceleration and a 1-meter position-error threshold, the

update interval is bounded above by approximately 0.5 second, matching the empirical dead-reckoning update rates observed in operational DIS exercises. Coordinated multi-participant exercises additionally require time synchronization across participating sites with clock offset

$$|t_i - t_j| \leq \epsilon_{\text{sync}}$$

for all site pairs (i, j), with ϵ_{sync} typically 10 to 100 milliseconds for training exercises and one millisecond or less for engineering evaluation exercises that use the simulation output for control-system analysis.

The SIMNET protocols were standardized as the Distributed Interactive Simulation hereafter DIS standard, published as IEEE 1278 in 1993, and later evolved into the High Level Architecture hereafter HLA standard, published as IEEE 1516 in 2000. The design and initial deployment of HLA is documented in Dahmann Fujimoto Weatherly 1997 published at the Winter Simulation Conference, the standard primary source on the Department of Defense HLA program. Both standards remain in operational use for defense and civilian distributed simulation, with HLA more common for engineering simulation and DIS more common for legacy training applications. The Simulation Interoperability Standards Organization hereafter SISO maintains both standards and coordinates their continued development.

Contemporary distributed simulation integrates flight simulators, ground-combat simulators, command-and-control workstations, and physics-based environment simulators into unified exercises that can span dozens of physical sites and thousands of participating entities. The Live Virtual Constructive framework combines three participant classes into single training or engineering exercises. Live participants are actual aircraft and personnel in the field. Virtual participants are humans operating simulators. Constructive participants are fully computer-generated forces. The engineering requirements of latency management, coordinate reconciliation, and time synchronization across the distributed exercise draw substantially on the SAGE-era distributed computing tradition treated in A240.

Framework Application to Aerospace Simulation

The six-axis framework introduced in A237 applies to aerospace simulation and real-time systems with axis weightings reflecting the character of this thread.

The first axis is numerical computation demand. Simulation demand is dominated by ordinary-differential-equation integration for aircraft dynamics, coordinate transformations for display generation, and physics computation for the simulated environment. Modern high-fidelity engineering simulators reach billions of floating-point operations per second per simulated entity, and distributed exercises with hundreds of entities scale accordingly.

The second axis is real-time control. Simulation is intrinsically real-time because human participants demand responses within human perceptual latency budgets and because hardware-in-the-loop configurations demand responses within actuator and sensor bandwidth. The real-time discipline that emerged from simulation and aerospace control applications became the general vocabulary for time-sensitive computing.

The third axis is reliability and verification. Simulator reliability requirements are less stringent than flight-hardware reliability requirements because simulator failure produces training-value loss rather than catastrophic outcomes. However, hardware-in-the-loop testing inherits the reliability requirements of the flight hardware under test, since simulator faults during hardware-in-the-loop testing can propagate to false confidence in flight-hardware acceptance.

The fourth axis is networking and distribution. Distributed simulation is one of the application areas that drove computer-network development from its ARPANET origins through

the contemporary internet. The dead-reckoning protocols, latency-tolerance techniques, and coordinate-synchronization mechanisms developed for distributed simulation have influenced network protocol design substantially, including online multiplayer computer game architectures that use directly derived techniques.

The fifth axis is software engineering as a discipline. Real-time operating systems, hardware-in-the-loop test frameworks, and distributed simulation infrastructures are all substantial software artifacts developed under the engineering constraints of aerospace applications. The programming languages, development methodologies, and quality-assurance practices used in these applications influenced the broader software engineering discipline through the transfer of aerospace-trained personnel to commercial employers.

The sixth axis is semiconductor economics and dual-use. Aerospace simulation drove specialized computing hardware development including image generators, motion controllers, and dedicated simulation processors, most of which was superseded by commercial computing hardware as the commercial industry reached parity in the capabilities aerospace required. The dual-use pattern of aerospace-first-then-commercial that characterized earlier eras began to reverse in the 1990s as commercial computing capability exceeded aerospace-specific hardware in most performance dimensions.

Conclusion

Aerospace simulation and real-time systems constitute a thread of the aerospace-computing coupling with a distinctive engineering character. Simulation supplied one of the earliest sustained demands for real-time computing, from the Link Trainer through the analog flight simulators to the digital simulators and eventually to the distributed interactive simulation networks of the contemporary period. Real-time operating systems emerged from aerospace and industrial control applications as a distinct engineering discipline whose vocabulary and techniques later diffused through essentially all safety-critical and time-sensitive computing. Hardware-in-the-loop testing established the engineering practice of exercising actual flight hardware against simulated environments as a standard part of aerospace development. Distributed simulation extended the simulator concept from single-cockpit training to large-scale multi-participant exercises supporting both training and engineering evaluation.

The next article in the series treats the Apollo Guidance Computer as the most-studied embedded computer in history, with focus on the Instrumentation Laboratory at MIT under Draper, the transition from analog to digital guidance, and the software engineering practices that produced the Apollo program’s reliability record.

References

Books

- Etkin 1996
- Kelly 1970
- Kopetz 2011
- Rolfe and Staples 1986

Reference

- ARINC 653
- Link Trainer Overview
- SISO
- VxWorks

Related Posts

- A237 Framing and the Co-Development Mechanism
- A238 Pre-War Computing Origins and Ballistics
- A239 Wartime Computing and Code-Breaking
- A240 Early Cold War Air Defense and SAGE

Research

- Baarspul 1990
- Dahmann Fujimoto Weatherly 1997
- IEEE 1278 DIS
- IEEE 1516 HLA
- Isermann Schaffnit Sinsel 1999
- Link 1930 Patent
- Miller and Thorpe 1995
- Rushby 1999