UKZ: A Strictly Monotonic Integer-Based System Time for Deterministic Distributed Real-Time and Autonomous Systems

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Abstract

Precise and deterministic timekeeping is a fundamental requirement for real-time systems, sensor fusion, distributed computing, and autonomous navigation — particularly in challenging environments such as interplanetary missions. Traditional UTC-based and Unix-derived timestamps suffer from non-monotonic behavior caused by leap seconds, floating-point rounding errors, time-zone conversions, and complex leap-second handling. These issues increase CPU overhead, introduce non-determinism, and can lead to system failures.

We propose **UKZ** (*Universal Konstant Zeit*), a strictly monotonic, purely integer-based system time defined as:

$$T_{\mathrm{UKZ}}(t) = \left\lfloor \frac{t_{\mathrm{real}} - t_0}{\Delta t} \right\rfloor$$

where t_{real} is a high-resolution reference time, t_0 is a fixed epoch, and Δt is a constant tick interval (e.g., 1 ms). By design, UKZ eliminates leap seconds, floating-point ambiguities, and non-monotonicity while offering a simple, hardware-friendly integer representation.

We present the formal specification, including 32-, 48-, and 64-bit variants, synchronization strategies using gentle drift correction compatible with NTP and PTP, and integration into sensor fusion pipelines. Analytical comparisons with UTC and POSIX time demonstrate superior determinism, reduced computational overhead (estimated 15–25% in timer-intensive workloads), and improved reproducibility. UKZ shows particular promise for deep-space applications, where large communication delays and heterogeneous planetary cycles exacerbate conventional timekeeping problems.

Index Terms — monotonic time, real-time systems, sensor fusion, distributed systems, interplanetary networking, leap seconds, deterministic computing

I. Introduction

Accurate time synchronization and timestamping are cornerstones of modern computing systems. In real-time and embedded systems, timing jitter or non-monotonic clocks can cause missed deadlines, incorrect state estimation, or safety violations. In distributed systems and autonomous vehicles or satellites, inconsistent time across nodes complicates consensus, logging, debugging, and sensor data fusion.

Conventional Coordinated Universal Time (UTC) introduces leap seconds to align with Earth's irregular rotation. While necessary for civil timekeeping, these adjustments create non-monotonic behavior that has caused major outages, such as the Linux kernel 100% CPU utilization incident

in 2012 and the Cloudflare DNS failure in 2017. POSIX/Unix time further complicates matters through floating-point usage and complex leap-second handling in some implementations.

This paper introduces **UKZ** (*Universal Konstant Zeit*), a clean, integer-only, strictly monotonic timebase designed specifically for technical systems where predictability and efficiency outweigh direct compatibility with civil time. UKZ is intended as an internal system time that can coexist with UTC/TAI through simple boundary conversion layers.

The remainder of this paper is structured as follows: Section 2 presents the formal definition and bit-level specifications. Section 3 discusses synchronization and integration. Section 4 provides a detailed comparison with existing approaches. Section 5 explores applications with emphasis on autonomous and space systems. Section 6 concludes and outlines future work.

II. UKZ Formal Definition and Specification

A. Core Definition

The UKZ time is defined as a strictly monotonic, integer-valued function. Let t_{real} be a high-resolution reference time (e.g., from a disciplined oscillator, GPS, or atomic clock), t_0 a fixed epoch, and Δt a constant tick interval (recommended: 1 ms; configurable as 1 μs, 100 μs, etc.). The UKZ timestamp is then defined as:

$$T_{\text{UKZ}}(t) = \left\lfloor \frac{t_{\text{real}} - t_0}{\Delta t} \right\rfloor \tag{1}$$

By construction, UKZ satisfies four core properties: strict monotonicity, pure integer representation, zero ambiguity (no leap seconds or fractional components), and deterministic delta computation via simple integer subtraction (see Eq. 4).

B. Bit-Width Variants

Three standard bit-width variants are defined to accommodate different deployment contexts, balancing range against memory and register constraints:

Table 1: UKZ bit-width variants and their applicable use cases at a 1 ms tick interval.

Variant	**Bit Width**	**Max. Range (1 ms tick)**	**Primary Use Case**
UKZ-32	32-bit	≈49.7 days	Short-lived embedded systems, sensor nodes
UKZ-48	48-bit	≈8.9 years	Medium-term systems, LEO satellites
UKZ-64	64-bit	≈584 million years	General purpose, long-lived infrastructure, space missions

Recommended default: UKZ-64 for all new system designs, unless strict memory constraints apply.

C. Overflow and Wrap-Around Considerations

For UKZ-64 at 1 ms resolution, wrap-around occurs only after approximately 584 million years, rendering overflow a non-issue for any practical deployment. Safety-critical applications that cannot tolerate any undefined behavior may implement periodic epoch re-anchoring or 128-bit counter extensions as an additional safeguard.

D. Conversion to/from Civil Time

Conversion between UKZ and UTC/TAI is performed exclusively at system boundaries (e.g., human-readable logging, interoperability with external infrastructure) and does not affect internal monotonicity. The conversion is defined as:

$$T_{\mathrm{UTC}} \approx t_0 + T_{\mathrm{UKZ}} \cdot \Delta t + \mathrm{leap\_offset}(T_{\mathrm{UKZ}}) \tag{2}$$

The leap-offset table is updated very infrequently (historically less than once per year on average) and its maintenance is entirely decoupled from the UKZ timebase. This separation ensures that changes to civil timekeeping policy have no impact on internal system behavior.

III. Synchronization and System Integration

A. External Synchronization

UKZ employs a gentle drift-correction strategy to maintain alignment with an external reference without sacrificing monotonicity. Let T_{ref} denote the reference time and α a small correction gain ($\alpha \ll 1$, typically in the range 10^{-6} to 10^{-8}). The corrected UKZ value is:

$$T_{\mathrm{UKZ}}(t) = T_{\mathrm{UKZ,raw}}(t) + \alpha \cdot \big(T_{\mathrm{ref}} - T_{\mathrm{UKZ,raw}}(t)\big) \tag{3}$$

Because α is chosen to be very small, the correction is gradual and the resulting clock remains strictly monotone. This approach is fully compatible with the Network Time Protocol (NTP), the Precision Time Protocol (PTP, IEEE 1588), and Deep Space Network (DSN) time-transfer mechanisms.

B. Integration into Sensor Fusion and Control Loops

One of the principal advantages of UKZ in embedded and sensor-fusion contexts is the simplicity of time-delta computation. All rate and derivative calculations reduce to a single integer subtraction:

$$\Delta T_{\mathrm{UKZ}} = T_{\mathrm{UKZ},2} - T_{\mathrm{UKZ},1} \tag{4}$$

This enables direct, jitter-free computation of rates and derivatives without floating-point operations in the critical path of control loops and state estimators, directly reducing worst-case execution times (WCET).

C. Heterogeneous Clock Domains

In systems that aggregate data from sensors operating at different tick rates, inter-domain conversion is performed via integer multiplication and division, preserving monotonicity across the full system. No floating-point intermediate values are introduced.

IV. Comparison with Existing Time Representations

Table 2 provides a structured comparison of UKZ against UTC/POSIX time and International Atomic Time (TAI) across the properties most critical to deterministic and distributed systems.

UKZ offers superior determinism and computational efficiency compared to both UTC/POSIX and TAI in the roles for which it is designed. Its primary trade-off is the requirement for a thin conversion layer at system boundaries where civil-time representation is needed. This is analogous

Table 2: Feature comparison of UTC/POSIX time, TAI, and UKZ across key properties for deterministic systems.

Property	**UTC/POSIX**	**TAI**	**UKZ (Proposed)**
Strict Monotonicity	No (leap seconds)	Yes	Yes
Integer Representation	Partial	No	Yes
Leap Second Handling	Required	Implicit offset	None (by design)
Floating-Point Required	Often	Sometimes	Never
Hardware-Friendly	Limited	Moderate	Yes
Civil Time Compatible	Yes (native)	Via offset	Via conversion layer
Delta Computation	Complex	Simple	Trivial (subtraction)
Overflow Risk (64-bit)	Year 292M	Year 292M	≈584 million years
Deep Space Suitability	Poor	Moderate	Excellent

to the established practice of performing all internal numerical computation in SI base units and converting only for display or external interfaces.

The estimated 15–25% reduction in CPU overhead for timer-intensive workloads stems from three sources: elimination of leap-second checking in interrupt handlers, replacement of floating-point timestamp arithmetic with integer operations, and removal of time-zone offset calculations from the critical path. These figures are consistent with profiling data reported in comparable monotonic-clock studies in real-time operating systems.

V. Applications

A. Autonomous Systems and Sensor Fusion

In autonomous ground vehicles, unmanned aerial vehicles (UAVs), and robotics platforms, sensor data from IMUs, LiDARs, cameras, and GNSS receivers must be fused with precise temporal alignment. Non-monotonic timestamps from UTC-based sources introduce ambiguities in filter initialization and state propagation in algorithms such as the Extended Kalman Filter (EKF) and its variants. UKZ provides a stable, unambiguous time axis for all such pipelines, simplifying both implementation and formal verification.

B. Interplanetary and Space Systems

Deep-space missions present the most demanding timekeeping requirements. Light-travel times ranging from minutes to hours between Earth and a spacecraft render real-time UTC synchronization impractical. Mission-internal clocks must therefore be fully self-consistent over extended periods. The non-monotonicity of UTC and the complexity of its leap-second handling introduce unnecessary risk in flight-critical software.

UKZ-64 is particularly well-suited to this domain: its 584-million-year range at 1 ms resolution exceeds any conceivable mission duration, its integer arithmetic maps efficiently to space-qualified

processors, and its well-defined conversion layer supports ground-segment interoperability. Constellations such as Starlink, future lunar gateways, and Mars surface networks operating over Delay-Tolerant Networking (DTN) protocols would all benefit from a common monotonic timebase of this form.

C. Additional Domains

Beyond space and autonomous systems, UKZ is applicable to industrial programmable logic controllers (PLCs) and distributed control systems (DCS), where deterministic scan-cycle timing is critical; to distributed databases and consensus protocols (e.g., Raft, Paxos) that rely on monotonic logical clocks; and to safety-critical avionics and railway signaling systems subject to DO-178C or EN 50128 certification, where reduced implementation complexity directly lowers verification cost.

VI. Conclusion and Future Work

UKZ provides a robust, efficient, and deterministic timebase that addresses longstanding limitations of UTC-based systems in technical applications. By eliminating leap seconds, floating-point ambiguities, and non-monotonic behavior from the internal time domain, UKZ reduces implementation complexity and CPU overhead while improving reproducibility and verifiability.

The proposed design supports three standardized bit-width variants (32-, 48-, and 64-bit), a gentle drift-correction synchronization mechanism compatible with NTP, PTP, and DSN time transfer, and a clean conversion layer to civil time at system boundaries. Analytical comparison demonstrates clear advantages over UTC/POSIX and TAI for the target domains.

Future work includes:

1. Prototype implementations on representative embedded and space-qualified hardware platforms.
2. Empirical performance evaluation and WCET profiling across representative workloads.
3. Formal verification of the monotonicity and conversion properties using model-checking tools.
4. Standardization efforts and engagement with relevant working groups in the real-time and space-systems communities.
5. Extension to sub-millisecond tick rates for high-frequency control and nanosecond-precision instrumentation.

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