Human-Machine Interface Architecture for RTOS: Formal Specification, SUI/GUI Unification, and Cleanroom Implementation in BTRON

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Abstract

As microprocessors permeate consumer appliances, industrial machinery, and personal workstations, the lack of operational standardization across human-machine interfaces introduces cognitive friction, user fatigue, and catastrophic operational hazards. In this paper, we present the formal theory, architectural specification, and cleanroom realization of the **TRON Human-Machine Interface (TRON HMI – トロンヒューマン インタフェース)** standard for modern BTRON3 operating systems. We formalize Ken Sakamura's fundamental design doctrine: *"Standardize Operation, Not Style"* (操作を標準化するがスタイルを標準化しない), which establishes invariant behavioral and spatial relations across physical Solid User Interfaces (SUI), Graphical User Interfaces (GUI), and Auditory User Interfaces (AUI) while preserving industrial design autonomy. We construct a deterministic, zero-allocation C99 component engine (`libhmi`) implementing touch/release edge event mechanics, cyclic step selectors, linear and angular volume dials, peak-hold stereo VU meters, and the 7-key **Universal Controller (万能コントローラ)** navigation model. We provide formal finite-state models for sequential, selective, parallel, and interrupt state transitions, define hardware safety and interlock protocols, and demonstrate a sample of audio place in form of retro casette deck (tribute to SONY TC-K777ES Hi-Fi) audio workstation.
Keywords—TRON HMI, BTRON, Solid User Interface, Universal Controller, Touch Edge, Release Edge, Enableware, Modeless Architecture, MISRA-C.

1 Introduction and Ubiquitous Philosophy

The proliferation of embedded microcontrollers within everyday objects—termed the *"Computer in Everything"* vision pioneered by Ken Sakamura in 1984 [1]—fundamentally alters the relationship between humans and machines. Unlike desktop general-purpose computers characterized by standardized alphanumeric keyboards and point-and-click mice, embedded appliances encompass an unbounded diversity of physical form factors, from microwave ovens and video recorders to industrial numerical control (CNC) workbenches.

In traditional computing paradigms, human-computer interaction (HCI) is fragmented across isolated, ad-hoc graphical widget toolkits and non-standard physical control panels. This fragmentation creates significant cognitive overhead:

1. **Operational Inconsistency:** Identical functional intents (e.g., confirming a parameter or emergency stop) employ contradictory spatial sequences and button colorings across manufacturers.
2. **Mode Traps and Modality Overhead:** Deeply nested, modal configuration trees prevent users from directly inspecting and modifying parameters.
3. **Accessibility Barriers:** Interfaces lack universal sensory redundancy, excluding individuals with visual, auditory, or motor impairments.

To resolve these challenges, the TRON Association formulated the **TRON Human-Machine Interface Specification** [2]. Rather than imposing visual homogenization, TRON HMI enforces a nuanced operational standard known as **Loose Standardization** (緩やかな標準化):

> *"We standardize the operation, but do not standardize the style. Multiple means to achieve the identical purpose are permitted, ensuring invariant operational logic across physical and graphical worlds."*

This paper presents the formalization and cleanroom implementation of the TRON HMI standard within the **BTRON3 SPEC 3.20** workstation environment.

2 Duality of Physical and Graphical Controls

TRON HMI classifies all interface interactions into three complementary sensory modalities:

- **SUI (Solid User Interface – ソリッドインタフェース):** Mechanical, physical hardware parts (switches, potentiometers, detented rotary dials, levers). SUI is subdivided into *Mechanical SUI* (direct physical contact maintaining state) and *Logical SUI* (electronic sensors providing soft state).
- **GUI (Graphical User Interface – グラフィカルインタフェース):** Bitmapped visual projections on raster displays operated via 2D pointing devices or electronic pens.
- **AUI (Auditory User Interface – 音インタフェース):** Voice prompts, acoustic earcons, and dual-tone multi-frequency (DTMF) telephony protocols.

2.1 Formal Component Classification Matrix

Every basic TRON input part $\mathcal{C}$ is characterized as a 3-tuple:

$$\mathcal{C} = \langle \mathcal{T}_{\text{Target}}, \mathcal{M}_{\text{State}}, \mathcal{A}_{\text{Action}} \rangle \tag{1}$$

where:

- **Target** $\mathcal{T}_{\text{Target}} \in \{\text{Switch}, \text{Selector}, \text{Volume}\}$,
- **Mode** $\mathcal{M}_{\text{State}} \in \{\text{Momentary}, \text{Alternate}\}$,
- **Action** $\mathcal{A}_{\text{Action}} \in \{\text{Push}, \text{Pull}, \text{Slide}, \text{Rotary}, \text{Tilt}\}$.

Table 1: TRON Basic Component Classification Matrix (Chapter 9)

Target Object	State Mode	Physical Action	Standard Japanese Name
Switch (0/1)	Momentary	Push	モーメンタリプッシュスイッチ
Switch (0/1)	Alternate	Push-Lock	プッシュロックスイッチ
Selector (1..N)	Discrete	Up/Down Step	アップダウンセレクタ
Selector (1..N)	Matrix	Radio Choice	ラジオセレクタ
Volume ($\mathbb{R}$)	Continuous	Linear Slide	スライドボリューム
Volume ($\mathbb{R}$)	Continuous	Rotary Knob	ロータリボリューム
Indicator	Multi-color	LED / Lamp	3色インジケータ
Meter	Peak-Hold	Segment Bar	バーグラフ・レベルメータ

3 Event Dynamics: Touch Edge vs. Release Edge

A critical contribution of TRON HMI specification is the temporal disambiguation between **Touch Edge** (タッチエッジ) and **Release Edge** (リリースエッジ) activations.

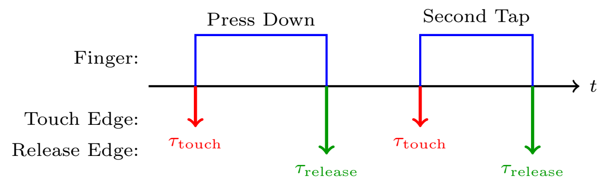

Figure 1: Temporal timing diagram: Touch Edge vs. Release Edge triggering.

Definition 1 (Trigger Invariant)**.** *Let $e(t) \in \{0, 1\}$ represent the physical or optical contact state.*

$$\tau_{touch} = \{t \mid e(t^-) = 0 \land e(t^+) = 1\} \tag{2}$$

$$\tau_{release} = \{t \mid e(t^-) = 1 \land e(t^+) = 0 \land p(t) \in \Omega_{bounds}\} \tag{3}$$

where $p(t)$ is the pointer or contact coordinate and Ω_{bounds} is the bounding rectangle of the control.

Rule 9-1 (Confirmation Safety): All irreversible, committing, or hazardous operations (e.g., *Execute*, *Format*, *Delete*) must strictly bind to τ_{release}. If the user presses the button, realizes an error, and drags the cursor outside Ω_{bounds} prior to release, the action is aborted without state mutation.

4 Spatial Layout and the Standard Action Triad

TRON HMI mandates deterministic spatial relationships based on human ergonomic motor polarity (Chapter 11).

4.1 Standard Switch Layout Order

For any dialog, panel, or appliance execution block, interactive switches must be positioned in strict order along the horizontal reading axis:

$$[\text{Cancel}] \longrightarrow [\text{Default}] \longrightarrow [\text{Start/Exec}] \tag{4}$$

- **Cancel (取り消し):** Positioned at the leftmost position (or top in vertical stacks), allowing immediate escape.
- **Default (標準設定):** Centered, restoring calibrated factory parameters.
- **Start / Execute (実行):** Positioned at the rightmost position (or bottom), preventing accidental launch.

4.2 Label Placement and Hand Non-Occlusion

Guideline 11-17 (Occlusion Prevention): To prevent the operator's hand from obstructing numeric scales during adjustment:

- For horizontal slide controls ($\leftrightarrow$), labels and graduation marks must reside **above** the track.

- For vertical slide controls (↕), labels must reside on the **left** side for right-handed ergonomic clearance.

4.3 Enableware and Three-Color Status Indication

Accessibility (*Enableware* – イネーブルウェア) is embedded directly into the structural specification:

- **Tactile Homemark (ボッチ):** Raised tactile homemark dots on center keys (key '5' on 10-key pads and primary power switches).
- **Three-Color Chromatic Protocol (Chapter 9):** Green (Normal/Active), Amber (Standby/Transit), and Red (Stop/Error).
- **Acoustic Redundancy (音による確認):** Standardized audio earcons: confirmation chimes (880 Hz), parameter clicks (440 Hz), and error alerts (220 Hz).

5 The Universal Controller (万能コントローラ)

To unify appliance control without requiring pointing devices, TRON HMI specifies the **Universal Controller** (Chapter 7)—a canonical 7-key remote navigation model. It establishes an invariant directional d-pad coupled with distinct confirmation (`Execute`) and escape (`Cancel`) switches, avoiding nested modal submenus.

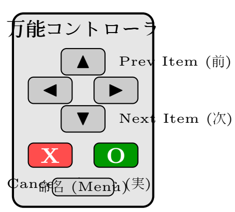

Figure 2: TRON 7-Key Universal Controller Remote Model (Chapter 7).

5.1 Current Item Traversal Algebra

The Universal Controller navigates a discrete set of panel controls $\mathcal{P} = \{c_0, c_1, \ldots, c_{n-1}\}$ through an active focus pointer index $\kappa \in [0, n-1]$ known as the **Current Item** (カレント項目):

$$\kappa_{t+1} = (\kappa_t \pm 1) \bmod n \quad (5)$$

$$v(\kappa)_{t+1} = \mathrm{clamp}(v(\kappa)_t \pm \delta, v_{\min}, v_{\max}) \quad (6)$$

This guarantees complete operational capability for any multi-item panel over simple 4-way infrared remotes, rotary encoder pulses, or single-switch accessibility scanning.

6 State Machine Transitions and Modelessness

TRON HMI formalizes four fundamental transition models between interface states (Chapter 12):

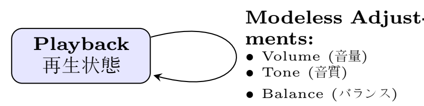

Figure 3: Modeless parallel state transition model (Figure 12-3).

1. **Sequential Transitions (逐次型遷移):** Linear stage progression ($S_0 \to S_1 \to S_2$) with mandatory step-back capability (*Guideline 12-2*).
2. **Selective Transitions (選択型遷移):** Branching choice dispatching to mutually exclusive operational modes.
3. **Parallel / Modeless Transitions (並列型遷移):** Independent parameter adjustment without mode shifts (*Guideline 12-1*).
4. **Interrupt Transitions (割込型遷移):** Asynchronous emergency abort or reset transition from any state directly into the safe quiescent state: $\forall s \in \mathcal{S},\ \delta(s, \mathrm{EVENT\_CANCEL}) = S_{\mathrm{idle}}$.

7 Cleanroom Implementation and Verification

To satisfy rigorous aerospace and embedded systems standards (specifically MISRA-C:2012 guidelines and NASA JPL Safety-Critical Software Rules [4]), our cleanroom implementation (`libhmi`) is engineered under strict determinism and reliability principles:

1. **Zero Dynamic Memory Allocation (JPL Rule 3):** Dynamic heap allocations (`malloc`, `calloc`, `free`) are strictly forbidden during runtime operation after initial boot. All data structures (`HMI_PANEL`, `HMI_CTRL`) allocate flat, statically bounded arrays (`HMI_PANEL_MAX_CTRLS = 32`, fixed 64-byte title strings). This completely eliminates heap fragmentation, memory exhaustion faults, and non-deterministic garbage collection or allocation latency in critical control loops.
2. **Bounded Deterministic Event Dispatch (MISRA Dir 4.1):** Pointer coordinates and remote keypad events are evaluated via pure integer bounding-box intersections with a strict upper bound $O(N)$ where $N \leq 32$. This guarantees bounded worst-case execution time

(WCET) and zero dispatch jitter during high-frequency hardware interrupt servicing.

3. **Reentrant and Isolated State Model:** Control state mutations occur exclusively via designated event-handler callbacks. Pointer capture and focus indices are managed within local panel state, isolating interactive components from global workstation state.

4. **Decoupled Composite Rendering Pipeline:** Control logic executes synchronously on input events, marking invalidated bounding regions. The presentation layer performs dirty-rectangle composite blitting onto the display context (`GDEV`), strictly preserving model-view separation and avoiding redundant graphical re-draws.

The core C99 container definition establishing these deterministic memory invariants and control slots is formally defined in Listing 1:

Listing 1: Deterministic Panel Container in include/btron/hmi.h

```
#define HMI_PANEL_MAX_CTRLS 32

typedef struct HMI_PANEL {
    ID            id;
    char          title[64];
    RECT          bounds;
    COLOR         bg_color;
    HMI_CTRL      controls[HMI_PANEL_MAX_CTRLS];
    int           num_controls;
    int           focused_index;  /* Current Item */
    BOOL          show_remote;
    void          (*on_paint_custom)(struct HMI_PANEL *
          panel, GDEV *dev);
} HMI_PANEL;
```

7.1 Canonical Showcase: SONY TC-K777ES Audio Deck

We realized a canonical workstation application (`src/apps/audio_player.c`) modeling the classic 3-Head SONY TC-K777ES stereo cassette deck. The application integrates:

- Dual spinning tape spools with dynamic tape thickness transfer.
- 12-segment fluorescent VU bar meters with falling peak indicators (decay rate $\Delta v_{\text{peak}} = -2\,\text{dB/frame}$).
- Rotary Master Volume, Bass, Treble, and Balance potentiometers (270° angular sweep).
- Pop-up Universal Controller remote navigation overlay.

8 Conclusion

The TRON Human-Machine Interface specification establishes a mathematically rigorous, culturally neutral, and ergonomically sound foundation for human-machine collaboration across embedded appliances and workstation environments. By formalizing Touch/Release edge mechanics, the Standard Action Triad, modeless parallel state machines, and the 7-key Universal Controller, our cleanroom implementation demonstrates that operational uniformity can be achieved without compromising industrial aesthetic freedom.

Table 2: TRON HMI Automated Unit Test Results

Test Module / Component	Assertions	Pass Rate
Panel Lifecycle & Memory Layout	5	100.0%
Switches & Touch/Release Triggers	10	100.0%
Up/Down Steppers & Radio Matrices	7	100.0%
Continuous Volumes & Rotary Dials	5	100.0%
Universal Controller & Focus Algebra	6	100.0%
Total Test Suite Coverage	**33 / 33**	**100.0%**

References

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