

# Alignment Charge: A New Control Primitive for Friction and Adhesion in Navigational Cybernetics 2.5

This paper discloses one node of a larger architectural framework — Navigational Cybernetics 2.5 — which addresses long-horizon adaptive systems, structural admissibility, and identity continuity under bounded resources. The alignment charge formalism presented here is an absolutely minuscule part of that architecture, shown in isolation to illustrate how NC2.5 principles translate into concrete engineering primitives.

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## Why Every Control System Gets This Wrong

Every robot that has ever slipped on a wet floor has something in common with every prosthetic hand that has ever crushed a grape: both treated friction as a given — a passive environmental parameter to be *compensated*, not *controlled*.

This is not a sensor problem. It is an architectural omission.

In classical control, friction and adhesion are modeled as external constants of the medium — numbers you measure, estimate, and work around. The Coulomb model gives you a static coefficient. LuGre gives you a dynamic one. PID compensates for the result. Adaptive regulators adjust gains. Force/torque controllers push harder when the surface gets slippery.

But none of these systems *control friction itself*. They control the response *to* friction. The coefficient of friction remains a parameter of the environment — something that happens to the system, not something the system regulates.

To be clear: the physical mechanisms for modifying contact conditions — ultrasonic vibration, electrostatic fields, thermal modulation — are well known and individually well studied. What does not exist is a normalized architectural layer that treats the system–medium alignment as a formally defined, stabilizable control variable, closes the loop through interaction physics rather than through controller gains, and integrates regime logic (hysteresis, dwell, anti-chatter) as a standard part of the control topology. The novelty is not in the physics. It is in the architecture.

I want to propose that architecture.

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## The Core Idea: Friction as a Controllable Variable

What if the degree of alignment between a system and its contact medium were not a passive observation but a formally defined, stabilizable, and controllable internal variable?

Not a sensor reading. Not a model parameter. Not an error signal. A *new kind of state variable* — one that lives in the interaction itself.

I call this variable the **Alignment Charge**, denoted  **$Q_A(t)$** .

The Alignment Charge is formed from measurable features of the system–medium interaction: contact impedance, phase mismatch, dielectric response, microvibration spectra, stick-slip indicators, medium response latency. But — and this is the critical architectural distinction —  $Q_A(t)$  is *not determined exclusively by* control error, energy, entropy, coherence, or derivatives of the system state. It is a formally independent interaction variable, irreducible to standard control metrics.

Once  $Q_A(t)$  exists as a defined quantity, something remarkable becomes possible: effective friction  $\mu_{eff}(t)$  and effective adhesion  $A_{eff}(t)$  become *functions of  $Q_A$*  — and therefore controllable through the regulation of  $Q_A$ , without requiring an increase in mechanical effort.

The system does not push harder. It aligns better.

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## Formalization

## Interaction Feature Vector

Let the system measure a vector of interaction features at the contact zone:

$$\mathbf{z}(t) = [z_1(t), z_2(t), \dots, z_n(t)]$$

These components may include contact impedance, resistance, conductivity, phase mismatch, response delay, spectral features of microvibrations, local thermo-electric oscillations, dielectric changes, stick-slip indices, or any parameters reflecting the medium's response to the system's action.

## Normalization

Features are normalized to a common scale:

$$\tilde{\mathbf{z}}(t) = (\mathbf{z}_i(t) - \mu_i) / (\sigma_i + \epsilon), \epsilon > 0$$

where  $\mu_i$  and  $\sigma_i$  are running estimates of mean and scale.

## Determination of the Alignment Charge

The alignment charge is computed as a bounded mapping from the normalized feature vector:

$$Q_A(t) = \varphi(\tilde{\mathbf{z}}(t))$$

Two non-limiting examples:

- **Projection form:**  $Q_A(t) = \tanh(w^T \tilde{\mathbf{z}}(t) + b)$ , where  $w$  and  $b$  are calibration parameters.
- **Distance form:**  $Q_A(t) = 1 / (1 + \alpha \|\tilde{\mathbf{z}}(t) - \tilde{\mathbf{z}}_0\|)$ , where  $\tilde{\mathbf{z}}_0$  is the baseline aligned state and  $\alpha > 0$  is a sensitivity coefficient.

In both cases,  $Q_A$  is bounded, smooth, and interpretable: higher values indicate better alignment between the system and the medium; lower values indicate mismatch.

A note on terminology: I use "charge" rather than "index" or "indicator" deliberately. An index is a passive diagnostic — you read it. A charge is something that accumulates, stabilizes, depletes, and drives dynamics.  $Q_A$  is stabilized through derivative suppression, held through dwell, and used as the control object that closes the actuation loop. It is consumed by drift and restored by alignment. The term reflects the functional role, not a physical analogy to electric charge.

## Charge Stabilization: Suppressing Runaway

Raw  $Q_A$  may fluctuate under transient perturbations. To prevent chatter and oscillatory switching, we compute first and second derivatives:

$$\dot{Q}_A(t) = (Q_A(t) - Q_A(t-\Delta)) / \Delta$$

$$\ddot{Q}_A(t) = (\dot{Q}_A(t) - \dot{Q}_A(t-\Delta)) / \Delta$$

and form a stabilized charge:

$$Q_A^{stab}(t) = Q_A(t) - k_1 \cdot \dot{Q}_A(t) - k_2 \cdot \ddot{Q}_A(t), k_1, k_2 \geq 0$$

This is derivative suppression — the same principle I use extensively in the broader NC2.5 architecture to suppress incoherent jerk in adaptive dynamics. Here, it serves a specific purpose: the stabilized charge becomes the control object, free from transient noise.

Other suppression forms — clipping, Huber, median filtering, bounded monotone damping — are equally admissible. The architectural point is the same: stabilize before you control.

## Stability Property: Anti-Chatter and Bounded Regime Tracking

The stabilized charge is constructed to ensure bounded operation and suppression of high-frequency oscillations in the interaction regime.

### Assumptions:

1. The alignment mapping  $\varphi$  is bounded by construction (e.g., tanh or inverse-distance form), so  $Q_A(t) \in [Q_{\min}, Q_{\max}]$  for all  $t$ .
2. The sampling interval  $\Delta$  is chosen above the dominant sensor-noise timescale.
3. Derivative terms are either bandwidth-limited by sensor physics or explicitly bounded via clipping or filtering:  $\dot{Q}_A^{\wedge}b(t) = \text{clip}(\dot{Q}_A(t), [-d_1, d_1])$ ,  $\ddot{Q}_A^{\wedge}b(t) = \text{clip}(\ddot{Q}_A(t), [-d_2, d_2])$ .

The stabilized charge is then defined as:

$$Q_A^{\wedge}\text{stab}(t) = Q_A(t) - k_1 \cdot \dot{Q}_A^{\wedge}b(t) - k_2 \cdot \ddot{Q}_A^{\wedge}b(t), \quad k_1, k_2 \geq 0$$

**Property 1 — Boundedness.** Under bounded  $\varphi$  and bounded (clipped) derivative terms,  $Q_A^{\wedge}\text{stab}(t)$  remains bounded for all  $t$ :  $Q_A^{\wedge}\text{stab}(t) \in [Q_{\min} - k_1 d_1 - k_2 d_2, Q_{\max} + k_1 d_1 + k_2 d_2]$ . No amplification beyond design limits can occur.

**Property 2 — Stationary Regime Tracking.** If the interaction regime becomes stationary so that  $Q_A(t) \rightarrow \bar{Q}$  and  $\dot{Q}_A(t), \ddot{Q}_A(t) \rightarrow 0$ , then  $Q_A^{\wedge}\text{stab}(t) \rightarrow \bar{Q}$ . The stabilized charge tracks the stationary alignment state without steady-state offset in the non-saturated regime. (Note: under derivative clipping saturation, a bounded bias proportional to  $k_1 d_1 + k_2 d_2$  may persist during transients; it vanishes as derivatives decay below clip thresholds.)

**Property 3 — High-Frequency Suppression.** The derivative terms penalize rapid variations in  $Q_A$ . This is equivalent to penalizing high-frequency components of  $Q_A$  via derivative feedback; under standard discrete-time assumptions, it attenuates oscillations with periods near  $\Delta$  while preserving slow drift components. Short impulsive perturbations generate large derivative terms, which are subtracted in  $Q_A^{\wedge}\text{stab}$ , reducing oscillatory switching between contact modes. This constitutes selective dissipation: fast oscillations are damped; slow alignment drift remains observable.

**Property 4 — Non-Chatter Mode Hold.** Let hysteresis thresholds and dwell time  $T_{\text{dwell}}$  define entry and exit conditions:  $|\dot{Q}_A| < \theta_1, |\ddot{Q}_A| < \theta_2$  for duration  $T_{\text{dwell}}$ . Then the hold regime cannot oscillate faster than the dwell constraint permits. Under bounded perturbations that do not exceed exit thresholds for the required duration, mode switching is prevented.

This is not Lyapunov equilibrium stability — the system tracks a time-varying interaction state. It is *regime stability*: bounded, non-oscillatory control of contact mode under bounded disturbances.

### Effective Friction and Adhesion as Functions of $Q_A$

Now the key step. We define effective friction and effective adhesion as bounded functions of the stabilized charge:

$$\mu_{\text{eff}}(t) = \mu_0 \cdot g(Q_A^{\wedge}\text{stab}(t))$$

$$A_{\text{eff}}(t) = A_0 \cdot h(Q_A^{\wedge}\text{stab}(t))$$

where  $g(\cdot)$  and  $h(\cdot)$  are bounded monotone functions. One non-limiting example:

$$g(Q) = (\mu_{\min} / \mu_0) + (1 - \mu_{\min} / \mu_0) \cdot 1/(1 + \exp(\beta(Q - Q^*)))^*$$

where  $Q^*$  is an alignment threshold and  $\beta$  controls the steepness of the transition.

This means: as the alignment charge increases (better system–medium alignment), effective friction can decrease — and the system slides more efficiently, with less energy loss, without increasing normal force. Conversely, if alignment decreases (mismatch, drift, surface change), friction rises, the system slows, and stability is preserved.

For adhesion, the coupling works in the complementary direction: better alignment can increase effective adhesion for gripping, holding, or stabilizing contact.

### Lemma: Monotone Friction Response

The coupling between alignment charge and effective friction must preserve interpretability and prevent control inversion.

Let  $\mu_{\text{eff}}(t) = \mu_0 \cdot g(Q_A^{\wedge}\text{stab}(t))$ , where  $g: \mathbb{R} \rightarrow [\mu_{\min}/\mu_0, 1]$  is continuous and strictly monotone. Without loss of generality, assume  $g'(Q) \leq 0$ , meaning higher alignment corresponds to lower effective friction (sliding regime). The complementary adhesion case

follows analogously with  $g'(Q) \geq 0$ .

If  $g(Q)$  is continuous and strictly monotone, and  $Q_A^{\text{stab}}(t)$  is bounded and free of chatter (as established above), then:

(i)  $\mu_{\text{eff}}(t)$  is bounded within physical design limits:  $\mu_{\text{eff}}(t) \in [\mu_{\text{min}}, \mu_0]$ .

(ii) Any monotone change in  $Q_A^{\text{stab}}(t)$  produces a monotone change in  $\mu_{\text{eff}}(t)$ . No inversion or non-physical regime switching can occur.

(iii) Small perturbations in  $Q_A^{\text{stab}}(t)$  produce proportionally bounded changes in  $\mu_{\text{eff}}(t)$ , with sensitivity governed by  $g'(Q)$ .

Thus, control authority over alignment translates directly and predictably into control authority over effective friction.

**Corollary (Regime Consistency).** If the contact regime is defined by thresholds in  $Q_A^{\text{stab}}$ , and  $g(Q)$  is monotone, then regime transitions in  $Q_A^{\text{stab}}$  correspond one-to-one with regime transitions in  $\mu_{\text{eff}}$ . No hidden friction regime exists outside the alignment variable. Stability of  $Q_A^{\text{stab}}$  implies stability of the friction regime. The same reasoning applies symmetrically to effective adhesion  $A_{\text{eff}}$ .

## Contact Micro-Model: Ultrasonic Friction Modulation

To ground the alignment charge in concrete physics, consider a minimal contact model.

A rigid body of mass  $m$  moves on a surface with baseline Coulomb friction coefficient  $\mu_0$  under normal load  $F_N$ . A piezoelectric actuator embedded in the contact pad generates ultrasonic vibration at frequency  $f$  and amplitude  $a_n$  normal to the surface. The well-known effect (reported in tribology literature since the 1960s, systematically studied by Storck et al. 2002, Dong & Dapino 2014, among others) is that normal ultrasonic vibration reduces the time-averaged effective friction by periodically reducing the instantaneous contact force.

Under sinusoidal excitation  $a_n(t) = A \sin(2\pi ft)$ , the contact force oscillates as:

$$F_{\text{contact}}(t) = F_N - m \cdot (2\pi f)^2 \cdot A \cdot \sin(2\pi ft)$$

When the vibration amplitude is sufficient that the contact force momentarily reaches zero (separation condition:  $m \cdot (2\pi f)^2 \cdot A \geq F_N$ ), the time-averaged tangential resistance drops. The effective friction becomes:

$$\mu_{\text{eff}} \approx \mu_0 \cdot (1 - T_{\text{sep}} / T_{\text{period}})$$

where  $T_{\text{sep}}$  is the fraction of each cycle during which contact is lost, and  $T_{\text{period}} = 1/f$ .

Now map this onto the alignment charge architecture:

- **Interaction features  $z(t)$ :** contact impedance (drops during separation), microvibration spectrum (shows harmonic peaks at  $f$ ), phase delay between commanded and measured vibration.
- **Alignment charge  $Q_A$ :** increases as the vibration parameters approach optimal separation conditions — i.e., as the system achieves better ultrasonic alignment with the surface.
- **Actuation:** adjusting  $A$  and  $f$  to drive  $Q_A^{\text{stab}}$  toward  $Q_A^{\text{target}}$ .
- **$\mu_{\text{eff}}$  as function of  $Q_A^{\text{stab}}$ :** the sigmoidal  $g(Q)$  maps the alignment state to the effective friction reduction achievable at that operating point.

The closed loop: measure impedance/vibration features → compute  $Q_A$  → adjust  $A$  and  $f$  → contact physics change → new impedance reading. The loop closes through the physics of ultrasonic contact modulation, not through gain adjustment.

This is one physical instantiation. Electrostatic modulation (squeeze-film effect), thermal softening of contact interfaces, and active microtexture deformation follow the same architectural pattern — different physics, same  $Q_A$  control topology.

## The Control Loop

The system now operates a closed loop:

1. **Measure** interaction features  $z(t)$

2. **Compute**  $Q_A(t)$  and stabilize to  $Q_A^{\text{stab}}(t)$
3. **Compute**  $\mu_{\text{eff}}(t)$  and  $A_{\text{eff}}(t)$
4. **Evaluate** current contact regime (stick / slip / transitional)
5. **Actuate** — change at least one interaction parameter to drive  $Q_A^{\text{stab}}(t)$  toward a target  $Q_A^{\text{target}}$

The interaction parameter to be changed is *not normal force*. It is selected from: local vibration or ultrasonic stimulation, electrostatic field modulation, local temperature regime, active microtexture or micropneumatic state, controlled acoustic probing, or compliance modulation.

The actuation modifies contact conditions, which modifies the interaction features measured in step 1 — closing the loop through the physics of interaction, not through an error signal.

### **Fixation: Anti-Chatter via Hysteresis and Dwell**

When stability conditions are satisfied:

$$|\dot{Q}_A(t)| < \theta_1 \text{ and } |\ddot{Q}_A(t)| < \theta_2 \text{ for a duration } T_{\text{dwell}}$$

the system holds the current alignment state  $\bar{Q}_A = \text{Hold}(Q_A^{\text{stab}}(t))$ . Entry and exit thresholds may differ (hysteresis), ensuring that transient fluctuations do not cause oscillatory regime switching.

This is the "contact held / contact changed" mode — binary, stable, and free from chatter.

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### **Why $Q_A$ Is Not a Friction Estimator**

This is the objection that must be addressed head-on: "You are just estimating the friction coefficient with extra steps".

No. The distinction is architectural, not quantitative.

A friction estimator is an *observer*. It takes sensor data, infers  $\mu$ , and feeds that estimate into a controller that adjusts force, trajectory, or gain. The friction coefficient remains an environmental parameter — the estimator watches it, the controller reacts to it. The loop closes through the controller's response to the estimate, not through the physics of the contact itself.

$Q_A$  is a *control object*. It is not an estimate of  $\mu$  — it is an independent variable from which  $\mu_{\text{eff}}$  is *derived*. The system does not observe friction and then compensate. It regulates  $Q_A$  through non-mechanical actuation (electrostatic, ultrasonic, thermal, microtexture), and  $\mu_{\text{eff}}$  changes as a consequence — because the physical conditions of the contact have been altered.

The difference becomes concrete in the control loop topology:

- **Friction estimator:** sensor → estimate  $\hat{\mu}$  → adjust controller gains → apply more/less force → observe result. The loop goes through the controller.
- **Alignment Charge:** sensor → compute  $Q_A$  → actuate interaction parameter (not force) → contact physics change → new sensor reading. The loop goes through the physics of the interaction.

In the estimator architecture, friction is something you learn about. In the  $Q_A$  architecture, friction is something you change. These are not two descriptions of the same thing. They are two different control topologies with different actuation channels, different closed-loop paths, and different achievable outcomes.

A friction estimator cannot reduce  $\mu_{\text{eff}}$  below the physical coefficient of the surface-material pair by adjusting gains alone.  $Q_A$ -based actuation can modify the physical interaction conditions — through ultrasonic vibration, electrostatic modulation, thermal adjustment, or surface-state change — that determine what the effective coefficient actually is. This is not a violation of physics; it is a change of the contact regime itself. (Ultrasonic friction reduction has been observed and systematically studied in tribology — see, e.g., Storck et al. 2002, Dong & Dapino 2014; the contribution here is the formal control architecture that makes it a closed-loop, stabilizable process rather than an open-loop physical effect.)

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### **Where Classical Control Fails**

Consider a mobile robot traversing a surface whose friction coefficient changes faster than the adaptive controller's convergence rate — for example, a floor with alternating wet and dry patches at intervals shorter than the estimator's sliding window.

A PID controller with friction compensation will oscillate between under- and over-correction, because its gain adaptation lags behind the surface changes. An adaptive controller with LuGre estimation will produce transient force spikes at each transition, because the model parameters cannot converge before the next surface change. The standard remedy: increase normal force to maintain traction through brute margin. This works, but at the cost of energy, wear, and mechanical stress.

A Q\_A-based system responds differently. It does not need to *estimate* the new friction coefficient before acting. It measures interaction features (impedance, microvibration spectrum, dielectric response) that respond to surface changes within a single sampling interval. Q\_A shifts immediately. The system actuates — adjusts ultrasonic stimulation frequency or electrostatic field — and the effective friction is regulated within the same closed-loop cycle. No convergence delay. No force increase. No estimation lag.

The architectural reason is simple: Q\_A is formed from *interaction features*, not from model identification. Interaction features are measured directly. Model identification requires fitting parameters over time. When the environment changes faster than the model can converge, the estimator fails. Q\_A does not.

A possible objection: "But  $\varphi(\tilde{z})$  still requires calibration — so Q\_A is just a faster estimator". The distinction matters. Calibration of  $\varphi$  is a one-time static mapping — setting w, b, or  $\alpha$  during system setup. It does not adapt at runtime to track a changing surface. Model identification in LuGre or adaptive friction compensation is a *continuous* parameter fitting process that must converge before the estimate is useful. Static mapping versus dynamic convergence: the former has zero convergence delay; the latter has convergence delay proportional to the rate of environmental change. Under fast-switching surfaces, the convergence delay is the failure mode. Q\_A eliminates it by construction.

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## Classical Compensation vs. Alignment Charge

Dimension	Classical	Q_A Architecture
Friction is...	Parameter to estimate	Controllable variable
Control channel	Force, gain, trajectory	Ultrasonic, electrostatic, thermal
Surface change response	Estimate → adapt → force (delay)	Features → actuate → immediate
Modify contact physics?	No — compensates $\mu$	Yes — alters contact conditions
Needs more normal force?	Yes, as safety margin	No
Loop closes through	Controller response	Interaction physics

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## Spin and Drift: The Rotational Mismatch Correction

In some embodiments, the system–medium interaction exhibits a rotational component — a torsional mismatch that manifests as directional drift. This is directly related to what I call "spin" in the broader NC2.5 framework: the non-potential divergence-free component of adaptive dynamics that prevents stagnation under bounded resources.

Here, spin enters the alignment charge as a correction:

$$Q_A(t) = \varphi(\tilde{z}(t)) - \gamma \cdot \tau(t), \gamma \geq 0$$

where  $\tau(t) = \Psi(\tilde{z}(t))$  is a rotational-component signal extracted from interaction features.

Meaning: if the system–medium pair exhibits torsional mismatch, the alignment charge decreases, and the interaction regime shifts toward more conservative, stable contact. Spin does not destabilize — it provides the signal that triggers stabilization.

This block is optional but extends the method's applicability to drifting, rotating, and unstable-contact media.

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## The Extension: Context, Moment State, and Sleep

The alignment charge alone is sufficient for contact control. But in systems that interact with humans — wearables, haptic interfaces, orthoses, prosthetics — there is a second layer that changes everything.

The human is not a constant. The same hand gripping the same handle at 2 PM and 3 AM operates in radically different physiological regimes. Fatigue, stress, arousal, sleep stage — all of these alter the contact conditions, not because the surface changed, but because the system's other half changed.

For this, I introduce a second formally defined variable: the **Moment-State Charge  $Q_M(t)$** .

$Q_M(t)$  is a bounded scalar (or low-dimensional vector) summarizing the instantaneous state of the system/user in context. It is computed from multi-modal sensor inputs — motion, temperature, heart rate, heart rate variability, electrodermal activity, respiration, impedance, audio features, optical features — combined with a context vector  $c(t)$  that includes sleep stage, circadian phase, activity regime, environmental conditions, and task type.

$$Q_M(t) = \varphi_M(\tilde{s}(t), c(t))$$

The system does not diagnose emotions. It classifies measurable state regimes: calm vs. activated, stable vs. unstable, recovered vs. fatigued, focused vs. scattered. These classifications are inferred from signals, not from psychological models.

The coupling to contact control is direct:

$$\mu_{\text{eff}}(t) = \mu_0 \cdot g(Q_A^{\text{stab}}(t), Q_M(t), c(t))$$

$$A_{\text{eff}}(t) = A_0 \cdot h(Q_A^{\text{stab}}(t), Q_M(t), c(t))$$

When  $Q_M$  indicates stress or high activation, or when the coherence metric  $C(t)$  indicates low stability relative to context-dependent normative bands, the system selects conservative contact regimes: less chatter, less jerk, safer adhesion margins — without increasing mechanical force.

Sleep/REM context gating deserves special attention. During REM, physiological variability patterns differ fundamentally from wakefulness. A wearable device that uses the same thresholds during sleep as during active use will either miss important state changes or generate false alarms. The normative bands  $N(c(t))$  switch based on sleep stage:

$$\text{sleep\_stage}(t) \in \{\text{wake}, \text{NREM}, \text{REM}\}$$

and thresholds, hysteresis criteria, dwell times, and allowed actuation modes all shift accordingly.

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## What This Changes

### For Robotics

A robot on a changing surface — wet tile to carpet to gravel — no longer needs to increase normal force when traction drops. Instead, it regulates  $Q_A$  through ultrasonic stimulation of its sole, or electrostatic modulation of its contact pad, or thermal adjustment of the contact zone. The same robot can stabilize an unstable object on fabric by locally increasing  $A_{\text{eff}}$  through alignment — achieving a "stable on edge" effect that would otherwise require mechanical clamping.

### For Manipulation

A gripper holding an object with uncertain contact properties does not need to squeeze harder when slip is detected. It measures interaction features, computes  $Q_A$ , and adjusts its contact regime — through microvibration, electrostatic modulation, or compliance modulation — to increase adhesion without increasing grip force. Less force means less damage, less energy, and more precision.

### For Wearables and Human–Machine Interfaces

A haptic device on a user's wrist measures skin impedance, temperature, microperspiration, and microvibration response. From these, it computes  $Q_A$  for the device–skin contact and  $Q_M$  for the user's physiological state. During high-stress moments, the device automatically shifts to a more conservative adhesion regime — gentler, less jittery, with wider hysteresis bands. During sleep, thresholds change entirely.

The user feels nothing change. The device simply works better when they need it most.

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## Energy and Trade-Offs

The claim "without increasing mechanical effort" requires an honest qualification:  $Q_A$ -based actuation does not increase normal force, but it is not free. Ultrasonic vibration requires electrical power to drive the piezoelectric element. Electrostatic modulation requires voltage supply. Thermal adjustment requires heat input and dissipation time. Active microtexture requires mechanical or pneumatic infrastructure.

The trade-off is between mechanical energy (pressing harder) and electrical/thermal energy (modulating the contact regime). In many practical cases this trade-off is favorable: piezoelectric actuators operating at ultrasonic frequencies consume milliwatts to low watts, while the mechanical force savings — reduced wear, lower actuator load, less structural stress — can be substantial. But the trade-off is not universal. On surfaces where the medium does not respond to available actuation channels (e.g., a dry rigid metal-on-metal contact with no dielectric gap),  $Q_A$ -based modulation may offer no advantage. The architecture applies where at least one non-mechanical actuation channel exists that can modify contact conditions.

Additional constraints include: acoustic noise from ultrasonic actuation in human-proximate applications, thermal limits in wearable devices, electromagnetic interference from electrostatic fields, and long-term degradation of piezoelectric elements or surface coatings under sustained operation. These are implementation constraints, not architectural ones — they define the boundary of applicability, not a flaw in the control topology.

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## Architectural Position

The Alignment Charge is not a replacement for force control, PID, or adaptive regulation. It is a new layer — a formally defined interaction variable that makes the system–medium contact regime an explicit object of control for the first time.

In the broader architecture of Navigational Cybernetics 2.5,  $Q_A$  occupies a specific position: it is the control primitive for the boundary between the system and the world.  $\Delta E$  provides coherence-driven stabilization of internal dynamics. UTAM provides direction and curvature of the adaptive trajectory. The alignment charge provides the point of contact — the surface where the system meets the medium, where theory touches physics.

This is where admissibility becomes engineering.

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*The alignment charge is one node of Navigational Cybernetics 2.5 — an architectural theory of long-horizon adaptive systems. The broader framework, including  $\Delta E$ , UTAM, CAS-T, structural burden, spin, admissibility, and meta-revision, is available at [petronus.eu](http://petronus.eu).*