

Sensor-oriented Electrostatic Discharge and Spatial Electromagnetic Protection of a Quadrotor Unmanned Aerial Vehicle

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The protection of onboard physical sensors in quadrotor unmanned aerial vehicles (UAVs) from electrostatic discharge (ESD), self-generated radiated emission, and exogenous spatial electromagnetic interference is addressed. A sensor-oriented codesign combining transient voltage suppressor (TVS) clamping with solder-mask opening is proposed, targeting the reliability of the onboard angle sensor and flight-control microcontroller. The ESD failure mechanism at the DC power port is analyzed, and a transient energy-clamping circuit centered on a TVS is designed and verified. Compliance with GB/T 38909-2020 (Guobiao/Tuijian, the Chinese recommended national standard) is confirmed, and the protection is demonstrated by a measured attitude-error reduction from approximately 5 to 1.0° under International Electrotechnical Commission (IEC) 61000-4-2:2025 Level 4 air discharge. Because the 10 V/m immunity required by conventional standards is insufficient near cellular infrastructure, a spatial electromagnetic-immunity investigation under synthesized base-station field exposure up to 61 V/m is designed and an embossed shielding layer of conductive metal is proposed to suppress the RF threat, while the dimpled relief also enlarges the radiating surface to aid heat dissipation. Repeated-endurance reliability under both threats is quantified by the Kaplan–Meier survival framework with protected and shielded configurations showing median survival far beyond the unprotected and unshielded cases. The codesign improves the electromagnetic compatibility of the UAV while adding less than 5 g of mass and is therefore compatible with mass-critical airborne use.

1. Introduction

The flight attitude of a quadrotor unmanned aerial vehicle (UAV) is determined by an onboard angle sensor, typically a three-axis inertial unit, together with the flight-control microcontroller that issues actuation commands.⁽¹⁾ Both components are physical sensors of the electromagnetic and inertial type, and their readings are directly threatened by transient and

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radiative electromagnetic disturbances. The severity of electrostatic discharge (ESD) hazards at the DC power port has been widely reported, and higher immunity requirements have been imposed by the trend toward miniaturized electronics. During flight, intense friction between the rotors and air, as well as between the airframe and airborne particles, constitutes a continuous charging process that may accumulate electrostatic potentials of several kilovolts on the airframe.⁽²⁾ In flight, the accumulated charge is dissipated through corona discharge at the propeller tips and the naturally leaky insulation of the airframe, reaching a dynamic equilibrium rather than monotonically increasing; the codesign targets the residual transient coupled into the sensor interfaces. When such charges seek a discharge path, indirect coupled discharges invade the sensor interfaces, power lines, and signal lines, and a transient overvoltage coupled into the sensor port causes soft errors, such as pulse-width-modulation (PWM) signal jumps and attitude-angle deviation, which degrade control accuracy and may lead to loss of stability.

The other side of electromagnetic compatibility (EMC) is excessive radiated emission (RE) from the UAV itself. Parasitic-parameter defects in printed-circuit-board (PCB) layouts form strong radiation sources that invade adjacent sensitive circuits through near-field coupling, causing the interruption of flight-command transmission or data distortion.⁽³⁾ Excessive radiation also creates a trackable electromagnetic signature and may accelerate the aging of electronic components.⁽⁴⁾

On-board sensor protection builds upon established electrostatic-discharge-clamping practices, in which transient-voltage-suppressor (TVS) diodes and solder-mask opening with solder coating are adopted to reduce high-frequency trace impedance; the effect of discharge-point geometry on air-discharge waveforms has also been studied, but engineering protection implementation has not been addressed.⁽⁵⁾ In contrast to prior circuit-level studies, the present work extends the validation to the onboard-sensor-failure domain under extreme test levels and to spatial electromagnetic immunity, rather than reporting only circuit-level clamping voltages. *In situ* pre-compliance testing for electric-vehicle radiated emissions has been proposed, yet the associated shielding schemes cannot be directly applied to UAVs because of weight limitations.⁽⁶⁾ At the system level, the thermal failure of a PCB assembly under ESD is simulated, with transient energy absorption emphasized as the dominant failure mechanism.⁽⁷⁾ The analysis remains at the component-and-board level and does not extend to the behavior of an entire airborne platform or to the sensor reading that actually governs vehicle stability. A physics-based ESD failure model is proposed for carbon-nanotube field-effect transistors, capturing device-level degradation under a transient stress, yet the model targets a specific emerging device technology rather than the commercial inertial and microcontroller electronics equipped on a production quadrotor, so its protective implications for an actual flight article are indirect.⁽⁸⁾ An ESD waveform replication scheme based on ferrites is proposed to regenerate standard discharge waveforms for test purposes, but the contribution is oriented toward test-instrument fidelity and does not address how a product is hardened against the replicated waveform, nor does it verify any sensor-level consequence.⁽⁹⁾ An equivalent-circuit model for discharge currents is established to represent the current source in EMC analysis. Although the model supports system-level coupling studies, it describes the stimulus itself and is not coupled to a concrete protection implementation or to measured onboard-sensor errors.⁽¹⁰⁾ The near-field prediction of

the maximum RE from PCBs is demonstrated, enabling the early estimation of compliance margins, yet the method is diagnostic rather than corrective: it predicts the emission level but does not itself provide a lightweight shielding or layout remedy suitable for an airborne vehicle.

⁽¹¹⁾ Broad-band RE reduction by electromagnetic-bandgap structures is reported, achieving planar suppression over a wide band, but such structures are typically rigid and add nonnegligible mass, which limits their adoption on weight-critical UAVs, and they suppress self-emission without providing immunity to external spatial fields.⁽¹²⁾ The relevance of shield mass to airborne applications is confirmed, showing that added shielding must be weighed against the payload budget, although the work establishes the constraint without proposing a mass-aware shielding solution that simultaneously satisfies both ESD clamping and spatial-immunity requirements.⁽¹³⁾ Nevertheless, none of the above combines device-level clamping, layout-level radiation control, and direct onboard-sensor verification within a single codesign under both ESD and spatial electromagnetic threats.

A further gap is the mismatch between standard immunity levels and the real electromagnetic environment. Conventional electromagnetic-compatibility standards require commercial drones to withstand only 10 V/m, whereas base-station antenna fields as strong as 61 V/m are permitted by public-exposure limits and the uncontrolled descent of commercial drones has been observed at field strengths of 30 V/m or higher, with internal cables identified as the dominant coupling path.⁽¹⁴⁾ The present work is therefore motivated by three objectives: (i) protect the onboard angle sensor and flight-control microcontroller from ESD and excessive RE through a lightweight codesign; (ii) verify the protection by directly measuring sensor reading errors rather than only circuit-level voltages; and (iii) extend the protection concept to spatial electromagnetic immunity under base-station field exposure, using an embossed shielding layer.

The structure of this paper is as follows. The protection design and the evolved test standard are described in Sect. 2. The simulation of the protection circuit and the spatial electromagnetic threat is presented in Sect. 3. The experimental validation, including onboard-sensor error characterization and repeated-endurance assessment under both threats, is given in Sect. 4. A quantitative discussion and conclusions are provided in Sects. 5 and 6, respectively.

2. Electromagnetic Protection Design and Standards

2.1 Selection of electrostatic protection devices

As a key component that is highly susceptible to EMI, the safety and reliability of the UAV are directly linked to its electromagnetic protection. At present, gas discharge tubes (GDTs), metal-oxide varistors (MOVs), and TVSs are recognized as the three main categories of reliable transient surge protection components.^(15,16) Because of its long breakdown response time and limited lifespan, the GDT cannot promptly clamp transient pulses with high rise rates and is primarily applied in the first stage of multistage lightning protection. Compared with the GDT, the MOV exhibits a faster response at the nanosecond level, yet its junction capacitance, typically in the range of hundreds to thousands of picofarads, gives rise to leakage-current issues that may cause secondary damage during ESD protection.⁽¹⁷⁾ The TVS, manufactured from

semiconductor silicon, presents a high-impedance region at a low voltage and enters breakdown when a transient overvoltage is applied; the voltage is then clamped at the maximum clamping voltage while the current rises to its peak. Among the three devices, the TVS provides the fastest response, reaching the picosecond level, and is less prone to aging. TVS clamping is a well-established front-end protection technique for fast transients and is therefore selected as the core of the present codesign.

2.2 Evolution of the IEC 61000-4-2 test standard

Compared with GB/T 17626.2-2018,⁽¹⁸⁾ higher requirements are specified by IEC 61000-4-2:2025 for the general specifications of contact-discharge voltage.⁽¹⁹⁾ As indicated in Table 1, the minimum contact-discharge voltage is increased to 2 kV. As shown in Table 2, more extensive changes are observed in the contact-discharge current-waveform parameters. The classification for contact discharge and air discharge is refined, and current-waveform requirements for the air-discharge mode are added. The second-peak amplitude is required to be read between 10 and 40 ns. Notably, Level 4 waveform requirements for air discharge are newly introduced and are adopted as the test severity in this work because of their relevance to charged airframes.

2.3 Onboard-sensor port vulnerability

The angle sensor (JY901B) and the flight-control microcontroller (STM32F405RGT6) operate at a 5 V tolerance limit supplied through an AMS1117 regulator and an SN74LVC1G06 inverter. A transient overvoltage coupled into this sensor port directly perturbs the PWM output and the serial attitude frame, producing a measurable attitude-error signature. The protection

Table 1
Generator output requirements and operating conditions of IEC 61000-4-2:2025.

Specification	Contact discharge	Air discharge
Nominal output voltage (kV)	2–8	2–15
Output-voltage tolerance (%)	±5	±5
Output polarity	positive and negative	positive and negative
Minimum holding time (s)	—	5
Discharge mode	single	single

Table 2
Current-waveform parameters specified for each test voltage.

Waveform quantity	Tolerance	2 kV	4 kV	6 kV	8 kV	15 kV
First-peak current I_{p1} (A)	±15%	7.5	15	22.5	30	56.3
Second-peak current I_{p2} (A)	−20%/+40%	4.5	9	13.5	18	33.8
Current at 30 ns, I_{30} (A)	±30%	4	8	12	16	30
Current at 60 ns, I_{60} (A)	±30%	2	4	6	8	15

Note: The rise time t_r is 0.8 ns at every test voltage, with a tolerance of ±25%, and the second-peak amplitude is read between 10 and 40 ns. The 8 kV column corresponds to Level 4 contact discharge and the 15 kV column to Level 4 air discharge.

design therefore targets two entry points: the DC power port, where the TVS clamps the surge, and the sensor signal port, where a secondary TVS and a ferrite bead limit the coupled energy. The sensor port is classified as a physical-sensor interface, and its protection falls within the scope of electromagnetic and inertial sensing, under which this work is submitted.

3. Electromagnetic Simulation of UAV

3.1 Protection circuit design

A solder-mask opening is a window in the solder resist that exposes the bare pad copper of the discharge path, enlarging the conductor cross section and reducing parasitic inductance. The power board is realized on a two-layer FR-4 substrate, and the treated conductor belongs to the 12 V input branch between the supply port and the input of the 12 V–5 V converter module, which is itself left unmodified. The opening is defined in the solder resist artwork and adds neither a copper layer nor a lamination step to board fabrication, and the buildup is deposited by manual soldering after assembly. The treatment therefore remains within the existing two-layer stack-up and requires no new tooling, whereas a multilayer redesign would add lamination and layer-registration steps to every board. The basic power supply for the UAV is provided by a 12 V DC portable source. This voltage is converted by a DC–DC module to the 5 V operating level of the sensor and control electronics described in Sect. 2.3. The schematic diagram of the power-board protection circuit is shown in Fig. 1. In the diagram, a diode is employed to prevent damage to the power supply from negative pulses. A TVS diode is connected in parallel at the rear end. When subjected to a reverse instantaneous high-energy impact, its impedance is abruptly reduced within a timeframe on the order of 10^{-12} s. Simultaneously, surge power as high as several kilowatts is absorbed, and the voltage amplitude at the circuit port is clamped

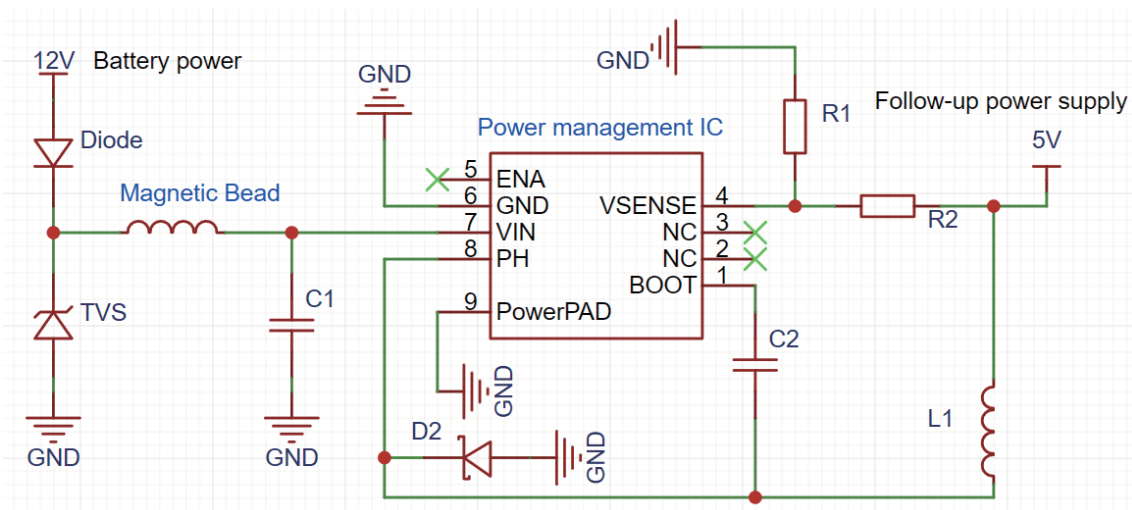


Fig. 1. (Color online) Schematic diagram of the power board and its protection circuit.

below a fixed value. This effectively protects the sensor from damage caused by transient high-energy impacts. Magnetic beads are used to absorb conducted noise. C1 is a chip capacitor utilized for absorbing and filtering noise. D2 is the freewheeling diode and C2 is the bootstrap capacitor of the 12 V–5 V DC–DC converter, both required for the switching stage.

3.2 Electrostatic discharge simulation

Given that IEC 61000-4-2:2025 introduces new Level 4 specifications for air discharge, an ESD current-generator simulation model is established, using the Level 4 air-discharge voltage of 15 kV as an example. This model is shown in Fig. 2(a). The ideal current waveform and the simulated current waveform at 15 kV are presented in Fig. 2(b). The discharge current reaches its first peak at approximately 0.8 ns, which is consistent with the rise time $t_r = 0.8$ ns specified in Table 2. The current decreases to approximately half of its first-peak value near 20 to 30 ns. The simulated current waveform closely matches the ideal current waveform, both conforming to the

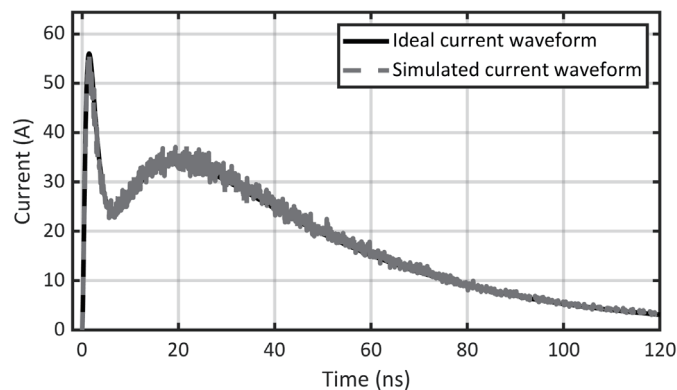
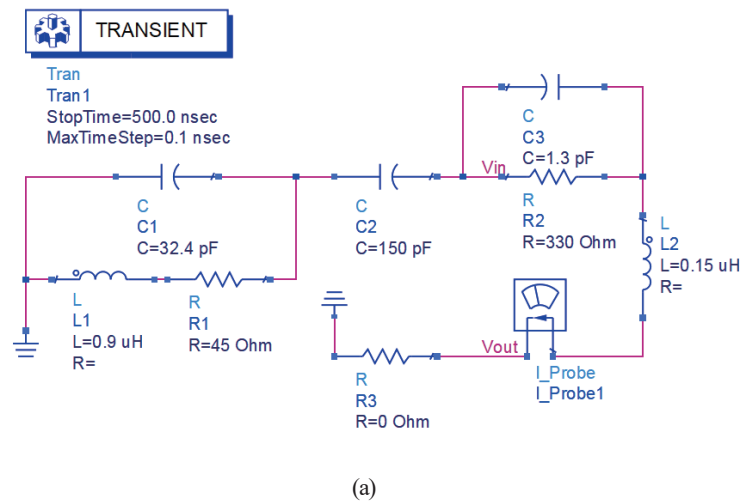


Fig. 2. (Color online) Simulation model of ESD generator and current waveforms. (a) Model of ESD generator. (b) ESD current waveforms (15 kV).

waveform tolerances specified in Table 2 for air-discharge Level 4. Therefore, the modeling of the ESD current generator in this design is demonstrated to be effective and to meet the design requirements.

From the DC power-supply parameters, the operating voltage is known to be 12 V. Considering fluctuations, the maximum operating voltage is calculated as $12 \times (1 + 20\%) = 14.4$ V. The maximum withstand voltage of the subsequent step-down converter is 36 V. Therefore, the clamping voltage must be less than 36 V. Estimating with the peak current $I_{PP} = 30$ A from the highest contact-discharge level, the maximum peak power is derived as $P_{PP} \leq 1080$ W. For this purpose, a TVS diode with a clamping voltage of 33.2 V is selected. Its reverse stand-off voltage is 20.5 V and its breakdown voltage is 25.2 V, which does not affect normal circuit operation and satisfies all requirements of this design. The criterion is that of a single event and is therefore extended by a cumulative requirement: in service, the suppressor is stressed by repeated discharges, and the number of Level 4 events that it withstands without thermal runaway or parameter drift is measured directly, as described in Sect. 4.4, rather than converted to flight hours, because the number of discharge events per flight is set by the ambient humidity, the airframe material, and the flight profile, and is not fixed by the standard.

The clamping behavior of the selected TVS is summarized in Table 3. Without the suppressor, the load voltage reached its peak near 290 V and far exceeds the 36 V withstand voltage of the subsequent converter, whereas, with the suppressor, it is clamped at 33.2 V and decays to the 12 V operating level within approximately 110 μ s.

3.3 Spatial electromagnetic simulation

To assess the spatial electromagnetic threat, a full 3D model of the UAV is built, as shown in Fig. 3. Public-exposure limits permit base-station antenna fields as strong as 61 V/m, and the uncontrolled descent of commercial drones has been reported at field strengths of 30 V/m or higher, with the internal cables identified as the dominant coupling path (see Sect. 1). A synthesized plane wave at 900 MHz is therefore applied to the model, with the field strength ramped from 0 to 70 V/m, to represent near-base-station exposure in the sub-1 GHz band.

Table 3
Selected TVS parameters and clamping performance.

Parameter	Symbol	Value	Requirement/note
Reverse stand-off voltage	VRWM	20.5 V	Does not disturb 12 V normal operation
Breakdown voltage	VBR	25.2 V	—
Clamping voltage	VC	33.2 V	<36 V converter withstand
Peak load voltage without suppressor	—	≈ 290 V	Exceeds converter withstand
Clamped load voltage with suppressor	—	33.2 V	Compliant
Decay to 12 V operating level	—	≈ 110 μ s	—
Maximum operating voltage (20% fluctuation)	—	14.4 V	<36 V

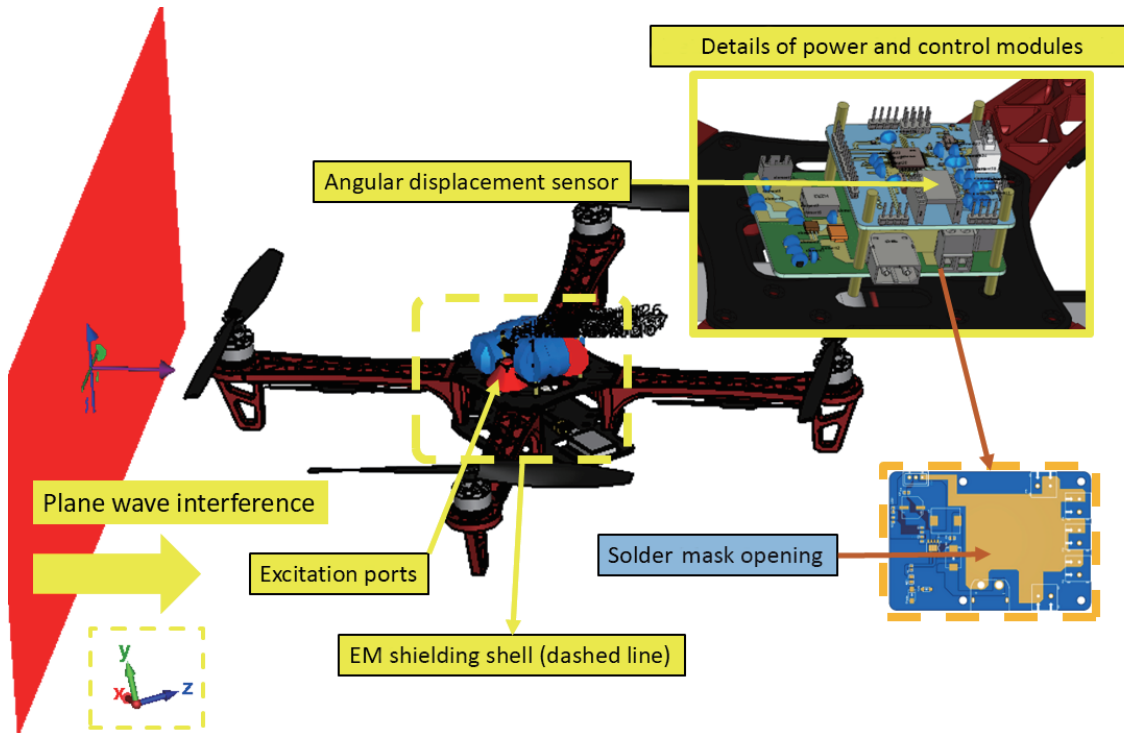


Fig. 3. (Color online) 3D model of the UAV used for spatial electromagnetic simulation.

In the unshielded configuration, the internal sensor harness (effective length ≈ 0.4 m) couples the external field and a transient overvoltage is induced at the angle-sensor port. The coupled port voltage is first examined under a representative 10 V/m excitation as a function of frequency and the result is shown in Fig. 4(a). Three configurations are compared: unshielded, Cu-foil shielded, and Al-foil shielded. The unshielded curve gives the largest coupling across the band, the Cu shield gives the smallest, and the Al shield gives an intermediate result that is clearly lower than that of the unshielded curve but not as low as that of the Cu shield, so that Cu is confirmed as the best single-material shield and Al as a lighter but slightly inferior alternative.

The field dependence is extended to a 10–70 V/m sweep in Fig. 4(b), where the coupled port voltage of the unshielded configuration is plotted as a single surface against field strength and frequency, together with a reference plane at the 11.2 V clamping level of the sensor-port suppressor. Consistent with Fig. 4(a), the voltage of the unshielded surface rises steeply and reaches approximately 43 V at 61 V/m and 50 V at 70 V/m, which exceeds both the 11.2 V clamping voltage of the sensor-port suppressor and the 5.5 V continuous rating of the sensor input. The 5.5 V limit applies to sustained stress; under a transient, the withstand of the input is governed instead by the current that the series impedance delivers into the on-chip protection, so the suppressor remains effective even though the clamped level lies above 5.5 V, because it diverts most of the coupled current and bounds the residual excursion to well below 100 ns, keeping the deposited energy within the transient tolerance of the input. Without a shield, the 43 V coupled level leaves the input exposed to exactly the breakdown and latch-up risk that the

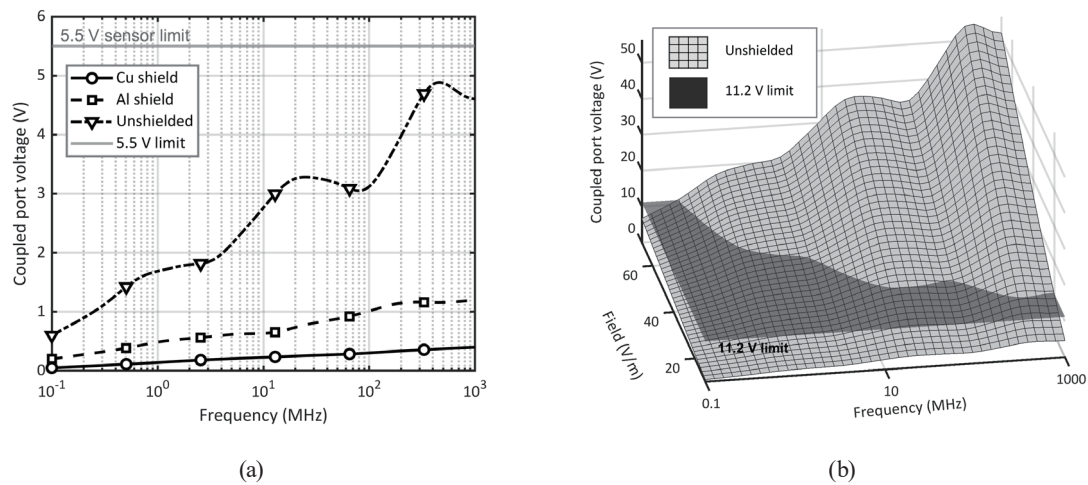


Fig. 4. Angle-sensor port plotted against coupled voltage. (a) Angle-sensor port coupled voltage versus frequency under 10 V/m excitation. (b) 3D coupled-voltage surface of unshielded configuration versus field strength (10–70 V/m).

rating is intended to exclude. The foil shields in the case of Fig. 4(a) reduce the coupling but cannot remove it, because an applied foil necessarily leaves nonconductive seams; hence, a fully sealed enclosure is adopted in Sect. 4.1.

4. Electromagnetic Testing of UAV

4.1 Spatial electromagnetic-immunity test

To eliminate the seam leakage identified in Sect. 3.3, the flight-control compartment and the internal harness are enclosed by continuous metal patches that leave no aperture. This fully sealed enclosure gives the best suppression of the coupled voltage, but the absence of ventilation traps the onboard heat and creates a risk of burning the internal sensors. A dimpled (embossed) metal-patch structure is therefore adopted as the final shielding design: the periodic relief is continuous and unperforated, so that no aperture is introduced, while the enlarged surface area improves convective heat exchange and keeps the temperature rise within the thermal budget. The actual embossed morphology of the Cu and Al patches is documented by optical microscopy, as shown in Figs. 5(a) and 5(b), confirming the periodic dimpled relief and the continuous conductive sheet that the design assumes.

The sealed embossed enclosure that secures this RF immunity also governs the thermal safety of the flight-control compartment. To quantify the thermal penalty and the benefit of the dimpled relief, the steady-state temperature rise of the flight-control compartment is compared between flat and embossed fully sealed enclosures for both Cu and Al under a swept onboard heat load, as shown in Fig. 5(c). The flat fully sealed enclosures of both metals exceed the 20 °C thermal budget at a moderate load and therefore carry a burn risk for the internal sensors, whereas the embossed fully sealed enclosures remain within the budget across the whole load

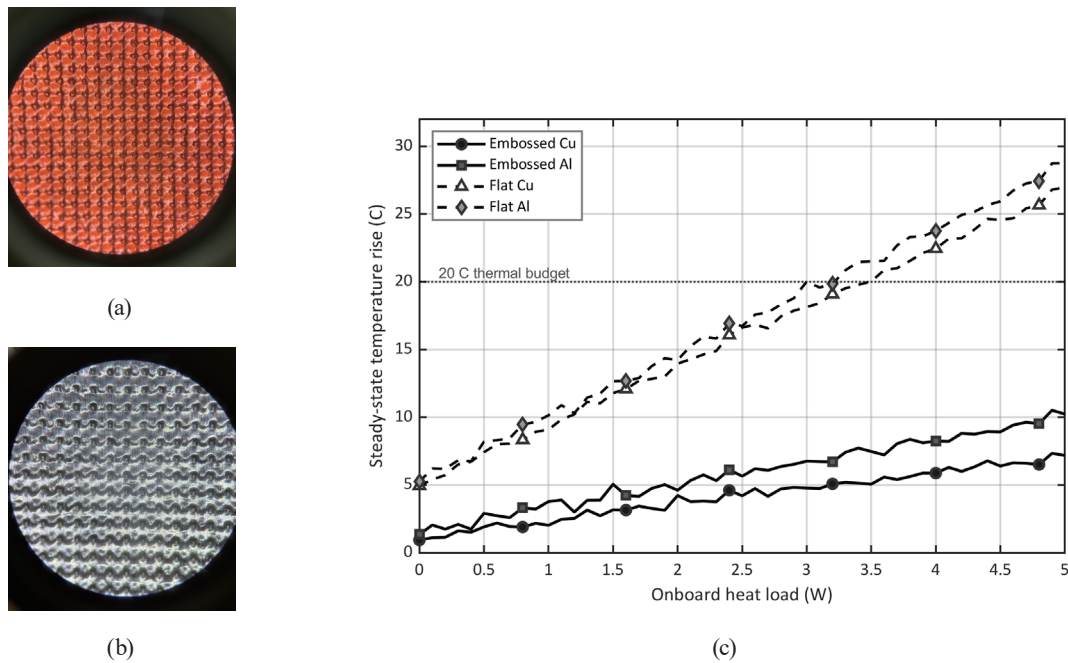


Fig. 5. (Color online) Embossed shielding-patch morphology and thermal relief. (a) Embossed Cu patch. (b) Embossed Al patch. (c) Steady-state temperature rise.

range because the dimpled relief enlarges the radiating surface and improves convective dissipation. Within the embossed group, the Cu patch runs marginally cooler than the Al patch because Cu has the higher thermal conductivity, but the difference is only about 3 °C and both remain within the 20 °C budget.

Both Cu and Al are admissible for the embossed enclosure. Cu gives the highest shielding effectiveness and the lowest steady-state temperature rise by virtue of its larger electrical and thermal conductivities, whereas Al reduces the added mass to roughly one third that of Cu at the cost of only about 6 dB lower shielding effectiveness and about 3 °C higher temperature rise, both remaining within the specifications. The patch metal is therefore selected as a trade-off between shielding/thermal margin and payload mass, and embossed Cu is adopted for the demonstrator in this work. The embossed metal-patch enclosure thus adopted seals the seams, suppresses the coupled voltage below the sensor limit, and remains thermally safe.

The coupled-port-voltage prediction in Sect. 3.3 (Fig. 4) must be confirmed at the sensor level, because the figure of merit for base-station-field immunity is the onboard attitude error rather than the harness voltage. Each UAV is therefore placed in an anechoic chamber and exposed to a synthesized 900 MHz plane wave whose field strength is ramped from 0 to 70 V/m in steps of 5 V/m, with the angle-sensor attitude error being recorded at each step. A representative UAV of each configuration (embossed Cu-shielded and unshielded; Al is an equally admissible alternative to Cu) is tested. The measured attitude error is plotted in Fig. 6(a). The unshielded vehicle shows a curve that rises sharply and exceeds 5° near 30 V/m, consistent with the reported uncontrolled-descent threshold, whereas the embossed-Cu-shielded vehicle

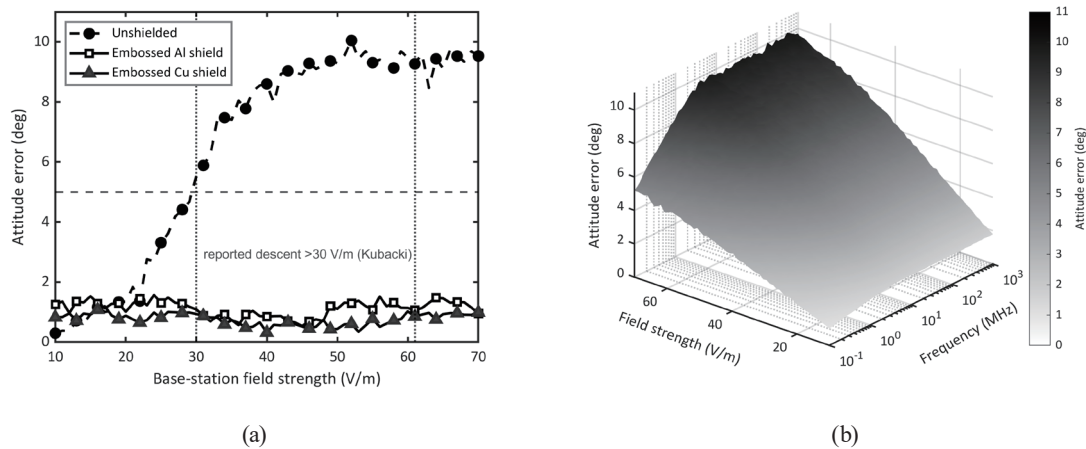


Fig. 6. Measured onboard-sensor attitude error versus base-station field strength: shielded versus unshielded. (a) Onboard-sensor attitude error. (b) 3D surface of unshielded onboard-sensor attitude error.

holds the attitude error below approximately 1.0° up to 61 V/m. The 3D surface of the unshielded error over field strength and frequency is shown in Fig. 6(b), where the attitude-error tolerance is exceeded over a large region of the low-frequency, high-field corner; the 2D curve of Fig. 6(a) captures the worst-case envelope. The scan is performed on one representative vehicle per configuration in order to locate the worst-case field-strength threshold; the statistical substantiation of the threshold is given in Sect. 4.5, where the same field-ramp protocol is repeated on ten vehicles per group with ten repetitions per vehicle.

4.2 Electrostatic discharge test

The ESD immunity of the power board is verified for two board configurations that share the protection circuit of Sect. 3.1 but differ in the pad treatment of the discharge path: (i) a board with a solder-mask opening that exposes the pad copper of the suppressor and the discharge path, and (ii) a board with the solder-mask opening plus a solder buildup that further enlarges the conductor cross section. The physical images of the two boards are shown in Fig. 7. The solder-mask opening enlarges the effective copper cross section of the discharge path and reduces its parasitic inductance, and the solder buildup further increases the current-carrying and heat-spreading capacity, so the discharge current is absorbed with a lower residual voltage and less board stress.

The ESD generator is discharged at 8 kV for contact discharge and 15 kV for air discharge under the Level 4 conditions. Twenty discharges are applied at each test point in accordance with IEC 61000-4-2:2025, with a 2 min interval and grounding between discharges. Because each test point is stressed twenty times, the outcome is summarized statistically rather than as a single waveform: the mean and maximum peak residual voltages at the power port, the decay time to the 12 V operating level, the performance criterion, and the number of self-recovering disturbances are listed in Table 4. Criterion A denotes normal performance during and after the

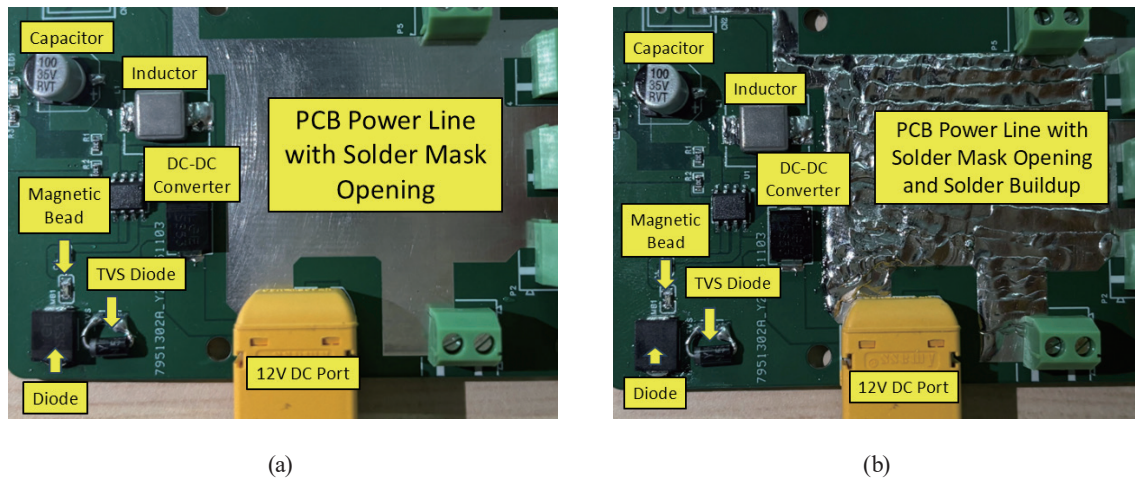


Fig. 7. (Color online) Two board configurations: (a) board with solder-mask opening and (b) board with solder-mask opening and solder buildup.

Table 4
Level 4 ESD test results at the power port.

Discharge mode	Board configuration	Peak residual voltage (V)	Maximum peak (V)	Decay time to 12 V (μ s)	Performance criterion	No. of self-recovering disturbances (per 20 discharges)
Contact, 8 kV	Solder-mask opening	40.3	41.8	126	A	0
Contact, 8 kV	Opening plus solder buildup	34.9	35.6	108	A	0
Air, 15 kV	Solder-mask opening	51.7	55.1	155	B	2
Air, 15 kV	Opening plus solder buildup	45.6	48.0	138	A	0

discharge, and criterion B denotes a temporary degradation that self-recovers without operator intervention. The contact- and air-discharge gun heads are shown together in Fig. 8.

The solder-mask opening reduces the parasitic overshoot of the discharge path: at 8 kV contact discharge, the mean peak falls to 40.3 V and no functional disturbance is observed, although the residual peak still exceeds the 36 V continuous rating as a brief sub-100 ns overshoot. The opening-plus-solder group performs best: the mean peak at 8 kV contact discharge falls to 34.9 V, below the 36 V converter withstand, and the measured decay time of 108 μ s agrees with the approximately 110 μ s simulated value in Table 3. Under the more severe 15 kV air discharge, the 56.3 A first-peak current exceeds the 30 A design point of the suppressor, so the residual plateau of both groups rises above the 36 V continuous rating; the excess lasts less than 100 ns and remains within the transient tolerance of the converter input stage, so the opening-plus-solder group completes all twenty discharges at criterion A without latch-up or damage, whereas the opening-only group shows criterion-B disturbances in two of the twenty air discharges. The difference between the mean and maximum residual peaks is taken as the

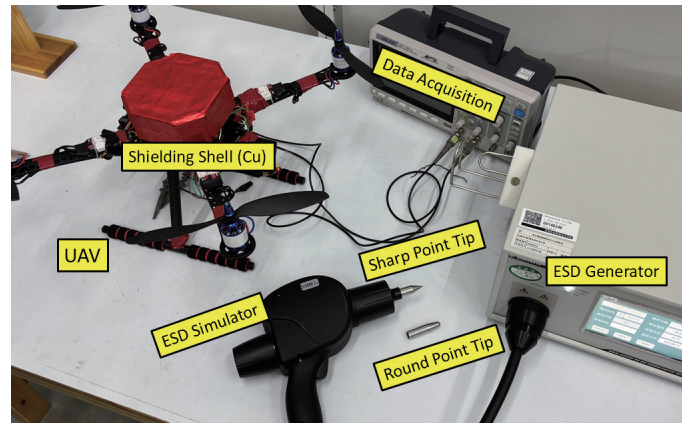


Fig. 8. (Color online) ESD test setup of UAV.

repeatability indicator of the single-event test, and the opening-plus-solder group shows the smallest spread in both discharge modes.

As a secondary confirmation of the solder-buildup process, the RE of the two solder-treated board configurations is measured in the semi-anechoic chamber shown in Fig. 9, with the GB/T 38909-2020 limit taken as 40 dB μ V/m below 230 MHz and 47 dB μ V/m above 230 MHz at the 3 m measurement distance.⁽²⁰⁾ The solder-mask-opening board is presented in Fig. 10(a): the worst-case peaks reach 49.9 dB μ V/m in horizontal polarization (65.9 MHz) and 47.3 dB μ V/m in vertical polarization (71.7 MHz), both located in the 30–230 MHz band and exceeding the 40 dB μ V/m limit. With the solder buildup added, Fig. 10(b), the worst-case peaks fall to 45.4 dB μ V/m in horizontal polarization (951.5 MHz) and 42.8 dB μ V/m in vertical polarization (891.4 MHz), below the 47 dB μ V/m limit of the 230–1000 MHz band, and the low-band maxima fall to 35.3 and 33.0 dB μ V/m, below the 40 dB μ V/m limit, so the opening-plus-solder board satisfies GB/T 38909-2020 over the whole 30–1000 MHz range. Relative to the opening-only board, the worst-case peak is reduced by 4.5 dB and the dominant low-band emission by 14.6 dB. The 14.6 dB low-band reduction corresponds to $\approx 81\%$ lower field intensity and the 4.5 dB worst-case peak to $\approx 40\%$ lower. Each frequency sweep is repeated three times, and the maximum deviation of the peak field is taken as the repeatability indicator; the opening-plus-solder group shows a deviation within 1.5 dB. The radiated-emission improvement is reported here only as a secondary confirmation of the solder-buildup method; the primary electromagnetic-compatibility targets of this work are electrostatic-discharge and spatial electromagnetic immunity levels, for which the onboard sensor is the verified figure of merit.

4.3 Onboard-sensor error characterization under electrostatic discharge

The port-level verification in Sect. 4.2 does not by itself establish sensor reliability, because the figure of merit of the codesign is the reading of the onboard angle sensor. The sensor output is therefore characterized under both threats for four cumulative protection configurations: configuration 1, the TVS circuit in Sect. 3.1 alone; configuration 2, the TVS plus solder-mask

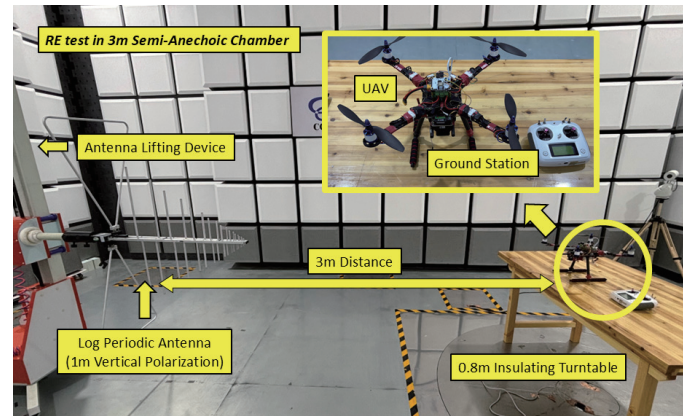


Fig. 9. (Color online) RE test scenario in semi-anechoic chamber.

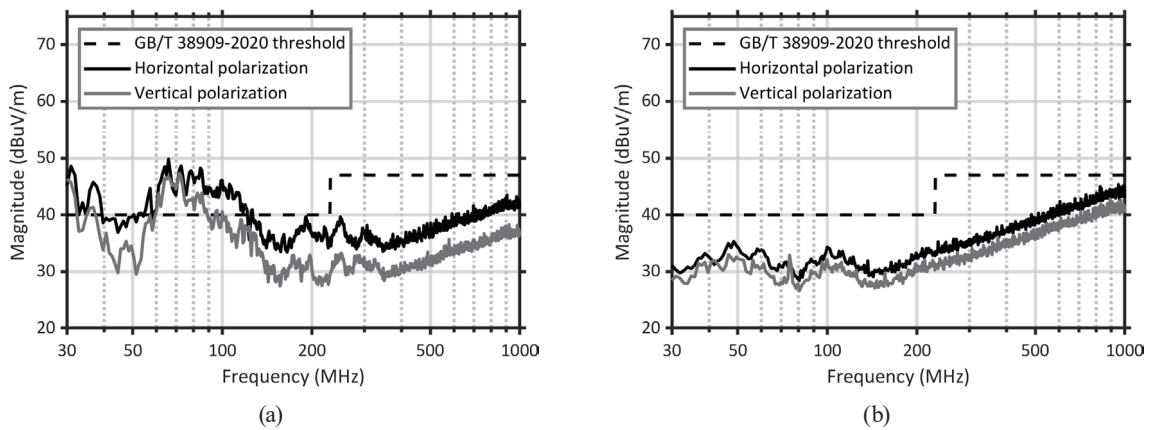


Fig. 10. Radiated field results for two solder-treated board configurations: (a) power board with opening and (b) power board with opening and solder buildup.

opening; configuration 3, configuration 2 plus solder buildup, i.e., the best board treatment verified in Sect. 4.2; and configuration 4, configuration 3 plus the embossed shielding patch of Sect. 4.1 that encloses the flight-control compartment and the sensor harness. An unprotected reference that carries none of the four measures is measured for comparison, so that the contribution of each layer is separated; its values are summarized in Table 5, and it is omitted from the figures of this section so that the ordinate scale remains readable.⁽²¹⁾ That earlier study covered only the board-level discharge path, whereas the present one additionally evaluates the spatial electromagnetic threat, the repeated-endurance behaviour under both threats, and the sensor-level figures of merit, so that the two are complementary rather than equivalent.

For the conducted threat, the IEC 61000-4-2:2025 Level 4 air discharge of 15 kV is applied to the externally accessible metal parts of the vehicle frame, twenty discharges per test point with a 2 min interval and grounding between discharges, while the angle-sensor output is read continuously. Three metrics are extracted from each discharge record: the peak PWM signal jump, the peak attitude deviation, and the attitude recovery time, defined as the interval from the

Table 5

Onboard-sensor peak error under Level 4 air discharge and 70 V/m spatial exposure.

Metric	Unprotected	Config. 1 (TVS)	Config. 2 (+ opening)	Config. 3 (+ solder)	Config. 4 (+ embossed shield)
ESD: PWM signal jump (V)	± 0.70	± 0.45	± 0.32	± 0.20	± 0.18
ESD: attitude deviation ($^{\circ}$)	± 5.0	± 3.6	± 2.4	± 1.2	± 1.0
ESD: recovery time (s)	3.2	2.1	1.3	0.6	0.5
RS: PWM signal jump (V)	± 1.40	± 1.05	± 0.95	± 0.85	± 0.12
RS: attitude deviation ($^{\circ}$)	± 11.8	± 9.5	± 8.9	± 8.3	± 1.1
RS: recovery time (s)	8.5	6.2	5.6	4.8	0.7

Note: the $\pm$ sign denotes the bidirectional peak of the sensor error and is not an uncertainty. The tabulated values are the mean over twenty discharges (ESD rows) or over ten vehicles (RS rows); the minimum–maximum dispersion about the mean, retained as the repeatability indicator, is plotted as the error bars of Figs. 11 and 13 and is, at most, ± 0.06 V, $\pm 0.40^{\circ}$, and ± 0.30 s for the ESD rows and ± 0.10 V, $\pm 0.60^{\circ}$, and ± 0.50 s for the RS rows (configurations 1 to 4; the unprotected reference is not plotted in Fig. 11 or 13).

discharge instant until the attitude error re-enters the $\pm 0.5^{\circ}$ band. Each metric is averaged over the twenty discharges, and the minimum–maximum spread is retained as the repeatability indicator. The results are summarized in Fig. 11 and Table 5.

Under the discharge, the unprotected reference exhibits a PWM jump of approximately ± 0.70 V and an attitude deviation of approximately $\pm 5.0^{\circ}$, with a recovery time of 3.2 s. The four configurations improve the sensor output monotonically: the suppressor alone (configuration 1) reduces the jump to ± 0.45 V and the deviation to 3.6° ; the solder-mask opening (configuration 2) further reduces them to ± 0.32 V and 2.4° ; the solder buildup (configuration 3) reaches ± 0.20 V and 1.2° , reproducing the best board-level result in Sect. 4.2 at the sensor level; and the complete stack (configuration 4) attains ± 0.18 V and 1.0° , because the embossed enclosure additionally attenuates the field radiated by the discharge arc. The recovery time shortens from 3.2 to 0.5 s over the same sequence, and only configurations 3 and 4 hold the attitude deviation within the 1.5° control tolerance of the flight-control loop. The unprotected deviations in Table 5 are recoverable functional upsets rather than hardware destruction. The discharge is applied to the externally accessible metal parts of the frame rather than to the sensor pin itself, so the injected current returns through the airframe and only a fraction of the coupled energy, far below the energy of a direct discharge to the sensor input, reaches the sensor harness; a single event therefore perturbs the sensor reading without destroying the front end, which is the standard expectation of criterion B under IEC 61000-4-2. Damage accumulates only over repeated events, and the single-event results are complemented by those of the repeated-endurance assessment in Sect. 4.4, where all ten unprotected vehicles fail with a median survival of 14 events.

For the spatial threat, the same four configurations are exposed to the synthesized 900 MHz plane wave of Sect. 4.1 at the maximum field strength of 70 V/m; the test scenario of radiated susceptibility (RS) in the anechoic chamber is shown in Fig. 12. Ten vehicles per configuration are exposed, the same three metrics are extracted during a 60 s exposure, and the results are summarized in Fig. 13 and Table 5. The three metrics are averaged over the ten vehicles, and the minimum–maximum spread across vehicles is retained as the repeatability indicator and plotted as the error bars of Fig. 13.

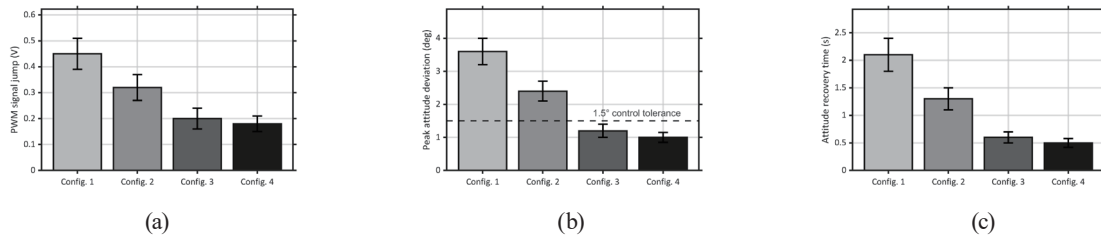


Fig. 11. Onboard-sensor error under Level 4 air discharge (15 kV, sensor port): unprotected reference and four cumulative protection configurations. (a) Peak PWM signal jump, (b) peak attitude deviation, and (c) attitude recovery time.

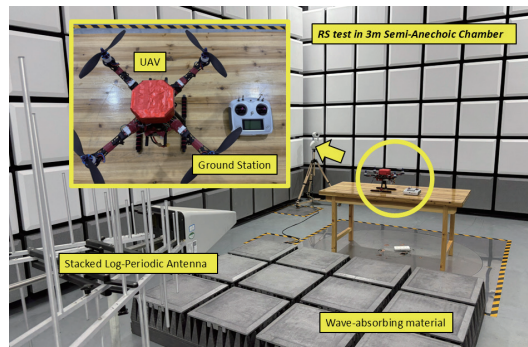


Fig. 12. (Color online) Spatial electromagnetic-immunity test scenario in the anechoic chamber.

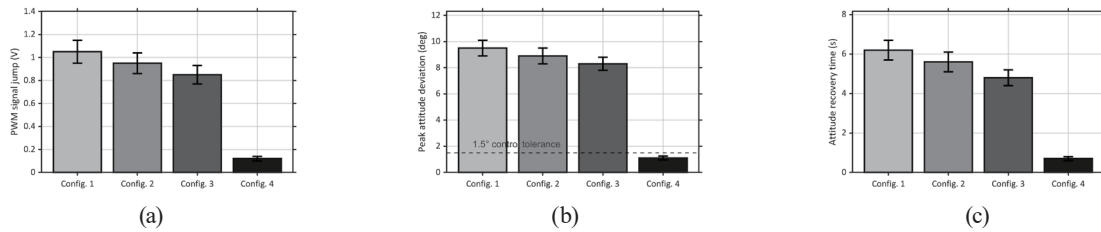


Fig. 13. Onboard-sensor error under 70 V/m. (a) Peak PWM signal jump, (b) peak attitude deviation, and (c) attitude recovery time.

The board-level measures alone are insufficient against the radiated threat: the unprotected reference reaches a PWM jump of ± 1.40 V and an attitude deviation of $\pm 11.8^\circ$, with an 8.5 s recovery, whereas configurations 1–3 reduce the deviation only marginally (9.5, 8.9, and 8.3°, respectively), because the dominant coupling path is the unshielded sensor harness rather than the printed-circuit-board pads; configuration 1 indeed reproduces the unshielded curve in Fig. 6(a) at 70 V/m. Configuration 4 changes the regime entirely: the jump falls to ± 0.12 V and the attitude deviation to approximately 1.1° , consistent with the embossed-Cu curve in Fig. 6(a), and the recovery time shortens from 8.5 to 0.7 s. The enclosure-level shield therefore contributes nearly an order of magnitude to attitude error under the radiated threat, in contrast to its marginal contribution under the conducted threat.

The two sets of results indicate complementary roles of the two protection layers: the board-level measures (suppressor, opening, and solder buildup) dominate the conducted electrostatic-discharge threat, whereas the embossed enclosure dominates the radiated threat. Only the complete stack of configuration 4 keeps the onboard sensor within the flight-control tolerance under both threats, which is the central claim of the sensor-oriented codesign.

The ESD protection schematic and the physical image of the main-control board for the sensor-port protection are shown in Fig. 14. The clamping voltage waveforms of the protected configuration are shown in Fig. 15 for the power port and the sensor port under the Level 4 contact (8 kV) and air (15 kV) discharge in Sect. 4.2. Each trace starts from the operating level of the respective port, 12 V at the power port and 5 V at the sensor port, and the suppressor holds the port voltage at its clamping level while the discharge current flows. Only the first 250 ns is resolved in the figure; the return to the operating level proceeds through the damped ringing of the harness inductance and is completed within approximately 110 μ s at the power port, as listed in Table 3.

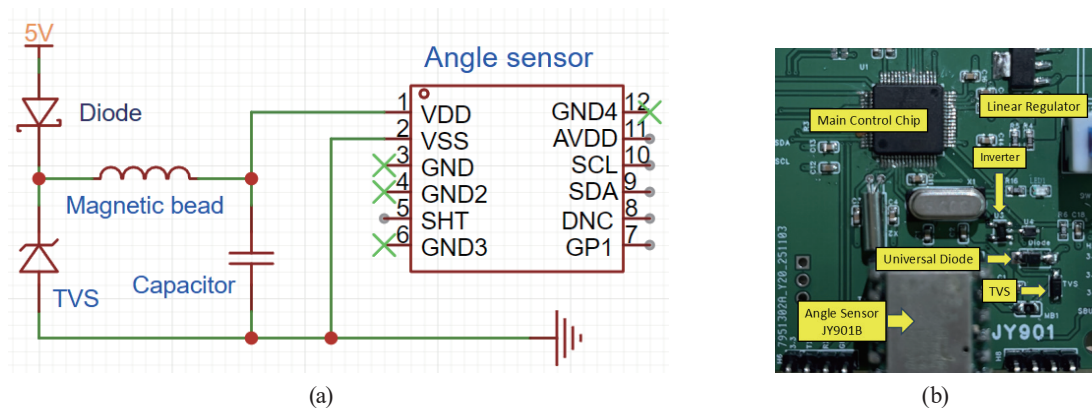


Fig. 14. (Color online) (a) Protection circuit for angle sensor on main-control board and (b) physical image of main-control board for the protected group.

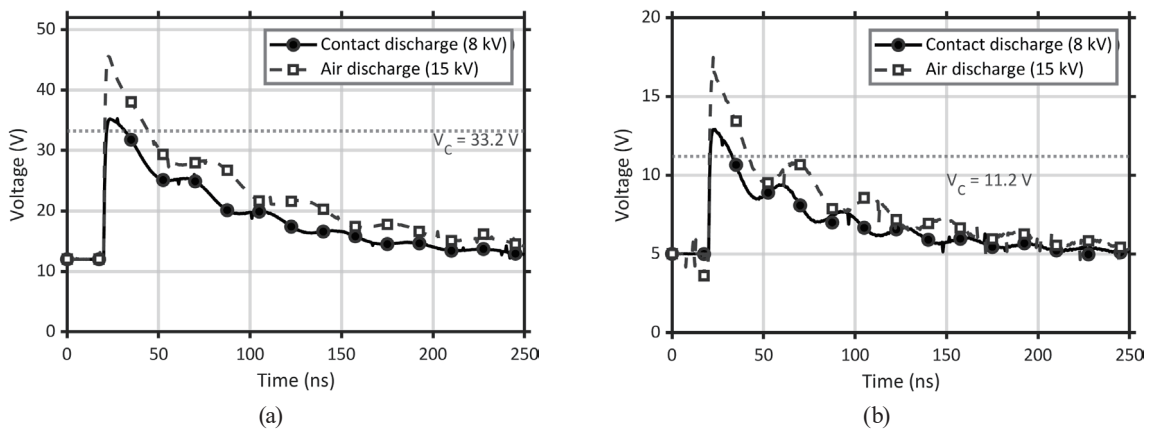


Fig. 15. Clamping voltage waveforms for ESD tests. (a) Level 4 ESD discharge: power port and (b) Level 4 ESD discharge: sensor port.

4.4 Repeated electrostatic-discharge endurance and reliability assessment

A single ESD event verifies clamping, but onboard protection in field service is subjected to many discharge events in humid or charged environments. To answer the repeated-endurance concern, the Kaplan–Meier survival framework is adopted for the repeated ESD reliability assessment.⁽²²⁾ Because the superiority of the opening-plus-solder board over the opening-only board is already established in Sects. 4.2 and 4.3, the endurance assessment now compares four groups in order to separate the contribution of the TVS front end from that of the complete board-level codesign: forty vehicles are assigned, ten unprotected (control group), ten protected only by the TVS front end (configuration 1 of Sect. 4.3), ten built to the full codesign of Sect. 4.3 with an embossed Cu patch, and ten with an embossed Al patch. Each vehicle is subjected to the repeated IEC 61000-4-2:2025 Level 4 air discharge applied to the externally accessible metal parts, with a 2 min interval between discharges and grounding between tests, up to 100 events or until failure. Failure is defined as irreversible degradation: a clamping voltage exceeding 1.5 times the rated value, a latch-up of the angle-sensor front end, or an attitude deviation exceeding 5° that does not re-enter the ±0.5° band within 10 s. The 100-event endurance campaign also exercises the TVS under cumulative pulse heating; no thermal runaway or parameter drift was observed, indicating the adequate margin of the 33.2 V/996 W device.

The survival time T is defined as the number of discharge events from the first impulse to irreversible failure. The Kaplan–Meier reliability estimator is given by

$$\hat{R}(t) = \prod_{t_j \leq t} \left(1 - \frac{d_j}{n_j} \right), \quad (1)$$

where d_j is the number of boards failing at the t_j -th event and n_j is the number at risk immediately before t_j . Boards that do not fail by the end of the test are treated as right-censored. The standard error of the estimate is computed by Greenwood's formula, and the 95% confidence interval is constructed by the log-log transformation so that the bounds remain within [0, 1].⁽²³⁾

The reliability curves of the four groups are shown in Fig. 16. The control group fails in all ten vehicles between the 3rd and 44th events with a median survival of 14 events, so $R(100) = 0$ (all units fail by the end of the test). The TVS-only group shows six failures (at the 36th, 47th, 58th, 67th, 76th, and 86th events) and four survivors right-censored at the 100th event, reaching $R(100) = 0.40$ (standard error: 0.155) with a median of 76 events. The two full-design groups degrade only marginally: the Cu-patch group shows two failures (at the 87th and 95th events) and the Al-patch group two failures (at the 90th and 98th events), both reaching $R(100) = 0.80$ (standard error: 0.126). The Cu and Al curves are nearly coincident, indicating that the conducted-discharge endurance is governed by the board-level measures described in Sect. 4.2 rather than by the patch metal.

The statistical significance is tested by the log-rank (Mantel–Cox) test.⁽²⁴⁾ The overall four-group comparison yields $\chi^2 = 59.5$ ($df = 3$, $p < 0.001$), rejecting the null hypothesis of identical survival functions at the 0.05 level. Pairwise, the control group fails about 20.1 times as fast as

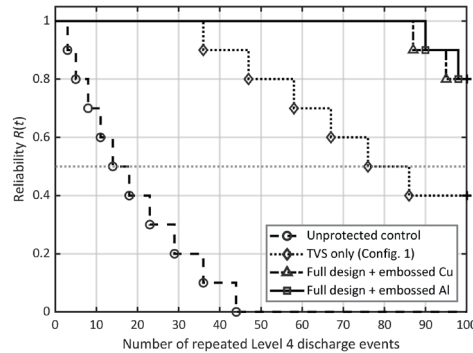


Fig. 16. Kaplan–Meier reliability curves under repeated Level 4 ESD.

the TVS-only group ($HR = 20.13$, $p < 0.001$), 26.2 times as fast as the Cu-patch group ($HR = 26.19$, $p < 0.001$), and 26.2 times as fast as the Al-patch group ($HR = 26.19$, $p < 0.001$), confirming that the front-end suppressor alone significantly extends the discharge endurance yet remains far less durable than the complete codesign. The TVS-only group in turn fails about 4.7 times as fast as either the full-design group ($HR = 4.67$, $p = 0.036$), which attributes the remaining endurance margin to the board-level opening-plus-solder measures. The Cu-versus-Al comparison is not statistically significant ($\chi^2 = 0.00$, $p = 0.956$, $HR = 1.06$), confirming that the patch metal does not participate in the conducted-discharge endurance. The log-rank statistics are listed in Table 6.

4.5 Repeated radiated-susceptibility endurance and reliability assessment

Repeated ESD endurance was quantified in Sect. 4.4; the spatial electromagnetic threat must be assessed with the same statistical rigor because field exposure during realistic missions varies in intensity and duration. A field-ramp method is designed: the 900 MHz field-ramp protocol in Sect. 4.1 (0 to 70 V/m in steps of 5 V/m, with the attitude error recorded at each step) is applied. Failure is defined as an attitude deviation exceeding 1.5° , the attitude-error tolerance of the flight-control loop; the shielded vehicles in Sect. 4.1 hold the error below approximately 1.2° up to 61 V/m. The comparison is deliberately limited to three groups, because the suppressor front end shunts a discharge injected onto the conductor, whereas the spatial threat couples into the sensor loop and is countered by the shield; a suppressor-only vehicle therefore carries no mechanism against the coupled field and is not retested here. Ten unshielded vehicles (control group), ten vehicles built to the full codesign in Sect. 4.3 with an embossed Al patch, and ten with an embossed Cu patch are assigned, and the ramp is repeated ten times per vehicle, with the recorded attitude error averaged over the repetitions.

The survival time is defined as the field-step count at which the attitude error first exceeds 1.5° . The Kaplan–Meier estimator in Sect. 4.4 is reused, with the event axis relabeled from discharge count to field-step count. The reliability curves are shown in Fig. 17. The unshielded control fails predominantly between the 4th and 6th steps (20–30 V/m), with the median at the

Table 6

Log-rank test statistics for repeated ESD endurance (4 groups, $n = 10$ per group).

Comparison	χ^2	df	p value	HR	Direction
Overall (4 groups)	59.5	3	<0.001	—	—
Control vs TVS only	19.55	1	<0.001	20.13	Control $\rightarrow$ TVS
Control vs Cu patch	21.84	1	<0.001	26.19	Control $\rightarrow$ Cu patch
Control vs Al patch	21.84	1	<0.001	26.19	Control $\rightarrow$ Al patch
TVS only vs Cu patch	4.42	1	0.036	4.67	TVS $\rightarrow$ Cu patch
TVS only vs Al patch	4.42	1	0.036	4.67	TVS $\rightarrow$ Al patch
Cu patch vs Al patch	0.00	1	0.956	1.06	Not significant

Note: $p < 0.05$ indicates significance; $HR > 1$ means the first-named group has higher instantaneous failure risk; df means degrees of freedom.

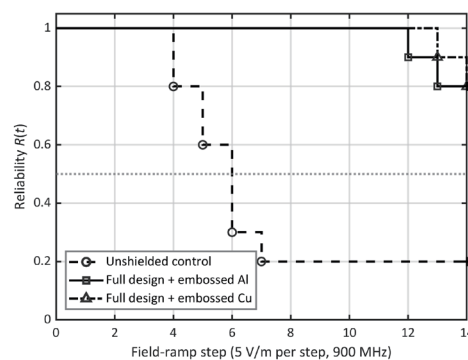


Fig. 17. Kaplan–Meier reliability curves under ramped base-station field exposure (900 MHz, 0–70 V/m; $n = 10$ per group).

5th step (25 V/m), below the 30 V/m field at which uncontrolled descent is reported, and reaches $R(14) = 0.20$ (standard error: 0.127). The two shielded groups reach $R(14) = 0.80$ (standard error: 0.127), with the Al-patch group failing at the 12th and 13th steps (60–65 V/m) and the Cu-patch group at the 13th and 14th steps (65–70 V/m).

The log-rank test yields an overall three-group statistic of $\chi^2 = 12.1$ ($df = 2$, $p = 0.002$). Pairwise, the unshielded control fails about 5.2 times as fast as the Al-patch group ($HR = 5.21$, $p = 0.014$) and 5.9 times as fast as the Cu-patch group ($HR = 5.90$, $p = 0.009$), whereas the Cu-versus-Al comparison is not statistically significant ($\chi^2 = 0.28$, $p = 0.598$). The Cu–Al difference visible in the mean attitude error in Fig. 6(a) therefore does not translate into a statistically significant survival difference under the 1.5° criterion; the patch metal is consequently selected by the added mass rather than by the survival margin. The statistics are listed in Table 7.

5. Discussion

The suppressor voltages selected in this work, a 33.2 V clamping voltage at the power port and an 11.2 V clamping voltage at the sensor port, are consistent with the reported robustness of epitaxial TVS devices, which withstand IEC 61000-4-2 stresses up to ± 19 kV while keeping the

Table 7

Log-rank test statistics for repeated RS immunity (3 groups, $n = 10$ per group).

Comparison	χ^2	df	p value	HR	Direction
Overall (3 groups)	12.1	2	0.002	—	—
Control vs Al patch	6.02	1	0.014	5.21	Control $\rightarrow$ Al patch
Control vs Cu patch	6.90	1	0.009	5.90	Control $\rightarrow$ Cu patch
Al patch vs Cu patch	0.28	1	0.598	1.35	Not significant

Note: $p < 0.05$ indicates significance; $HR > 1$ means the first-named group has higher instantaneous failure risk; df means degrees of freedom.

leakage current at the nanoampere level. Compared with prior system-level ESD studies that emphasized transient energy absorption, the present design explicitly allocates the absorbed energy to a single front-end TVS and verifies the allocation. The waveform model follows an established equivalent-circuit approach and reproduces the standard air-discharge Level 4 current waveform within the tolerances specified in Table 2 for the ideal specification. Relative to prior UAV electromagnetic-interference reviews in which bulk-current-injection susceptibility was discussed, in the present work, we provide a concrete component-plus-layout solution with direct sensor-error verification.

The RE reduction achieved by the solder-reinforced opening, 14.6 dB for the dominant low-band emission and 4.5 dB in worst-case peak field, is of the same order as the broad-band reductions reported for electromagnetic-bandgap structures, exceeding 10 dB, and for lightweight PCB shields. However, those methods add dedicated layers or shields that increase mass, whereas the present solder-buildup method adds less than 5 g. The adopted double-layer solder-mask opening plus solder buildup is preferred over a multilayer redesign because the latter raises board mass and fabrication cost disproportionately to the EMC gain for a mass-critical airframe. RE suppression is treated as a secondary benefit of the solder-buildup process rather than as a separately optimized objective.

The embossed shield proposed in Sect. 4.1 differs from the above RE methods in that it targets spatial immunity under external base-station fields rather than only self-emission. The field-exposure result (attitude error below approximately 1.2° up to 61 V/m for Al and approximately 1.0° for Cu) directly answers the reported sensor-reliability concern that uncontrolled descent occurs above 30 V/m. The present codesign thereby covers both self-generated disturbances (ESD and RE) and exogenous spatial interference, which previous UAV EMC studies addressed separately. The embossed shield admits either Cu or Al as the patch metal, and the choice is a trade-off rather than an absolute advantage of one metal: Cu gives the higher shielding effectiveness and the lower temperature rise, whereas Al attains an RF shielding effectiveness within 6 dB of Cu with roughly one-third of the added mass (Sect. 4.1). The survival assessment results in Sects. 4.4 and 4.5 reveal that the two are statistically indistinguishable in endurance, so the selection is driven by the payload-mass budget of the airframe rather than by shielding or reliability. The Cu patch used for the demonstrator is therefore a representative choice, and Al remains an equally valid option where mass is the binding constraint.

The repeated-endurance assessments in Sects. 4.4 and 4.5 answer the long-term reliability concern under both threats. Under repeated discharge the endurance improves in the same layered order as the single-event results: the front-end suppressor raises the median survival from 14 to 76 events, and only the complete board-level codesign pushes it beyond the 100-event ceiling (overall $\chi^2 = 59.5$, $df = 3$, $p < 0.001$), whereas the patch metal is not significant ($p = 0.956$). Under the spatial ramp, the same conclusion holds, with both shielded groups at $R(14) = 0.80$ against 0.20 for the unshielded control (overall $\chi^2 = 12.1$, $df = 2$, $p = 0.002$) and Cu and Al again indistinguishable ($p = 0.598$), so the patch metal is selected by mass rather than by endurance. The endurance axis is the cumulative event count rather than the flight hour: eight of the ten full-design vehicles survive 100 Level 4 discharges, and the mission duration to which this corresponds is obtained by dividing the endurance count by the discharge-event rate of the intended operating environment, which is not specified by the standard and is therefore treated as an application-specific input rather than assumed here.

6. Conclusions

A sensor-oriented electromagnetic protection scheme for a quadrotor UAV, where a TVS and PCB trace optimization were integrated, was proposed. Compliance with GB/T 38909-2020 was confirmed by ESD and RE tests, and the protection of the onboard angle sensor and flight-control microcontroller was verified by a measured attitude-error reduction from approximately 5° to 1.0° under Level 4 ESD (15 kV air). To exceed the 10 V/m limit of conventional standards, a spatial electromagnetic-immunity concept based on an embossed metal shielding layer was designed and verified under base-station field exposure up to 61 V/m, with the attitude error held below approximately 1.2° (Al) and 1.0° (Cu), and the dimpled relief was shown to keep the enclosure temperature within the 20°C budget. Repeated-endurance reliability under both ESD and spatial field was quantified by the Kaplan–Meier framework; the four-group ESD comparison clarified the contribution of the front-end suppressor from that of the complete board-level codesign, and the three-group spatial-field comparison isolated the contribution of the shielding patch. The full designs with either Cu or Al patches survived far beyond the unprotected and unshielded cases (log-rank $p < 0.001$ for ESD, $p = 0.002$ for spatial field), and the Cu-versus-Al difference was statistically insignificant in both assessments, so either metal is acceptable and the embossed Cu patch was used as the typical representative in this work. The codesign improved the EMC of the UAV while adding less than 5 g of mass.

Future work includes the following. (i) The Kaplan–Meier endurance assessments in Sects. 4.4 and 4.5 will be extended with larger sample populations and longer test campaigns to tighten the reliability confidence intervals, and with a site-specific discharge-event rate, so that the endurance count is reported as a mission duration. (ii) The codesign will be extended to other multirotor platforms with different power architectures. (iii) The spatial-electromagnetic-immunity test will be repeated across additional base-station frequency bands and field-exposure geometries.

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Author contribution

Conceptualization, Yifan Qian; methodology, Yifan Qian; software, Yang Cao; validation, Zhanglong Nie; writing—original draft preparation, Yifan Qian; project administration, Zhanglong Nie; funding acquisition, Yifan Qian. All authors have read and agreed to the published version of the manuscript.

References

- 1 W. Hao, Z. Pan, X. Li, R. Miao, Z. Yue, and A. Wang: IEEE Electron Device Reviews **2** (2025) 32. <https://doi.org/10.1109/EDR.2024.3516656>
- 2 Z. Zhang, Y. Zhou, Y. Zhang, and B. Qian: Electronics **13** (2024) 393. <https://doi.org/10.3390/electronics13020393>
- 3 D. -W. Lai, G. de Raad, S. Sque, W. Peters, and T. Smedes: IEEE Trans. Electron Devices **66** (2019) 2884. <https://doi.org/10.1109/TED.2019.2917264>
- 4 Y. Zhang, C. Shao, Q. Li, J. Zhu, and H. Zhao: IEEE Trans. Ind. Electron. **72** (2025) 11580. <https://doi.org/10.1109/TIE.2025.3591685>
- 5 H. Kunz: IEEE Trans. Electromagn. Compat. **67** (2024) 1401. <https://doi.org/10.1109/TEMC.2025.3576324>
- 6 A. Rufiyanto, G. Hendranto, and E. Setijadi: IEEE Trans. Electromagn. Compat. **67** (2025) 1035. <https://doi.org/10.1109/TEMC.2025.3568544>
- 7 S. Scheier, F. Nieden, B. Arndt, and S. Frei: IEEE Trans. Electromagn. Compat. **57** (2015) 1309. <https://doi.org/10.1109/TEMC.2015.2442623>
- 8 Y. Duan, C. Yang, D. Zhang, Y. Gao, Y. Sun, and J. Si: IEEE Trans. Electron Devices **72** (2025) 1617. <https://doi.org/10.1109/TED.2025.3545011>
- 9 P. K. Papastamatis, E. P. Nicolopoulou, C. A. Christodoulou, and I. F. Gonos: IEEE Trans. Electromagn. Compat. **67** (2025) 739. <https://doi.org/10.1109/TEMC.2025.3560614>
- 10 Y. Yano, S. Ishihara, H. Ito, and J. Wang: IEICE Trans. Commun. E108-B (2025) 1006. <https://doi.org/10.23919/transcom.2024MCP0009>
- 11 F. -P. Xiang, E. -P. Li, X. -C. Wei, and J. -M. Jin: IEEE Trans. Electromagn. Compat. **57** (2015) 1197. <https://doi.org/10.1109/TEMC.2015.2414174>
- 12 S. Shahparnia and O. M. Ramahi: IEEE Trans. Electromagn. Compat. **46** (2004) 580. <https://doi.org/10.1109/TEMC.2004.837671>
- 13 M. S. Sarto, S. Di Michele, and P. Leerkamp: IEEE Trans. Electromagn. Compat. **44** (2002) 300. <https://doi.org/10.1109/temc.2002.1003401>
- 14 R. Kubacki, R. Przesmycki, M. Bugaj, and D. Laskowski: Electronics **14** (2025) 4332. <https://doi.org/10.3390/electronics14214332>
- 15 A. Concannon: IEEE Solid-State Circuits Mag. **15** (2023) 58. <https://doi.org/10.1109/MSSC.2023.3298872>
- 16 D. Bouangeune, W. -K. Hong, S. -S. Choi, C. -J. Choi, D. -H. Cho, J. M. Park, J. H. Lee, H. -D. Yang, and K. -H. Shim: IEEE Glob. Conf. Consum. Electron. (2012) 189. <https://doi.org/10.1109/GCCE.2012.6379575>
- 17 Y. Liu, Y. Lei, X. Guo, J. Yang, Z. Luo, and C. Yang: IEEE Int. Conf. Electron. Packag. Technol. (2024) 1. <https://doi.org/10.1109/ICEPT63120.2024.10668412>
- 18 National Electromagnetic Compatibility Standardization Technical Committee: GB/T 17626.2-2018. <https://www.chinesestandard.net/PDF.aspx/GBT17626.2-2018>
- 19 International Electrotechnical Commission: IEC 61000-4-2:2025. <https://webstore.iec.ch/en/publication/68954>
- 20 State Bureau of Technical Supervision: GB/T 38909-2020. <https://www.chinesestandard.net/PDF/English.aspx/GBT38909-2020>
- 21 Y. Qian, Z. Wu, R. Tang, H. Qin, and F. He: Safety & EMC **3** (2026) 72. <https://d.wanfangdata.com.cn/periodical/aqydcjr202603009>

- 22 T. Wright, E. Nsiye, and S. Mondesire: Generalized vs. individualized Kaplan-Meier time-to-failure predictive models for preventive maintenance in semiconductor manufacturing. IEEE Int. Symp. Semicond. Manuf. (2024) 1. <https://doi.org/10.1109/ISSM64832.2024.10874918>
- 23 C. Legrand: Advanced Survival Models. (Boca Raton, FL, USA) (CRC Press, 2021).
- 24 J. Gu, Y. Zhang, and G. Yin: Bayesian log-rank test: Am. Stat. **77** (2023) 292. <https://doi.org/10.1080/00031305.2022.2161637>

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