

Solar Rooftop Inspection Drone for Dust Detection and Energy Meter Monitoring: Design and Pre-Flight Feasibility Analysis

Dr. M. Ahmed¹, Safal Meshram², Himaanshu Mule³,
Nihal Dinesh Waghade⁴, Lokesh Wade⁵, Sujwal Waghmare⁶

¹Project Guide, Department of Electrical Engineering

²⁻⁶B.Tech. Final Year Students, Department of Electrical Engineering
Priyadarshini College of Engineering, Nagpur, Maharashtra, India

Abstract: Rooftop solar plants in Indian cities are seldom inspected once commissioned, partly because checking the array or reading the generation meter means climbing onto the roof. This paper describes a low-cost first-person-view (FPV) quadcopter built to inspect rooftop photovoltaic (PV) arrays for dust and to read energy meters from the air, and asks a question that hobby-grade surveillance builds usually skip: can the chosen hardware meet the mission objectives? The airframe uses a KK2.1.5 flight controller, four 1400 KV motors with 8-inch propellers, a 3S 2200 mAh Li-Po battery, a FlySky 2.4 GHz radio and a 5.8 GHz analog video link to an Android phone. Using momentum theory, free-space link budgets and camera ground-sampling geometry, we estimate a hover endurance of 6.7 to 9.1 min, a control range of about 0.87 km and a video range of 0.46 to 0.80 km at the required fade margins, against a stated objective of 1.5 km. The FPV camera can screen modules for soiling from up to 6 to 11 m, but reading 9 mm meter digits would require flying within 0.2 m of the meter. The paper turns these findings into a safe inspection envelope, an ordered upgrade path and a flight-test protocol for validation.

Keywords: UAV inspection, rooftop photovoltaics, soiling, FPV video link, link budget, ground sampling distance, energy meter reading, quadcopter endurance.

I. INTRODUCTION

Rooftop photovoltaic (PV) systems have become a familiar sight on Indian homes, schools and small commercial buildings. Once commissioned, however, many of them are looked at only when the monthly generation figure disappoints. A common cause of quiet loss between services is dust. Ilse et al. estimated that soiling reduces global solar power production by at least 3 to 4% even with optimised cleaning, a loss worth at least 3 to 5 billion euro a year [1], and reviews of field studies report much larger losses at individual dusty sites [2].

Checking a rooftop array is simple in principle, but in practice it means climbing onto a roof that often has no guard rail, and reading a generation or net meter installed near the inverter can require the same climb. For a building owner, for an installer who services many small sites, or for a utility verifying net-metered output, a quick look from the air is attractive.

Unmanned aerial vehicles (UAVs) already do this kind of work on large PV plants. Light UAVs carrying visual and thermal cameras have been demonstrated for plant inspection [3], aerial infrared thermography of PV modules is covered by an IEC technical specification [4], and convolutional neural networks (CNNs) can estimate soiling loss and locate soiled regions from ordinary RGB images [5]. Automatic reading of meter counters with CNNs is also well developed [6]. Most of this work assumes a capable platform with a stabilised digital camera and an onboard or ground-station computer [7], [8]. Student-built FPV quadcopters cost a fraction of that, and several have been reported



for surveillance [9], [10], but their papers describe the build and report success in qualitative terms. They do not state how far the drone can fly, how long it stays up, or how much detail actually reaches the operator's screen.

This paper reports the design stage of such a low-cost FPV quadcopter, built by a final-year team in the Department of Electrical Engineering, Priyadarshini College of Engineering, Nagpur, for two rooftop tasks: spotting dust on PV modules and reading the energy meter. The project set four objectives at the outset: (i) a self-built, autonomous aerial platform for real-time monitoring; (ii) a surveillance radius of at least 1.5 km; (iii) a flying height of at least that of a five-storey building; and (iv) use of the platform for rooftop dust detection and meter reading. Fig. 1 shows the block diagram of the drone. The airframe and the video system have been assembled, and flight tests are scheduled. Before flying, we wanted to know whether the hardware on the bench could meet each objective and, if not, what would have to change.

The contributions of the paper are:

- a documented reference design for a low-cost FPV inspection quadcopter assembled from parts that student teams in India can readily buy;
- a pre-flight analysis that ties each objective to a physical budget: hover power and endurance from momentum theory, radio link margin from free-space path loss, and image detail from ground sampling distance;
- an objective-by-objective verdict stating which goals the present hardware meets, which it cannot, and the smallest change that would close each gap; and
- a safe inspection envelope and a flight-test protocol that will be used to validate the analysis.

Section II reviews related work. Section III describes the system, and Section IV presents the pre-flight analysis. Section

V sets out the inspection envelope and the test protocol, Section

VI discusses the findings, and Section VII concludes the paper.

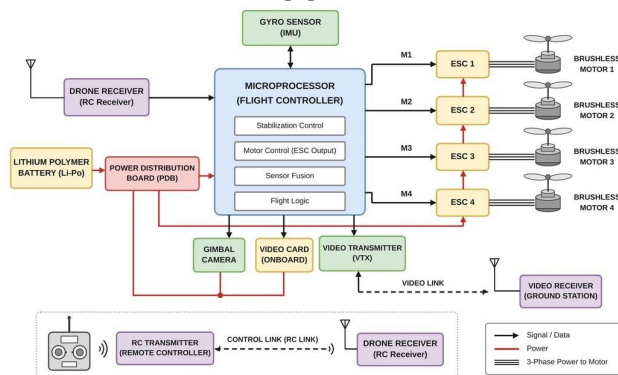


Fig. 1. Block diagram of the inspection drone.

II. RELATED WORK

A. Soiling and Its Detection

Dust on the module glass reduces the light reaching the cells, and the size of the loss depends on climate, tilt, particle type and cleaning interval [2]. Menoufi reviewed published soiling experiments and found them hard to compare, because each used its own PV technology, test equipment and way of reporting results; he proposed a Photovoltaic Soiling Index to put them on a common footing [11]. On the imaging side, Mehta et al. trained a fully convolutional network on more than 45,000 panel images to predict power loss and to localise soiling without pixel-level labels, running at 22 frames per second on a desktop GPU [5]. These results show that soiling is visible in RGB images, but they were obtained from clear digital pictures rather than through an analog video link.



B. UAV Inspection of PV Plants

Quater et al. showed that light UAVs carrying visual and thermal cameras can work together to inspect PV plants [3], and IEC TS 62446-3 sets out requirements for outdoor infrared thermography of PV modules and plants [4]. Thermal imaging is the established way to find hot spots and failed cells. Soiling, however, is mainly an optical problem, so a visible-light camera is the natural first sensor for a low-cost rooftop drone.

C. Real-Time Detection From UAV Imagery

Cao et al. reviewed 77 studies of real-time object detection from UAV remote sensing [7]. Seventy-two of them used edge computing; multirotor platforms and RGB cameras dominated; the NVIDIA Jetson TX2 was the most common processor; and most systems ran between 1 and 30 frames per second. Wang et al. adapted YOLOv8 to the many small objects in aerial images by adding a Wise-IoU v3 box loss, a BiFormer attention block and a Focal FasterNet feature-fusion module. On VisDrone2019 their model raised mean detection accuracy by 7.7% over the baseline while using fewer parameters [8]. Bird droppings and isolated dust patches on a module are small objects in exactly this sense.

D. Low-Cost FPV Surveillance Quadcopters

The builds closest to ours are student projects. Tauseef et al. assembled an FPV quadcopter around a KK2.1.5 flight controller with 1000 KV motors, 30 A ESCs, a 2200 mAh Li-Po battery and a FlySky FS-i6 radio, streaming a 1200TVL camera to a phone through an OTG receiver [9]. Vijaya Kanth et al. described an RC-controlled surveillance drone with a live FPV camera and a MobileNet object detector trained on COCO, and reported a mean average precision of 0.75, a precision of 0.82 and a recall of 0.78 for the detector [10]. Table I compares these builds with ours. Neither reports flight time, link range or the image resolution that reaches the operator, and these are the quantities that decide whether an inspection drone is useful.

E. Meter Reading

Laroca et al. treated automatic meter reading as a two-stage problem, detecting the counter with Fast-YOLO and recognising the digits with a CNN, and released the 2000-image UFPR-AMR dataset [6]. In India, the Revamped Distribution Sector Scheme (RDSS) aims to replace consumer meters with 250 million prepaid smart meters; by March 2025 about 13.4 million were communicating [12]. Until a site is covered by the roll-out, its meter still has to be read by eye, so visual reading from the air remains a reasonable use case.

TABLE I : COMPARISON WITH RELATED LOW-COST BUILDS

Feature	Tauseef et al. [9]	Vijaya Kanth et al. [10]	This work
Flight controller	KK2.1.5	Not specified	KK2.1.5
Propulsion	4 × 1000 KV, 30 A ESCs	Four high-RPM motors	4 × 1400 KV, 30 A ESCs, 8 in props
Video	1200TVL, OTG to phone	FPV camera, live feed	1000TVL, 5.8 GHz, OTG to phone
Application	General surveillance	Surveillance, object detection	PV soiling, meter reading
Quantitative budget	Not reported	Detector metrics only	Endurance, link margin, GSD (Sec. IV)

III. SYSTEM DESIGN

A. Hardware Architecture

Fig. 2 shows the system, and Fig. 3 shows the assembled quadcopter. The airframe is an F450-class quadcopter with a plastic frame and an integrated power distribution board. Four A2212/10T 1400 KV brushless motors turn 8 × 4.5 in propellers in counter-rotating pairs, each driven by a 30 A electronic speed controller (ESC). A 3S 2200 mAh 60C Li-Po pack (11.1 V nominal, 24.4 Wh) supplies the ESCs and the video transmitter, and a plug-in cell monitor with a buzzer warns of low voltage. A FlySky FS-CT6B six-channel transmitter talks to an FS-R6B receiver at 2.4 GHz using



frequency hopping (AFHDS). The KK2.1.5 flight controller reads the receiver, fuses the MPU6050 gyroscope and accelerometer on an 8-bit ATmega644PA, and drives the four ESCs.

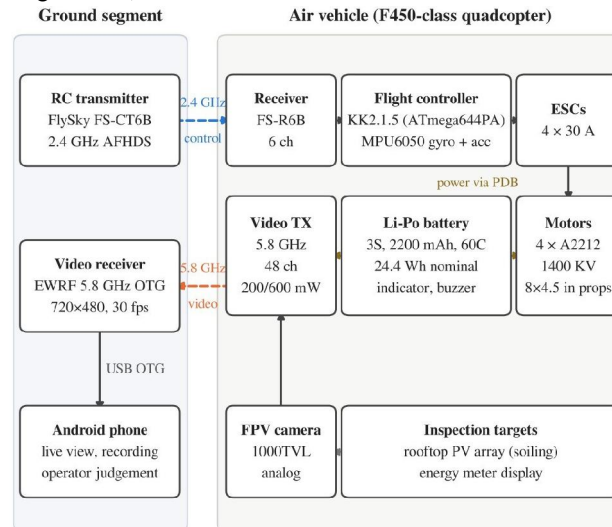


Fig. 2. System architecture. Solid arrows are wired signal and power paths; dashed arrows are the 2.4 GHz control link and the 5.8 GHz video link.

The camera is a 1000TVL analog FPV unit feeding a 48-channel 5.8 GHz transmitter rated at 200 mW or 600 mW. On the ground, an EWRF OTG receiver scans the channels, digitises the picture at 720×480 pixels and 30 frames per second, and shows it on an Android phone over USB with a quoted latency of about 100 ms. The phone also records the video for later review.



Fig. 3. The assembled quadcopter (F450-class frame).

One property of the flight controller shapes everything that follows. The KK2.1.5 levels the aircraft but has no barometer, magnetometer or satellite receiver [13]. It therefore cannot hold altitude or position, return home or fly a waypoint route; the pilot controls height and position by eye and through the FPV view.

Table II lists the airborne components with typical masses from manufacturer listings. Vendor listings for the A2212 motor do not agree on its mass, and we use 55 g per motor. The total is 960 g. The analysis uses a rounded all-up mass of 1.0 kg, which lies inside the 0.8 to 1.6 kg take-off range given for the F450 frame [14]. The actual mass will be measured before the first flight (Section V).



TABLE II : AIRBORNE COMPONENTS AND MASS BUDGET

Item	Specification	Mass (g)
Frame	F450-class, 450 mm, integrated PDB	282
Motors	4 × A2212/10T, 1400 KV	220
ESCs	4 × 30 A	100
Propellers	4 × 8 × 4.5 in, CW and CCW	32
Battery	Li-Po 3S, 2200 mAh, 60C	185
Flight controller	KK2.1.5, ATmega644PA, MPU6050	21
RC receiver	FlySky FS-R6B, 6 channels	15
Video payload	1000TVL camera, 5.8 GHz transmitter	30
Alerts	Buzzer, battery indicator	15
Wiring	Leads, connectors, straps	60
Total	Analysis value: 1.0 kg	960

B. Inspection Concept

The operator stands at ground level or on a neighbouring roof, launches the drone, climbs above the parapet and moves over the array. The FPV camera, fixed at the front of the frame, gives an oblique view of the modules, and the operator judges dust coverage on the phone screen while the pass is recorded. For a meter, the drone is brought in front of the meter display. Section IV examines whether each of these steps is physically achievable with the present parts.

IV. PRE-FLIGHT ANALYSIS

A. Requirements

We first restated the objectives as numbers that can be checked:

- Range: reach 1.5 km, spend at least 3 min on station and land with 1 min in reserve.
- Height: exceed a five-storey building, about 16 m at 3.2 m per storey, while staying below the 120 m (400 ft) ceiling of the green zone under the Drone Rules, 2021 [15], [16].
- Control link: keep at least 20 dB of fade margin, which covers a Rayleigh fade with 99% probability [17].
- Video link: stay at least 10 dB above the receiver threshold so that the analog picture is free of noise. This figure is our working assumption.
- Soiling: at least 6 pixels across a 182 mm cell for module screening, a ground sampling distance (GSD) of 30 mm per pixel or finer; at least 4 pixels across a 40 mm bird dropping for local soiling, or 10 mm per pixel.
- Meter: single-phase static meters supplied to MSEDCL must have digits of at least 9×5 mm [18]. We ask for 16 pixels of digit height for reliable reading (0.56 mm per pixel) and treat 8 pixels as the bare minimum (1.1 mm per pixel).
- Stand-off: keep at least 2 m from walls, parapets and modules, to allow for gusts and propeller clearance.

B. Hover Power and Endurance

Momentum theory gives the ideal induced power of a rotor in hover [19]. With all-up mass m shared by four rotors, each rotor carries $T = mg/4$ and needs

$$P_i = T^{3/2} / (2\rho A)^{1/2} \quad (1)$$

where A is the disc area and ρ the air density. The electrical power drawn from the battery is

$$P_e = 4P_i / (FM \eta_m \eta_e) + P_{aux} \quad (2)$$

where FM is the rotor figure of merit, η_m and η_e are the motor and ESC efficiencies, and P_{aux} covers the camera, video transmitter, receiver and flight controller. The endurance in minutes is



$$t = 60 k E / P_e (3)$$

with E the nominal battery energy in Wh and k the usable fraction.

For Nagpur, about 310 m above sea level, at 30 °C the air density is close to 1.12 kg/m³. An 8 in propeller sweeps $A = 0.0324$ m². With $m = 1.0$ kg, each rotor carries 2.45 N, and (1) gives 14.2 W per rotor, or 57.0 W in total. Full-size helicopter rotors reach figures of merit of about 0.7 to 0.8 [19]; small fixed-pitch propellers working at low Reynolds number do worse, and we bracket FM between 0.50 and 0.60. Motor efficiency is taken as 0.70 to 0.80, ESC efficiency as 0.95 and Paux as 3.5 W. With $k = 0.8$, so that the pack is not drained below about a fifth of its capacity, the 24.4 Wh battery offers 19.5 Wh. Table III gives the results. The drone needs 128 to 175 W to hover, a battery current of 11.6 to 15.7 A, and stays up for 6.7 to 9.1 min, with 7.9 min as the nominal figure. The current is only 5 to 7 C for a 60C pack and under 4 A per motor for 30 A ESCs, so neither part is stressed. Vendor data for the A2212/10T motor give about 550 g of static thrust with an 8×4.5 in propeller on 3S [20]. That is a thrust-to-weight ratio of 2.2 at 1.0 kg, so hover needs about 45% of the available thrust and leaves a fair reserve for gusts.

The height objective is easy to meet: climbing to 16 m at 2 m/s takes 8 s. The range objective is not. At a cruise speed of 8 m/s, and taking cruise power equal to hover power, which is a conservative simplification at moderate speed, the 1.5 km trip out and back takes 6.25 min. That leaves 0.6 min on station in the nominal case and nothing in the pessimistic case. If 3 min on station and a 1 min reserve are required, the endurance supports a radius of 650 to 1230 m, about 930 m nominally.

TABLE III: HOVER POWER, ENDURANCE AND MISSION RADIUS

Quantity	Optimistic	Nominal	Pessimistic
Figure of merit, FM	0.60	0.55	0.50
Motor efficiency, η_m	0.80	0.75	0.70
Electrical power (W)	128	149	175
Battery current (A)	11.6	13.4	15.7
Current per motor (A)	2.8	3.3	3.9
Discharge rate (C)	5.3	6.1	7.2
Hover endurance (min)	9.1	7.9	6.7
Time on station at 1.5 km (min)	1.9	0.6	none
Radius with 3 min on station (m)	1230	930	650

C. Radio Links

Both links were checked with the free-space path loss [17]

$L_{fs} = 20 \log_{10} d + 20 \log_{10} f + 32.44$ (4) with d in km and f in MHz, and the link margin

$$M = P_t + G_t + G_r - L - L_{fs} - S \quad (5)$$

where P_t is the transmitter power, G_t and G_r are the antenna gains, L lumps polarisation mismatch, airframe shadowing and cable loss, and S is the receiver sensitivity. Table IV lists the inputs. For the control link we used the manufacturer's figures for the FS-CT6B and FS-R6B (output below 20 dBm, sensitivity -105 dBm) and 0 dBi for the short wire antennas. The sensitivity of the video receiver is not published, so we assumed -90 dBm, the typical value for the widely used RX5808 5.8 GHz receiver module [21]. L was set to 6 dB on both links.

TABLE IV: LINK BUDGET INPUTS AND RESULTS

Parameter	Control, 2.4 GHz	Video, 5.8 GHz
Transmitter power	20 dBm	23.0 / 27.8 dBm (200 / 600 mW)
Antenna gains, Tx / Rx	0 / 0 dBi	2 / 2 dBi (8 dBi patch option)
Implementation loss L	6 dB	6 dB
Receiver sensitivity S	-105 dBm	-90 dBm (assumed)



Required margin	20 dB	10 dB
Path loss at 1.5 km	103.7 dB	111.2 dB
Margin at 1.5 km	15.3 dB	-0.2 / 4.6 dB (10.6 dB with patch)
Range at required margin	0.87 km	0.46 / 0.80 km (1.60 km with patch)

At 1.5 km the control signal arrives at -89.7 dBm, 15.3 dB above sensitivity but short of the 20 dB we asked for. The required margin holds out to 0.87 km, which agrees with the 500 to 1000 m range the manufacturer quotes for this radio. The video link is the tighter constraint (Fig. 4). At 200 mW its margin at 1.5 km is -0.2 dB, so the picture would be lost; the 10 dB requirement holds only to 0.46 km. At 600 mW the limit moves to 0.80 km. Replacing the receiver whip with an 8 dBi directional patch adds 6 dB, which doubles the free-space range and gives 10.6 dB of margin at 1.5 km.

These are free-space figures and are optimistic over a city. On a 1.5 km path the first Fresnel zone has a radius of 6.8 m at mid-path at 2.4 GHz and 4.4 m at 5.8 GHz, so with the drone at roof height and the operator at street level, trees, water tanks and neighbouring buildings will intrude into it and add loss. Range also runs into regulation. At about 1 kg the drone falls in the micro category (250 g to 2 kg), which must be registered on the Digital Sky platform, although no remote pilot licence is needed for non-commercial use, and airspace close to an airport is a yellow zone where permission is required [16]. A drone of this size is also hard to keep in sight at a kilometre.

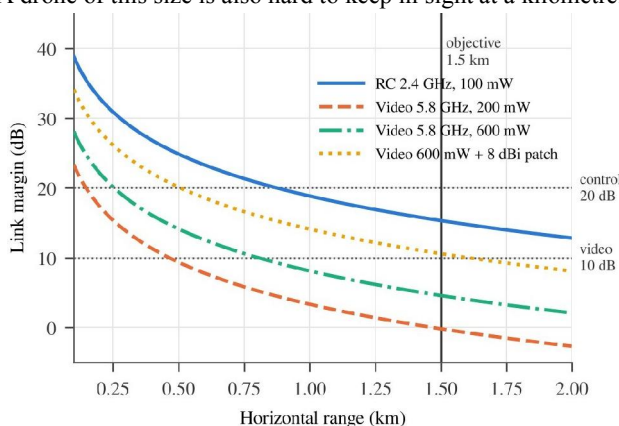


Fig. 4. Free-space link margin against range for the control link and three video configurations. Dotted lines mark the required margins; the vertical line marks the 1.5 km objective.

D. Imaging Geometry

The ground sampling distance of a camera with N pixels across a horizontal field of view θ at distance d is

$$\text{GSD} = 2d \tan(\theta/2) / N \quad (6)$$

The receiver digitises 720 pixels per line, so $N = 720$ sets an upper bound on the detail the operator can see; analog noise and bandwidth will lower it further. The field of view of the kit lens is not stated, so we evaluated 90° and 120° , which bracket typical FPV lenses, together with two digital cameras with a 40° field, one 1080p and one 4K (Fig. 5, Table V).



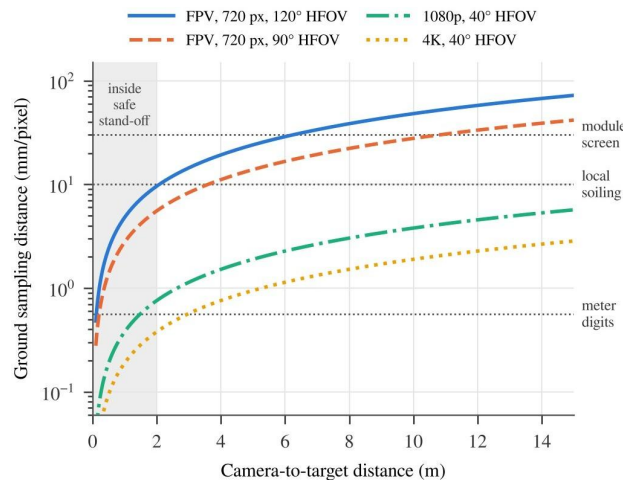


Fig. 5. Ground sampling distance against distance for the FPV camera and two digital alternatives. Dotted lines mark the requirements of Section IV-A; the shaded band lies inside the 2 m stand-off.

TABLE V: MAXIMUM CAMERA DISTANCE FOR EACH TASK

Task (required GSD)	FPV 90°	FPV 120°	1080p 40°	4K 40°
Module screening (30 mm/px)	10.9 m	6.3 m	80 m	160 m
Local soiling (10 mm/px)	3.6 m	2.1 m	26 m	53 m
Meter, 16 px (0.56 mm/px)	0.20 m	0.12 m	1.48 m	2.97 m
Meter, 8 px (1.1 mm/px)	0.41 m	0.23 m	2.97 m	5.93 m

For screening a module, the FPV camera is adequate. Cells resolve to 6 pixels or more from up to 10.9 m with a 90° lens and 6.3 m with a 120° lens, comfortably beyond the stand-off. Local soiling needs the drone within 3.6 m (90°) or 2.1 m (120°), which is practical only with the narrower lens. Meter reading is a different matter. Sixteen pixels of digit height require a distance of 0.20 m with a 90° lens and 0.12 m with a 120° lens, and even 8 pixels need 0.41 m and 0.23 m, all well inside the stand-off. The FPV camera therefore cannot read a meter safely. At a 3 m stand-off the field of view would have to shrink to 7.7° with 720 pixels, 20.4° with 1080p or 39.6° with 4K; a 4K camera with a 40° lens reaches 16 pixels per digit at 2.97 m.

Two further effects matter in the field. The first is the rotor wake. Momentum theory puts the induced velocity at the disc at $(T/2\rho A)^{1/2}$, about 5.8 m/s here, and the far wake approaches twice that [19]. A drone hovering a metre or two above a dusty module can blow loose dust and leaves about and alter the very thing it is inspecting, which is one more reason to view the array obliquely from the side rather than from straight above. The second is glare. A module is a sheet of glass, and when the camera sits near the mirror direction of the sun the analog sensor saturates. Choosing a viewing direction that keeps the sun's reflection out of the frame avoids the problem.

E. Objective-by-Objective Verdict

Table VI brings the budgets together. The platform objectives are met, the 1.5 km radius is not, dust detection is met in part, and meter reading is not met with the present camera.

TABLE VI: OBJECTIVES AGAINST THE PRESENT HARDWARE

Objective	Finding	Verdict	Smallest change
Self-built real-time platform	Airframe and FPV chain assembled	Met, flight test pending	None
Autonomous operation	No barometer, compass or satellite receiver on the KK2.1.5	Not met	Flight controller with satellite positioning and barometer



Radius of 1.5 km	Video 0.46 to 0.80 km, control 0.87 km, endurance 0.65 to 1.23 km	Not met	Directional ground antenna, long-range control radio, 4000 mAh pack
Height of five storeys (about 16 m)	8 s climb, thrust-to-weight 2.2, below 120 m ceiling	Met (manual height control)	Barometer for altitude hold
Dust detection	Screening up to 6.3 to 10.9 m; local soiling within 2.1 to 3.6 m	Partly met	Narrower lens or digital camera, onboard recording
Meter reading	Needs 0.12 to 0.20 m with the FPV camera	Not met	1080p or 4K camera with a 40° lens

V. INSPECTION ENVELOPE AND FLIGHT-TEST PROTOCOL

A. Inspection Envelope

Putting the budgets together gives an envelope that the present drone can fly with margin:

- Radius: up to 0.4 km with the 200 mW setting, or 0.7 km at 600 mW, in clear line of sight. Video, not endurance, is the limit.
- Transit height: 20 to 30 m above ground, above the surrounding roofs and far below the 120 m ceiling.
- Inspection: 3 to 6 m from the plane of the array, viewed obliquely from the side away from the sun's reflection, with no low hover directly over the modules.
- Flight time: land at 6 min, which keeps a margin over the pessimistic endurance.
- Meters: not attempted with the FPV camera.

B. Flight-Test Protocol

Table VII lists the tests that will validate the analysis. Every test will be run three times or more, and the measured values will replace the assumptions behind Tables II to V.

TABLE VII PLANNED VALIDATION TESTS

#	Test	Method	Output
1	Mass and thrust	Weigh the aircraft; thrust stand for one motor up to hover throttle	Mass (g), hover current (A)
2	Endurance	Hover in calm air until the pack rests at 3.7 V per cell	Flight time (min)
3	Control range	Ground range check, then flights in steps to 0.8 km in an open field	Range (m)
4	Video range	200 and 600 mW, whip and patch antennas; note where noise appears	Range (m)
5	Field of view	Photograph a 1 m scale from 2 m	HFOV (°)
6	Resolution	Bar target at 2, 3, 5 and 8 m	Smallest bar seen (mm)
7	Soiling detection	Graded dust on one module of a string; compare operator calls with string current	Detection rate, loss (%)
8	Meter reading	Meter display at 2 and 3 m	Digits read correctly (%)

VI. DISCUSSION

The analysis brings out something that is easy to miss when a project is planned around a surveillance range: on this drone the airframe and battery are not the weak point. The motors offer about twice the thrust needed, the battery and ESCs run far below their ratings, and the height objective is met with room to spare. What limits the mission is the camera and the video link, the two parts that decide what the operator can actually see.



That ordering also sets the upgrade path. The first priority is a 1080p or 4K digital camera with a 40° lens that records onboard, so that meters can be read and soiling graded from the recording rather than the live feed. The second is a flight controller with satellite positioning, a barometer and a compass, running open-source autopilot software, to hold altitude and position over the array, fly repeatable passes and return home on signal loss; this is also what the “autonomous” objective requires. The third concerns the links: a directional patch at the ground station is the cheapest 6 dB available, and a long-range control radio is worth adding only if flights beyond 0.8 km are really needed. Last comes the battery. By the same model, a 3S 4000 mAh pack would raise the nominal endurance to about 11.8 min at an all-up mass of about 1.14 kg, keeping the thrust-to-weight ratio near 1.9. Once digital video is recorded, the detection methods reviewed in Section II become usable. A small-object detector of the UAV-YOLOv8 type [8] could flag droppings and dust patches, and a DeepSolarEye-style network [5] could estimate loss from the image, both running at the ground station in the edge-computing arrangement that most real-time UAV systems use [7]. Running either on 720-pixel analog video would be wasted effort. There is a commercial point as well. As smart prepaid meters are rolled out under RDSS [12], aerial meter reading becomes a bridging use for legacy meters on hard-to-reach roofs rather than a lasting product. Soiling inspection has the stronger case, because dust returns every dry season whatever meter is installed. The analysis has limits. Component masses are typical values, the figure of merit and the efficiencies are assumed ranges, the propagation model is free space with a fixed 6 dB implementation loss, and the camera field of view is unknown. The tests in Table VII are designed to replace each of these assumptions with a measured number.

VII. CONCLUSION

We have described a low-cost FPV quadcopter for inspecting rooftop PV arrays and energy meters, and checked its objectives against physical budgets before its first flight. The airframe, propulsion and battery are adequate: hover needs about 149 W, the nominal endurance is 7.9 min (6.7 to 9.1 min), the thrust-to-weight ratio is about 2.2, and flying above a five-storey building is straightforward. The 1.5 km radius is out of reach. The stock video link supports 0.46 km at 200 mW and 0.80 km at 600 mW, the control link about 0.87 km, and the endurance leaves little time on station at that distance. The FPV camera can screen modules for dust from 3 to 6 m but cannot read a meter from a safe distance, whereas a digital camera with a 40° lens can. These findings define a safe envelope for the coming flight tests and a short, ordered list of upgrades led by the camera and the flight controller. The flight tests will replace the assumed values with measurements, and the next stage of the work will add recorded digital imagery and automated soiling detection.

ACKNOWLEDGMENT

The authors thank the Department of Electrical Engineering, Priyadarshini College of Engineering, Nagpur, for laboratory facilities and support during the project.

REFERENCES

- [1] K. Ilse et al., “Techno-economic assessment of soiling losses and mitigation strategies for solar power generation,” *Joule*, vol. 3, no. 10, pp. 2303–2321, Oct. 2019, doi: 10.1016/j.joule.2019.08.019.
- [2] T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, “A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches,” *Renew. Sustain. Energy Rev.*, vol. 22, pp. 698–733, Jun. 2013, doi: 10.1016/j.rser.2012.12.065.
- [3] P. B. Quater, F. Grimaccia, S. Leva, M. Mussetta, and M. Aghaei, “Light unmanned aerial vehicles (UAVs) for cooperative inspection of PV plants,” *IEEE J. Photovolt.*, vol. 4, no. 4, pp. 1107–1113, Jul. 2014, doi: 10.1109/JPHOTOV.2014.2323714.



- [4] Photovoltaic (PV) Systems: Requirements for Testing, Documentation and Maintenance, Part 3: Photovoltaic Modules and Plants, Outdoor Infrared Thermography, IEC TS 62446-3:2017, International Electrotechnical Commission, Geneva, Switzerland, 2017.
- [5] S. Mehta, A. P. Azad, S. A. Chemmengath, V. Raykar, and S. Kalyanaraman, "DeepSolarEye: Power loss prediction and weakly supervised soiling localization via fully convolutional networks for solar panels," in Proc. IEEE Winter Conf. Appl. Comput. Vis. (WACV), 2018, pp. 333–342, doi: 10.1109/WACV.2018.00043.
- [6] R. Laroca, V. Barroso, M. A. Diniz, G. R. Gonçalves, W. R. Schwartz, and D. Menotti, "Convolutional neural networks for automatic meter reading," J. Electron. Imag., vol. 28, no. 1, Art. no. 013023, 2019, doi: 10.1117/1.JEI.28.1.013023.
- [7] Z. Cao, L. Kooistra, W. Wang, L. Guo, and J. Valente, "Real-time object detection based on UAV remote sensing: A systematic literature review," Drones, vol. 7, no. 10, Art. no. 620, 2023, doi: 10.3390/drones7100620.
- [8] G. Wang, Y. Chen, P. An, H. Hong, J. Hu, and T. Huang, "UAV-YOLOv8: A small-object-detection model based on improved YOLOv8 for UAV aerial photography scenarios," Sensors, vol. 23, no. 16, Art. no. 7190, 2023, doi: 10.3390/s23167190.
- [9] S. Tauseef, M. M. Ali, A. Ahmed, and A. Aleem, "Surveillance quadcopter," Int. J. Res. Publ. Rev., vol. 5, no. 6, pp. 2366–2370, Jun. 2024.
- [10] T. Vijaya Kanth, G. Anjanee Devi, J. Sirisha, C. Venkateswarlu Reddy, and G. Viswa Sainath, "Surveillance drone with object detection," Int. J. Creative Res. Thoughts, vol. 12, no. 4, pp. d468–d473, Apr. 2024.
- [11] K. Menoufi, "Dust accumulation on the surface of photovoltaic panels: Introducing the Photovoltaic Soiling Index (PVSI)," Sustainability, vol. 9, no. 6, Art. no. 963, 2017, doi: 10.3390/su9060963.
- [12] Prayas (Energy Group), "Smart metering in India: A work in progress," Pune, India, 2025. [Online]. Available: <https://energy.prayaspune.org/power-perspectives/smart-metering-in-india-a-work-in-progress>
- [13] "KK2.1.5 multirotor LCD flight control board," product specification, Flying Tech. [Online]. Available: <https://www.flyingtech.co.uk/product/kk2-1-5-multirotor-lcd-flight-control-board/> (accessed Oct. 14, 2026).
- [14] "DJI Flame Wheel F450 ARF kit," product specification, GetFPV. [Online]. Available: <https://www.getfpv.com/dji-flamewheel-f450-arf-kit.html> (accessed Oct. 14, 2026).
- [15] Ministry of Civil Aviation, Government of India, "The Drone Rules, 2021," G.S.R. 589(E), Gazette of India, Aug. 25, 2021.
- [16] Press Information Bureau, Government of India, "Backgrounder: The Drone Rules, 2021," Jan. 2022. [Online]. Available: <https://static.pib.gov.in/writereaddata/specificdocs/documents/2022/jan/doc202212810701.pdf>
- [17] T. S. Rappaport, Wireless Communications: Principles and Practice, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2002.
- [18] Maharashtra State Electricity Distribution Co. Ltd., "Technical specification for LT single phase static energy meters," Spec. No. DIST/MM-IV/009, May 2008.
- [19] J. G. Leishman, Principles of Helicopter Aerodynamics, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 2006.
- [20] "A2212/10T 1400 KV brushless motor for drone," product data, Aryabot. [Online]. Available: <https://aryabot.in/a2212-10t-1400kv-brushless-motor-for-drone/> (accessed Oct. 14, 2026).
- [21] "RX5808 product specification," ver. 1.0, Sep. 2010. [Online]. Available: <https://mikrocontroller.net/attachment/172723/RX5808-Spec-V1.pdf>

