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Elevating Power Piping Inspections: Introducing Drones for Power Plant Pipe Hanger Surveys

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***Abstract*—Pipe hanger and support inspections are critical for maintaining the integrity and reliability of high-energy piping systems (HEP) in power plants. Conventional inspection methods, however, often face challenges such as limited accessibility to pipe hanger and support, safety risks, and high cost due to scaffold erections and time-consuming procedures. This paper presents feasibility study of initial application of unmanned aerial vehicles (UAVs), or drones, for inspecting pipe hangers at a thermal power plant. The initiative aimed to improve inspection efficiency, safety, and data quality—particularly for hanger locations that are difficult or unsafe to access manually. Challenges encountered during on-site implementation, such flight stability and condition changes are discussed. The results showed that the drone achieved full accessibility and coverage with 100% of planned hangers inspected in both boiler and turbine area, demonstrating scalability across different inspection scenarios. Most captured images provide sufficient visibility and resolution for visual inspection and defect detection during and after flight. Drone-based inspection also delivered significant safety benefits by reducing man-hours of exposure to risks compared to traditional scaffold-based method. These findings highlight the potential of drones to enhance HEP condition-based inspection practices in terms of safety, cost, and reliability in the power generation**

***Keywords*—Drone-based inspection, Pipe hangers and supports, Piping support systems, High-energy piping, Digital maintenance**

I. INTRODUCTION (HEADING 1)

High-energy piping (HEP) system is one of the critical components in power plants where it convey high-pressure steam (290 Bar) at high-temperature (612°C) during operation from boiler to the turbine. Weight of the pipe, thermal expansion and operation upset events generate enormous forces and stresses in the system. Pipe hanger and support systems play a critical role in maintaining the structural integrity and stress balance of HEP networks in power plants. Pipe hanger and support are often refer to any type of support, restraint or sway brace. The common categories of hanger support used in power plant are flexible supports, rigid supports, snubbers and sway braces, and dampers. Flexible supports such as variable (load) spring hanger, constant (load) spring hanger used helical coiled springs and bell crack lever arm to provide continuous supporting force from cold to hot cycle. Rigid supports such as restraint, guides, anchors or limit stop, are used in location where the pipe movement needs to be limited or must completely prevented. Snubbers and sway braces restrict the horizontal movement of the pipe through the use of rigid rods. They are shock absorbers that extend or retract to accommodate slow movement (thermal expansion or contraction) but lock under shock event (seismic or water hammer). Their performance directly affects load transfer, thermal expansion management, and the long-term reliability of boiler and turbine piping systems. American Society of Mechanical Engineers (ASME) B31.1, "Power Piping" provides guidance in Appendix V on displacement recording, documentation, marking and visual surveys [1, 2]. Although non-mandatory, these practices are essential for ensuring safe operation.

Conventional pipe hanger inspection methods, however, present multiple challenges. These include restricted accessibility to elevated supports, the need for scaffolding or rope access, significant man-hours, and safety risks to inspection personnel working at height or in confined areas. Moreover, manual visual inspections are often constrained by support position, condition (heat radiation) and location. These constraints may not provide comprehensive photographic or video records for condition monitoring and engineering analysis. Inaccessibility and photographic technique may limit the accuracy of reading support position indicators due to restrictions such as support poor viewing angle, tight space, poor lighting, sun glaring and dusty [2]. These limitations drive the need for alternative inspection approaches that can improve safety, efficiency, and data quality.

Recent advances in unmanned aerial vehicles (UAVs), or drones, have created opportunities to transform inspection practices in the power generation sector. Drones equipped with high-resolution cameras and stabilizing systems allow access to difficult or hazardous locations without the need for extensive scaffolding. In industrial applications, drones have been successfully applied in boiler inspections [3, 4], wind turbine blade inspection [5], bridge inspection [6, 7], power line assessments [8], construction sites [9, 10], road network inspection [11], and chemical process plant [12]. However, studies on their feasibility for pipe hanger inspections in high-energy piping systems remain limited.

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This paper presents a field-based case study on the introduction of drone for pipe hanger inspection at a 1000 MW thermal power plant. Multiple drone platforms were deployed, including DJI FPV with a customized protective cage and confined space drone Flyability Elios 3. The work was carried out under a structured Hazard Identification, Risk Assessment, and Determining Control (HIRADC) framework to ensure operational safety. Inspection path planning strategies were explored based on piping system grouping, hanger sequencing, spans, and distance with inspections conducted in both the outdoor boiler area and the indoor turbine hall. Distinct challenges were encountered in each environment, such as weather conditions, elevated hanger locations, confined spaces, low light, dust area, and obstacles (pipes, steel structures).

The objective of this paper is to evaluate the feasibility, benefits, and limitations of drone-assisted pipe hanger inspections through a field-base case study at thermal power plant. The findings aim to provide practical insights and recommendations for power plant operators seeking to adopt drone-based solutions for the condition monitoring of high-energy piping systems

II. PIPE HANGERS AND SUPPORTS

Pipe hangers and supports in HEP systems carry the combined loads of piping materials, insulation, contained fluid, live loads, wind, and seismic activity, in addition to thermal expansion effects. The pipe hangers and supports protect the piping systems from operation transient load such as steam hammer and water hammer events that generate enormous forces and stresses in the system. They are therefore vital in maintaining stresses within allowable limits and ensuring sufficient pipe movement between cold and hot operating conditions. When non-ideal condition of support system exists, considerable stresses can be created in the pipe and the terminal point connections (boiler header and turbine). These stresses can be elevated and causes degradation on the piping components and eventually lead to premature failure of the pipe welds [13] crack and leak.

Non-ideal conditions such as excessive travel deviation, overstressed snubbers, or fully extended piston, and pipe structural interferences can restrict thermal movement. Piping support system malfunction can be caused by degradation of the hanger/support condition such as wear of bearings, foreign material in the spring, spring metal degrades due to overloading, corrosion of bearings, and damage to hanger components due to dynamic load or other external load [14]. Operation transient conditions such as start-up, shut down and water hammer contribute to support degradation where the pipe can be deflected dramatically and does not return to its normal position. ASME B31.1., "Power Piping" prescribes requirements for inspection of piping systems in Section VII-Operation and Maintenance, states, "significant displacement variations from the expected design displacement shall be considered to assess the piping system's integrity" [1].

III. DRONE TYPES

In the field of pipe hanger inspection, the choice of drone type is crucial, as the different drone design offer varying capabilities in terms of manoeuvrability, stability, endurance, and resistance to environmental conditions. Most pipe hangers at a power plant are located above ground level, exposed to weather conditions (rain, glare, wind), surrounded by obstacles (pipes, steel beams), low light, dust, tight and narrow space, and in a hot environment of thermal radiation from steam pipes. All these factors need to be taken into account in choosing the suitable drone for inspection. There are three common types of drones that can be used for aerial inspection: fixed-wings, hybrid drones, and rotary-wing drones. The multi-rotor drones are more likely appropriate for pipe hanger inspection because it enables more stable hovering, vertical take-off and landing, and close-range flight environments such as power plants (5). The common designs such as quadcopter (four rotors), hexacopters (six rotors), and octocopters (eight rotors), with each configuration offering slightly different levels of stability and power (13). For the pipe hanger inspection, the quadcopter is the most preferable because they are small in size, agile, and precise manoeuvring and hovering in tight, confined and hazardous environments. Although multi-rotor drones have shorter endurance and lower payload capacity than fixed-wing or hybrid models, they remain the most suitable choice for industrial inspections where access, precision, and safety outweigh wide-area coverage

IV. FIELD TEST AND INSPECTION

This section discusses the field test method performed in this study. The inspection was performed on Main Steam pipe (MSP), Hot Reheat pipe (HRP) and Cold Reheat pipe (CRP) of a supercritical power plant unit. The MSP has a design pressure of 293 Bar and a design temperature of 603°C; the HRP has a design pressure of 57 Bar and 612°C design temperature; and the CRP has 59 Bar design pressure and 371°C design temperature. The targeted area to deploy drone inspection are at the boiler area (outdoor) and the turbine hall area (indoor). The boiler area. A total of 54 hangers identified as inaccessible for manual inspection were targeted for drone deployment. These were distributed across two main zones: (a) the outdoor boiler area, covering piping from the boiler header to the turbine hall wall, with hanger elevations of 5-15 m above operating platforms; and (b) the indoor turbine hall, where piping routes from the turbine wall penetration to turbine terminals. Safe take-off and landing zones for drone operations were established in both areas during a pre-inspection risk assessment.

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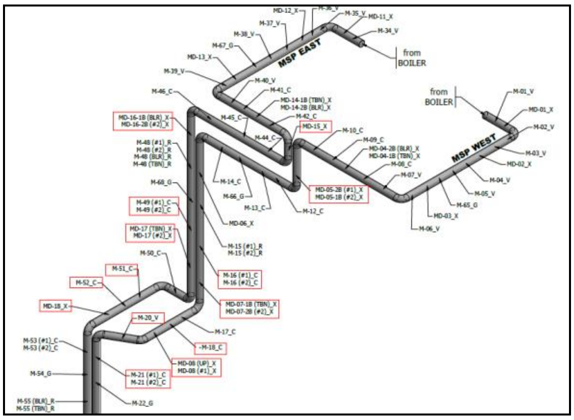

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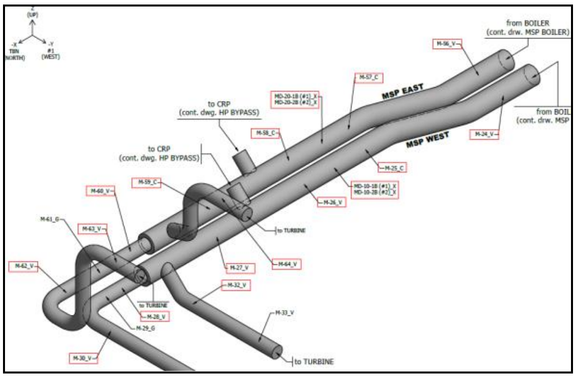

(b)

Figure 1. Example of MSP (a) boiler area and (b) turbine hall area with inaccessible and above ground pipe hangers and supports.

A. Inspection Zones

The inspection was divided into two primary areas:

- Boiler Area (Outdoor): Characterized by elevated hanger locations at heights of 5 to 15 meters, exposure to weather conditions (rain, glare, wind), surrounded by obstacles (pipes, steel beams) thermal radiation from steam pipes. The outdoor environment required careful scheduling to avoid adverse weather and minimize risks associated with unstable flight conditions.
- Turbine Hall Area (Indoor): Characterized by dark, dusty, surrounded by obstacles (pipes, steel beams), tight and narrow spaces with residual heat from steam pipes. Confined layouts limited drone manoeuvrability, requiring the use of drones with strong lighting, dust tolerance, and collision-resistant designs

B. Drone-based Pipe Hanger Inspection Procedure

The proposed drone-based pipe hanger inspection methodology comprises of 1) data collection, onsite risk assessment and flight path plan; 2) performing drone-based inspection; and 3) inspection data review. The main objective of this part are assessing risk and hazard at flying area and plan the inspection flight path. The other part is to evaluate appropriate drone for a particular purpose and, perform drone-based inspection. On the other hand, the focus of the second part is to identifying and assessing the condition of the piping system. As shown in Figure 1, several steps are performed in this study as the first try of introducing drone in pipe hanger inspection.

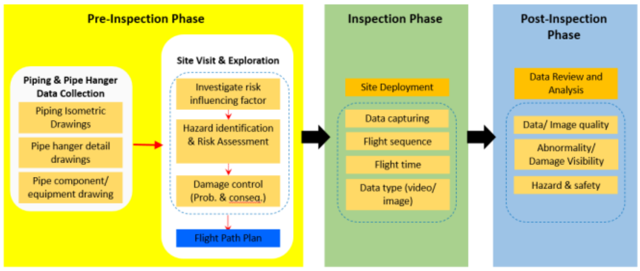

Figure 2. Drone-based inspection procedure.

C. Safety Framework and Preparatory Work (Pre-Inspection Phase)

Before commencing the inspection, a Hazard Identification, Risk Assessment, and Determining Control (HIRADC) exercise was conducted to ensure personnel and equipment safety. The assessment identified potential hazards such as falling objects, drone collision and obstacles, electrical proximity, steam pipe heat, poor visibility, and weather-related risks. For each hazard, risk levels were evaluated and appropriate control measures established, including the use of protective equipment, flight zone demarcation, restricted personnel access, and pre-flight checklists. This structured safety framework formed the foundation for all subsequent inspection activities

Activities	R/NR*	HAZARD IDENTIFICATION			RISK ASSESSMENT				DETERMINING CONTROL		
		Hazard	Consequences	Current Risk Ctrl	L/Hood	Severity	R/Level		Type of Ctrl	Further Action / Ctrl	PIC (Due Date)/Status
Drone-based pipe hanger inspection	NR	Poor weather: gust, strong wind, rain	Lost stability, poor visibility, damage drone	Operate in VLOS, check weather prior to operation	2	1	2	L	Admin Control & PPE	Limitation of working period	-
	NR	Dust/ rust	Dust Inhalation	PPE- face mask	1	1	2	L	Admin Control & Use PPE	Current risk control is adequate	-
	NR	Heat (about 40-50°C) from high temperature components	Skin burn, heat stress	Drone can stand up to 50°C	1	1	1	L	Admin Control & Use PPE	Current risk control is adequate	-
	NR	Falling Object	Physical Injuries	Wear safety helmet & safety shoes	1	2	2	L	Admin Control & Use PPE	Current risk control is adequate	-
	NR	Lost control of drone due to poor visibility, technical issue	Collision, drone could drop & damage	Plan and assign drone fly areas and paths	1	1	1	L	Admin Control	Current risk control is adequate	-
				Perform drone check & test prior to fly	1	1	1	L	Admin Control	Current risk control is adequate	-
				Perform emergency landing immediately	1	1	1	L	Admin Control	Current risk control is adequate	-
				Operate in VLOS	1	1	1	L	Admin Control	Current risk control is adequate	-
	NR	Drone hit structures	Drone lose control & could be damaged	Protect drone (blades) with cover, cage.	1	1	1	L	Admin Control	Current risk control is adequate	-

Figure 3. Example of the drone-based inspection risks assessment

D. Drone Platform Deployed

As stated in the Section 2, the quadcopter is the most preferable drone because they are small in size, agile, and precise manoeuvring and hovering in tight, confined and hazardous environments. Thus, two different drone platforms were deployed to accommodate different inspection environments and access requirements:

- DJI FPV (customized with protective cage): Enhanced collision tolerance and agility, suitable for elevated hanger locations in outdoor boiler areas.
- Flyability Elios 3: Purpose-built for confined-space inspections with a collision-tolerant spherical cage, integrated high-definition camera, and lighting system, ideal for dark and dusty turbine hall conditions

A summary of the technical specifications of these drones, relevant to pipe hanger inspection, is presented in Table 1. These specifications provided the basis for determining flight strategy, safety considerations, and data capture methodology.

TABLE I. TECHNICAL SPECIFICATIONS OF DRONES USED IN PIPE HANGER INSPECTION [15, 16]

Specification	DJI FPV	Flyability Elios 3
Configuration / Type	Quadcopter FPV drone	Ducted-fan quadcopter
Weight / Mass	~ 795 g (with propellers)	2,350 g (with LiDAR) / 1,900 g (without LiDAR)
Dimensions / Size	255 × 312 × 127 mm (with propellers)	48 × 38 cm (cage / envelope)
Flight Time / Endurance	Up to ~20 minutes in ideal conditions	~9 min with LiDAR, ~12 min without LiDAR, up to 17 minutes
Operating Temperature Range	0 °C to 40 °C	0 °C to 50 °C
Max Speed / Performance	Top speed ~39 m/s	Maximum speed ~7 m/s
Wind Resistance	Wind resistance ~13.8 m/s (approx.)	Wind resistance ~7 m/s
Camera / Resolution	1/2.3″ CMOS, 12 MP photo; supports 4K video at 60 fps	4K main camera + thermal; unobstructed 180° field of view

The use of multiple platforms allowed comparison of operational suitability across different situations and conditions. The choice of drones was guided by operational requirements such as confined-space accessibility, visual clarity, flight stability, and environmental tolerances. The platforms included a DJI FPV drone equipped with a customized protective cage and the Flyability Elios 3.

DJI FPV, originally designed for agile and fast flight, was adapted with a protective cage to enhance survivability during close-proximity inspection of high-energy piping. The Elios 3 was specifically engineered for industrial inspections in confined and hazardous environments, with collision-tolerant design and integrated lighting.

TABLE II. STRENGTH AND LIMITATION FEATURES OF DJI FPV AND ELIOS 3.

Feature	DJI FPV	Flyability Elios 3
Speed, Agility	High top speeds (in Manual mode), smooth responsiveness	Slower movement, smoother, controlled. Its speeds are modest
Durability / Collision Tolerance	Built strong but less protected (limitation). Limitation: Crashes especially at high speed often lead to damage.	Designed with collision tolerance: retractable structures, sensors to protect itself.
Operating Environments	Best in open outdoors, line-of-sight, good light, less obstacles. It has GPS in Normal mode etc.	Designed to work indoors, in GPS-denied settings, dark, dusty, confined spaces. Stable hover, sensors to stabilize in complex airflows.
Lighting & Visuals for Inspection	Good camera: 4K video, high frame rates. Limitation: No lighting for dark/dusty environments.	Strong lighting system (10,000 lumens), multiple modes (oblique light, selective, etc.).
Data / Inspection Features	Mainly video. Limitation: No photo	Strong inspection tools: distance-lock (to keep consistent distance from surfaces)
Safety & Worker Risk	Limitation: Less focused on reducing risk in hazardous/confined environments. crashes can be dangerous.	The protective cage helps avoid damage to both drone and surroundings.
Flight Time / Endurance	Battery life drops fast especially when flying aggressively.	Limitation: about 10 minutes in optimal conditions. In dark/dusty or with intense lighting, might be less.

E. Justification of Drone Selection

The boiler area inspections, carried out in outdoor conditions, required drones with longer flight endurance and stable imaging to capture multiple hanger points located at elevated positions (5 to 15 meters). The DJI FPV was deployed in this area as its higher flight speed, stability in open environments, and longer battery duration enabled wider coverage despite environmental challenges such as glare, dim light, wind, and obstacles.

In contrast, the turbine hall inspections involved dark, dusty, obstacles, and confined conditions where visibility and collision avoidance were critical. The Flyability Elios 3 was the primary choice for this environment due to its collision-tolerant cage, integrated lighting arrays, and dust-resistant design, allowing safe navigation around narrow clearances and piping clusters.

By assigning drones to environments that aligned with their technical strengths, the inspection team was able to maximize data collection efficiency while mitigating operational risks.

F. Inspection Path Planning

Path planning comprises defining an optimal flight path to ensure maximum coverage of pipe hangers while adhering to a range of operational constraints. These constraints are energy consumption, collision avoidance, inspection precision and data quality. Main purpose of path planning includes optimizing inspection coverage, minimizing power usage and ensuring safe operation near piping systems and power plant structures. Inspection routes were developed to balance efficiency, safety, and inspection coverage. Two primary strategies were assessed:

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- Piping system-based sequencing – inspecting hangers according to their associated piping system.
- Side-by-side hanger sequencing – inspecting adjacent hangers sequentially, leveraging their physical proximity

Vertical sequencing options were also considered, including inspections starting from lower elevations progressing upward and the reverse, starting from higher elevations downward. These path-planning strategies were assessed for practicality during field execution, considering drone battery endurance, visibility, and operator line of sight.

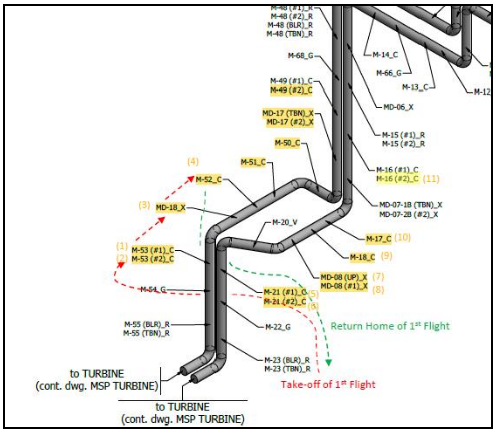
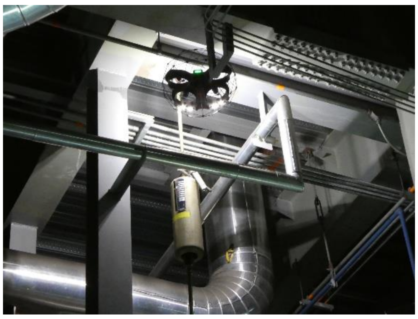


Figure 4. Example of path flight plan on a piping system.

(a)



(b)

Figure 5. Drone-based inspection at (a) boiler area and (b) turbine area.

V. RESULTS AND DISCUSSION

This study and inspections presented in this section were conducted at a boiler area (outdoor) and turbine hall area (indoor) of a thermal power plant unit. The results presented here aim at demonstrating that the method presented in Section 3 work in this particular environment. The results give an indication of the performance and feasibility level that can be achieved using manually piloted ready-made commercial drone.

A. Coverage and Accessibility

Out of the total 54 pipe hangers & supports were identified within the study area, the drone-based inspection successfully covered 54 hangers and supports (100%) as shown in Table 3 and Figure 7. Despite the environmental constraints in the boiler area such as dim light, glare, wind, obstacles and height (5 to 15 meters), pilot and inspector managed to overcome the challenges and manoeuvre the drones to the identified pipe hangers & supports. However, there is a hanger nameplate, travel scale and indicator not visible due to huge beam structure blocking drone to come close at accessible angle (Figure 6). Protective cage helps pilot to confidently manoeuvre drone close to pipe hanger and safe protect the drone and pipe components from major contact, impact and collision. Nevertheless, the achieved coverage demonstrates that quadcopter-based platforms are capable of inspecting the majority of pipe hangers, including those located at elevated positions of 15 meters.

In the turbine area, the lack of light constraint, obstacles, dust and heat are the main challenges in the hanger inspection. The pipe hangers' location and position are above ground level with height of about 5 meters, shorter spans and side by side among the piping systems. Thus, deploying a confined-space quadcopter drone such as the Elios 3 is favourable in this situation. Bright on board lighting on Elios 3, provide exceptional visibility for drone to manoeuvre avoiding obstacles and visual inspection on pipe hangers. Dust-proof is indispensable feature for drone-based inspection, enabling drone motors operation in dusty condition. Protective cage helps pilot to confidently manoeuvre drone close to pipe hanger and safe protect the drone and pipe components from major contact, impact and collision.

Figure 6. Huge beam structure restricting drone close approach to hanger.

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TABLE III. SUMMARY OF PIPE HANGERS AND SUPPORTS INSPECTION COVERAGE ASSESSMENT

Area	System	Planned Hangers	Inspected Hangers	Missed Hangers	Coverage (%)
Boiler	MSP	11	11	0	100
	HRP	13	13	0	100
	CRP	10	10	0	100
Turbine	MSP	11	11	0	100
	HRP	6	6	0	100
	CRP	3	3	0	100

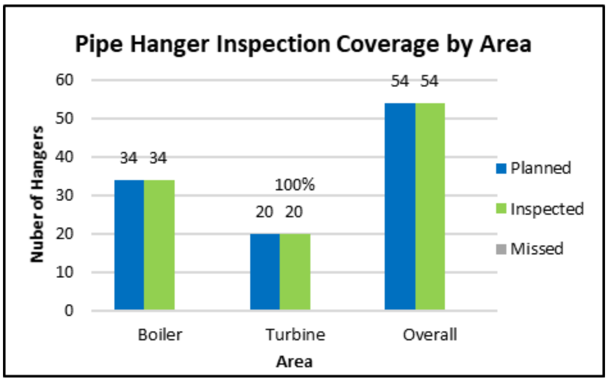

Figure 7. Number of pipe hangers & supports inspected in drone-based inspection

B. Image Quality

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

Captured images and videos were evaluated based on resolution; image detail, clarity and sharpness for diagnostic usefulness. The Table 3 shows the assessment summary of hanger features observed include as nameplate, travel indicator scale, load indicator and scale, hanger rod, spring can, clevis, clevis pin, clevis bracket, lock nut and support plate. In boiler area, in well-lit conditions, image quality was consistently rated good to excellent, with clear identification of hanger components such as nameplate details and travel scale details (Figure 9) and load scale details (Figure 10), hanger rod (Figure 11), hanger clevis and rod threads (Figure 12), and minor corrosion on hanger rod (Figure 14). Text and number with font size 14 and bigger are readable and easily recognized. However, in less sunlight (dim) such as cloudy or in the evening sunset conditions, fine details are less clear reduced sharpness, making it difficult to recognize small fonts size (Figure 8(b)).

In contrast, indoor turbine hall inspections required reliance on on board lighting, where dust and darkness reduced visibility. With bright on board lighting, image detail, clarity and sharpness are not compromised and most images remained sufficient for visual inspection and defect detection such as travel deviation, hanger load, detached hanger casing (Figure 15), minor corrosion, etc. However, the drone needs to have to a suitable standoff distance from the hanger to prevent too much light that can cause glare on the hanger features such as nameplate and travel scale, load scale, surfaces resulting in poor image quality.

The high level of image detail, combined with the ability to review, slow down, and replay footage, enables thorough inspections that can identify abnormal findings, common difficulties, and routine maintenance requirements. This level of detail also supports more precise planning of repairs based on reliable visual evidence. In contrast, traditional inspections using long-zoom cameras without scaffolding often produce blurred or low-quality images of elevated pipe hangers, leading to uncertain maintenance decisions. By comparison, data acquired by skilled drone pilots is consistently clearer and more actionable, reducing unnecessary shutdown time and, in some cases, even preventing operational interruptions.

Overall condition of pipe hanger features and components are visible, but fine details less clear when at dim light (cloudy weather, evening sunset) typically with no on board lighting on drone.

TABLE IV. SUMMARY OF PIPE HANGERS AND SUPPORTS FEATURES OBSERVED IN DRONE-BASED INSPECTION

Drone Model	DJI FPV		Elios 2 (w light)
Area	Boiler Area (Outdoor)		Turbine Area
Hanger Features	Well-lit	Dim	Dark, Dusty
Nameplate Details	☑ TRUE	☐ FALSE	☑ TRUE
Travel Scale	☑ TRUE	☑ TRUE	☑ TRUE
Travel Indicator	☑ TRUE	☑ TRUE	☑ TRUE
Load Scale	☑ TRUE	☐ FALSE	☑ TRUE
Load Indicator	☑ TRUE	☑ TRUE	☑ TRUE
Hanger Rod	☑ TRUE	☑ TRUE	☑ TRUE
Turnbuckle	☑ TRUE	☑ TRUE	☑ TRUE
Lock Nut	☑ TRUE	☑ TRUE	☑ TRUE
Clevis	☑ TRUE	☑ TRUE	☑ TRUE
Clevis Pin	☑ TRUE	☑ TRUE	☑ TRUE
Clevis Bracket	☑ TRUE	☑ TRUE	☑ TRUE
Travel Slot	☑ TRUE	☑ TRUE	☑ TRUE
Support Plate	☑ TRUE	☑ TRUE	☑ TRUE
Score	100% Excellent	85% Good	100% Excellent

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(a)

(b)

Figure 8. Support (snubber) nameplate on cloudy day (a) with on board lighting (b) without on board lighting.

Figure 9. Alost bottom over-scaled hanger travel and visible hanger nameplate.

(a)

(b)

Figure 10. (a) General view of load scale (b) Zoom in with design load (marked).

Figure 11. General view hanger top rod.

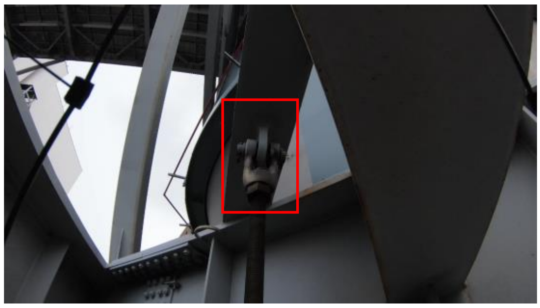

Figure 12. Condition of hanger clevis, lock nut, clevis bracket.

Figure 13. Example of close vicinity of drone (with safety cage) and pipe hanger.

Figure 14. Minor corrosion on hanger rod.

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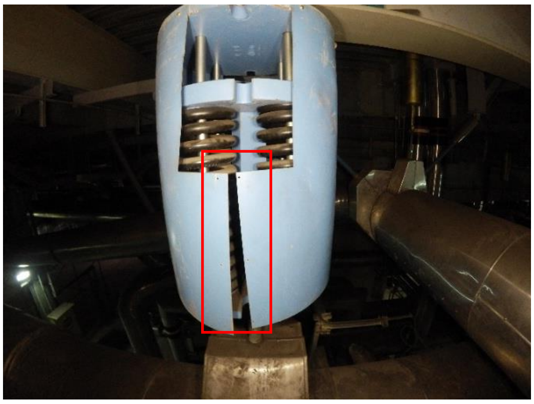

Figure 15. Detached hanger casing.

C. Flight Performance

Table 5 shows flight performance assessment summary for drone inspection at boiler and turbine areas. A total of 12 inspection flights were conducted with average flight duration was 9.58 minutes, with a throughput of 4.25 hangers inspected per flight. Stability was generally maintained under calm conditions, though performance was impacted during cloudy, light rain and minor windy (5m/s) conditions in the boiler area, requiring frequent manual correction. From this inspection flights observation, drone with cages or confined space drone is the definitive choice to be deployed due to the obstacles and narrow-, tight- space condition of piping systems at boiler and turbine areas as the drone needs to be manoeuvred in close vicinity to pipe hanger in order to inspect the condition and capture images.

Incidents were minimal, with 1 Return-to-Home event, none of which caused damage to equipment or the facility or the uninvolved human around the inspection site area. This indicates that quadcopters drone can maintain stable performance in both indoor and outdoor industrial environments, with cage-equipped drones showing added resilience in tight-, narrow-, and confined spaces.

As can be seen from Table 4, the number of hangers inspected per flight varies based on hangers' location (5 m or 15 m), obstacles (structures, pipes), narrow space and drone model. At boiler area where hangers are located at 5 to 7 meters high and less obstacles (more clearance), 4 hangers managed to be inspected using DJI FPV drone. However, only 2 hangers were managed to be inspected for hangers at 15 meters high, more obstacles and tight-space locations.

As for hangers at turbine area, the hangers location are lower (5 m high), closer, shorter spans and side by side among the pipelines. These conditions allow for more convenient drone manoeuvring for inspection despite the challenges of dark, dusty, tigh-, narrow-space and the need to avoid obstacles (structures and pipes). Furthermore, the Elios 3 drone were used in the turbine area as the drone is equipped with on board lighting, cage and dust-proof features, make it perfect for such situation.

TABLE V. SUMMARY OF FLIGHT PERFORMANCE

Flight No.	Drone Model	Boiler Area (Outdoor)	Flight Duration (min)	Battery Warnings	Hangers Inspected	Contacts (Minor/Major)	RTH Events	Notes
1	DJI FPV (caged)	MSP East High Hangers (5-7m)	10	30%	4	Minor contacts on obstacle	0	Smooth flight, slow manoeuvring
2	DJI FPV (caged)	MSP East High Hangers (5-15m)	10	30%	3	Minor contacts on obstacle	0	Shorter flight & less hangers due to higher hangers location and more obstacles (structures & pipes)
3	DJI FPV (caged)	MSP West High Hangers (5-7m)	10	30%	4	Minor contacts on obstacle	0	Smooth flight, slow manoeuvring
4	DJI FPV (caged)	HRP East High Hangers (5-7m)	10	30%	4	Minor contacts on obstacle	0	Smooth flight, slow manoeuvring
5	DJI FPV (caged)	HRP East High Hangers (5-15m)	10	30%	2	Minor contacts on obstacle	1	Shorter flight & less hangers due to higher hangers location and more obstacles (structures & pipes)
6	DJI FPV (caged)	HRP West High Hangers (5-7m)	10	30%	3	Minor contacts on obstacle	0	Smooth flight, slow manoeuvring
7	DJI FPV (caged)	HRP West High Hangers (5-15m)	10	30%	2	Minor contacts on obstacle	0	Shorter flight & less hangers due to higher hangers location and more obstacles (structures & pipes)
8	Elios 2	CRP High Hangers (5-7m)	9	20-30%	7	Minor contacts on obstacle	0	More hangers inspected due to Elios 2 fast manoeuvring and less obstacles on CRP line (more clearance)
Flight No.	**Drone Model**	**Turbine Area (Indoor)**	**Flight Duration (min)**	**Battery Warnings**	**Hangers Inspected**	**Contacts (Minor/Major)**	**RTH Events**	**Notes**
9	Elios 2	MSP East Hangers (2-5m)	9	20-30%	5	Minor contacts on obstacle	0	More hangers inspected due to: 1.Elios 2 fast manoeuvring and 2. hangers' spans are nearer, lower and side by side position
10	Elios 2	MSP West Hangers (2-5m)	9	20-30%	6	Minor contacts on obstacle	0	
11	Elios 2	HRP East & West Hangers (2-5m)	9	20-30%	6	Minor contacts on obstacle	0	
12	Elios 2	CRP and HPBP East Hangers (2-5m)	9	20-30%	5	Minor contacts on obstacle	0	
Mean Flight Time	**Mean hangers/ flight**	**Hangers/ Min.**	**Min./ Hanger**	**RTH Freq.**	**No-RTH Rate**	**Ave. Flight Duration**	**Hangers insp./ Flight**	**Notes**
9.58	4.25	0.44	2.25	8%	92%	9.56	4.25	-

D. Safety

The conventional inspection of pipe hangers need an amount (m^3 size) of scaffolds to be erected typically for high, narrow-, tight-space locations. This condition expose engineers and inspectors to risk of height and awkward body postures (tight-space) threaten inspector health. In addition, hot condition inspection means that inspectors exposed to heat radiation from high temperature steam. Dark and dusty work area typically at turbine hall area exacerbated the risks of health (inhalation) and safety.

A safety assessment of the inspection in Table 6 and Figure 15 showed that the drone-based inspection approach reduced overall risks and hazards exposure in term of man-hours. The drone-based inspection quantified man-hours at height (0 hours), heat (0 hours), awkward body posture (0 hours) and dust (3 hours) showed significant reduction compared to conventional inspection (using scaffolds), highlighting the strong safety advantage. Safety observation score based HIRADC revealed that the drone inspection approach reduced overall exposure to hazards from 5 (medium risk) to 2.3 (low risk) compared to traditional approach. This potentially increase the safety and health of inspectors during inspection works at site.

However, residual risks were observed in terms of minor drone minor contacts, dust blown by drone and battery-related issues, which require ongoing procedural controls and improvements. As inspectors and pilots become more familiar with the piping systems routing and plant area, drone manoeuvre technic and skills can be improved overtime. Additional PPE such as goggle and dust mask are essential for drone-based inspection in condition such as the turbine hall area.

TABLE VI. SUMMARY OF SAFETY ASSESSMENT.

KPI	Time (Hours)		
	Conventional Inspection (scaffolds)	Drone-Based Inspection	Risk Reduction
Ave. exposure time at height	25	0	100%
Ave. exposure time at heat	15	0	100%
Ave. exposure time at awkward body posture	15	0	100%
Ave. exposure time at dust	15	3	80%

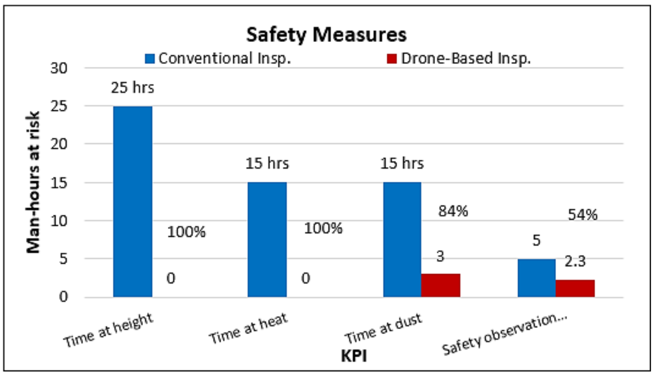

Figure 15. Man-hours exposure to risks on conventional inspection vs drone-based inspection.

VI. CONCLUSION

Pipe hanger and support systems are key component of the power plant HEP systems in maintaining the forces and stresses created within the allowable limits; and, to allow sufficient movement from cold to hot conditions. Employing drones for performing pipe hanger inspection in hard-to-reach locations and parts of complex piping system which associated with the safety and health risk exposure (at height, heat, dust, confined space), data quality; is one of the latest advancement in piping inspection. In this study, drone-based inspection is carried out at a coal-fired power plant on the HEP systems.

In summary, the pipe hanger and support drone-based inspection was considered feasible from a technical point of view by the study performed by the piping inspection and drone pilot subject matter expert. This study provided an understanding of the applicability of specific drones to HEP pipe hanger inspection of power plant, in terms of hanger coverage, image captured, flight performance, and safety and health. The results revealed that the drone achieved full accessibility and coverage with 100% of planned hangers inspected in both boiler and turbine area, demonstrating excellent scalability across different inspection scenarios. Most captured images provide sufficient visibility and resolution for visual inspection and defect detection during and after flight. Drone-based inspection also delivered significant safety benefits by reducing man-hours of exposure to height, dust, awkward body posture and heat compared to traditional scaffold-based method.

This innovative has the vital impacts in enabling predictive maintenance and preventive failures from the meaningful high-quality data. In addition, it reduces the need of large amount of scaffolds, lowering the inspection and maintenance cost. Furthermore, the drone technology is easily scale and adapted to different inspection scenarios, and future integration with AI for automated defect detection is possible. These findings highlight the potential of drones to enhance HEP condition-based inspection practices in terms of safety, cost and reliability in the power generation sector.

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