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ARTICLE

RPAS TECHNOLOGY FOR ENHANCED FOD DETECTION: KLIA CASE STUDY

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Abstract: This paper is focused on the issues of Foreign Object Debris (FOD) detection on the airport runways, specifically at Kuala Lumpur International Airport (KLIA) Aerodrome. Current manual FOD detection methods are rather time-consuming, error-prone and pose risks to the aviation safety, causing operational disruptions, financial losses and possible fatal risks. The current manual procedure includes the time taken by runway safety officers to reach the search area, perform the FOD search, detect and remove the foreign objects, and potentially conduct full-length runway inspection before notifying the Aerodrome Air Traffic Controller (ATC) that the "Runway is Clear from FOD". These procedures can lead to operational disruptions that subsequently result in unscheduled runway closures. In this study, an improved solution is proposed, which involves integration of the Remotely Piloted Aircraft Systems (RPAS) or drones, particularly those with the Beyond Visual Line of Sight (BVLOS) capabilities, into air traffic management (ATM) for immediate, accurate and reliable runway FOD detection. However, designing the safe and efficient BVLOS RPAS system within the ATM framework also presents few challenges. This research aims to develop an effective runway inspection approach within the context of ATM, considering both RPAS and traditional methods. Through comprehensive analysis, the study seeks to enhance runway safety, optimize the inspection procedures and improve the airport operation. Successful implementation of this proposed innovative FOD detection approach will maintain runway conditions, enhance capacity, minimize disruptions and improve operational efficiency.

Keywords: aviation safety; foreign object debris; RPAS; air traffic management; runway inspection

1. Introduction

The aviation industry, a testament to human ingenuity and technological progress, grapples with a range of safety and also operational challenges. Among these, the detection and management of foreign object debris (FOD) on airport runways stands out as a critical concern [1]. FOD encompasses a wide array of objects, from metallic fragments to wildlife, that capable of posing severe risks to aircraft during take-off and landing. To address these risks, airports typically rely on current conventional practices for FOD management such as employing ground vehicle inspections that depend merely on human visual capabilities. This inspection is vital for ensuring day-to-day flight safety in areas like runaways, taxiways and aprons. Indeed, current FOD management practice is overseen by international aviation authorities such as the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) [2]. However, the current practice typically involves multiple steps that are time-consuming. The procedure could lead to operational disruptions, resulting in unscheduled runway closures, particularly at densely populated airspace areas such as KL International Airport (KLIA) aerodrome, which features three runways with each measuring at four kilometers in length and approximately 60 meters wide. One of the most tragic reminders of the dangers posed by FOD on the runway is the Concorde Air France Flight 4590 near airport air disaster in the year 2000 at Charles de Gaulle Airport, France, that killed all 109 persons on board [3]. In this instance, a stray piece of metal on the runway, which was identified as a fallen FOD from a DC10 aircraft that took-off 5 minutes earlier, has led to a tire blowout, triggering a catastrophic chain of events. Modern aircraft engines, with their increasing power and also efficiency, elevate potential consequences of the FOD ingestion, therefore making the FOD management as an integral component of aviation safety [4].

The guidelines and recommendations from the ICAO and FAA emphasize systematic inspections, early detection mechanisms and immediate removal procedures to mitigate risks associated with FOD [5]. However, the guidelines normally offer a starting point, and further continuous improvement and adaptation by the local authorities are often essential. FOD management remains central to the aviation safety, demanding constant vigilance and also adaptation to technological and regulatory advancements [6]-[7]. Traditional FOD management practices, which are relying on manual ground vehicle inspection, routine patrol and human vigilance, have served the industry well but are not without some limitations [8]. Manual inspections are labor-intensive and time-consuming, which will greatly affect the operational efficiency [9]. Human error remains a big concern as many reports have shown missed FOD items [10]. Routine patrols and inspections may necessitate runway closures, disrupting aviation's tight scheduling [11]. Despite existing protocols and guidelines set forth by aviation authorities such as ICAO and FAA, the traditional methods of runway inspection, and FOD detection and removal by using ground vehicle inspection with full human intervention have demonstrated limitations in terms of speed, efficiency and accuracy, which pose a significant risk to aviation safety, particularly considering the robust rebound in recorded passenger air traffic following the post-pandemic COVID-19 period.

The advent of Remotely Piloted Aircraft Systems (RPAS) technology, commonly known as drones or Unmanned Aircraft System (UAS), has introduced a disruptive element into the FOD management. These autonomous or semi-autonomous aerial vehicles offer rapid and precise inspections of critical airport zones, including runways, taxiways and aprons. Integrating RPAS into the ATM for immediate FOD detection represents a paradigm shift in FOD management. While RPAS technology with Beyond Visual Line of Sight (BVLOS) capabilities also presents challenges, the potential benefits make it worth pursuing with several careful considerations [12]. The systematic methodology is critical to develop an effective domain-system architecture that balances safety, efficiency and also regulatory compliance. To this end, this study employs comprehensive framework that is combining Systematic Literature Review (SLR) and meta-analysis to explore the possibility and potential approach to effectively and efficiently integrate BVLOS RPAS technology into the FOD management.

2. Methodology

This study explores the integration of BVLOS RPAS technology for FOD management at KLIA through comprehensive and systematic methodology that combines SLR and meta-analysis. In general, SLR allows for the synthesis of a vast body of knowledge while meta-analysis quantitatively examines the available data to extract any valuable trends, patterns and critical insights. The overall framework is illustrated in Figure 1.

2.1 Data collection

The data collection process in this study involves gathering relevant information from published literatures and domain experts to aid in the development of effective BVLOS RPAS system architecture.

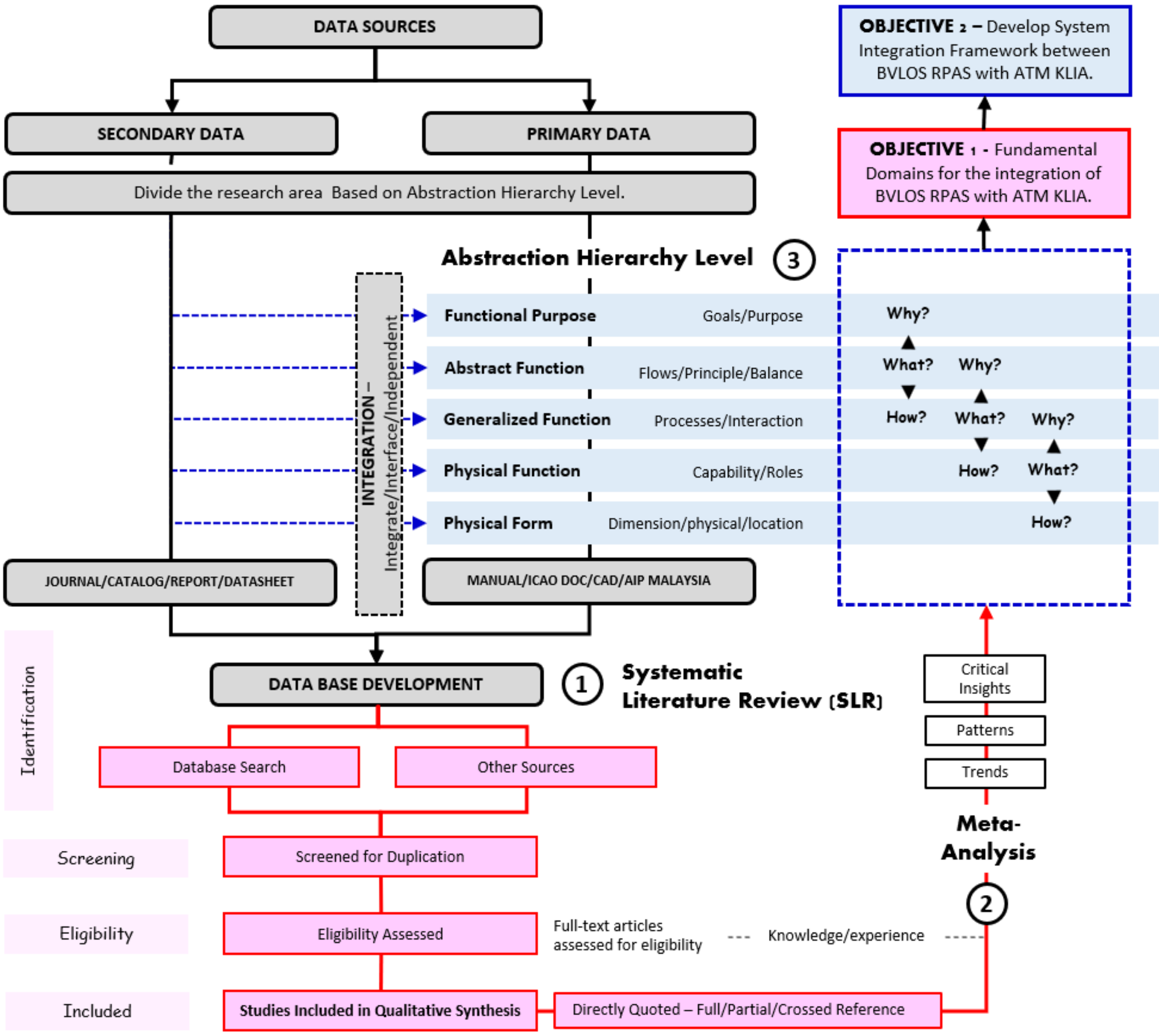

Figure 1: The overall research framework for this study

The SLR method is a rigorous approach involving setting clear inclusion and exclusion criteria and systematically extracting essential insights and findings from selected studies. In this study, it should be noted that the primary data comes from the regulators and authorities that are closely associated with the current operational procedures, representing the existing regulations for integrating BVLOS RPAS, particularly for runway FOD detection. Primary Data takes precedence over the Secondary Data, which focuses on BVLOS RPAS applications across domains, as aligned to primary data requirements. It aims to align with the requirements of Primary Data, maintaining aerodrome safety standards.

Building on the SLR findings, abstraction hierarchy theory is then applied to develop a specialized BVLOS RPAS domain framework. This involves delineating five levels of abstraction, from high-level characterizations to detailed physical forms. Such hierarchy process ensures a structured methodology that is aligned with safety, airspace management and operational procedures.

2.2 Data sources

In conducting the SLR for both primary and secondary data, a comprehensive set of data sources has been utilized, which include the following list:

- Academic databases such as PubMed, IEEE Xplore and Google Scholar to cover diverse research areas including life sciences, engineering, technology and aviation
- Authoritative documents from aviation regulatory bodies like ICAO, CAAM, FAA and EASA to incorporate guidelines and regulations
- International organizations for insights into aviation standards and recommended practices
- Specialized aviation-related websites and industry news sources for current perspectives

The reliability and validity of data sources are important selection criteria in conducting the SLR. By consolidating a wide range of literatures, this approach has enabled a holistic synthesis of knowledge from multiple disciplines that are relevant to BVLOS RPAS integration.

2.3 Data analysis

A systematic data analysis process is applied to extract the meaningful insights from the collected literature. This involves two key techniques that are tailored to specific data types. Firstly, meta-analysis is conducted systematically within the SLR to extract and synthesize information from selected studies. Key steps include data extraction, synthetization and categorization of RPAS applications into distinct domains. This process aims to provide a clear overview of BVLOS RPAS applications, together with possible integration with ATM, enhancing the understanding of their multidimensional uses. Secondly, the Abstraction Hierarchy method is applied to guide the development of the domain framework, which structures the framework into five hierarchical levels, ensuring the alignment with research objectives, addressing safety concerns, optimizing airspace management and streamlining operational procedures. Since an effective RPAS integration faces numerous challenges, including regulatory compliance, safety considerations, weather conditions, technology limitations, cost and privacy concerns [13], the resulting framework offers a holistic and adaptable solution for BVLOS RPAS usage in runway inspections at KLIA through ATM integration. In short, this method operates on five-level hierarchical structure as highlighted in Figure 2 and detailed as follows:

- **Functional Purpose**: At the highest level, it defines "Why?" the framework is needed, addressing its primary objectives in RPAS utilization for runway inspections
- **Abstract Function**: Outlines key functionalities the framework must achieve in terms of core functions and features
- **Generalized Function**: Focusing on broader operational aspects, it begins to answer "How?" the framework should operate practically
- **Physical Function**: Focus on the tangible components and operational procedures required for successful framework implementation
- **Physical Form**: Deals with specific physical forms and configurations the framework may take, addressing practical implementation and technological aspects

On the whole, the Abstraction Hierarchy method ensures a structured development, aligning with safety, airspace management and operational objectives. It facilitates a holistic approach, resulting in a comprehensive solution for BVLOS RPAS usage in KLIA runway inspections via ATM integration.

This multifaceted research strategy allows in-depth investigation into FOD management practices, exploration of the RPAS technology potential, evaluation of system architecture significance and also meticulous examination of factors influencing BVLOS integration feasibility [14]-[15]. It is essential to acknowledge inherent limitations of this study, including exclusive focus on KLIA, regulatory variances, technological and resource constraints. However, the aim is to remain steadfast in the commitment to provide invaluable insights that enhance the FOD detection and contribute to aviation safety, efficiency, RPAS integration knowledge, particularly within ATM context. This research establishes a framework that can potentially serve as an airport blueprint.

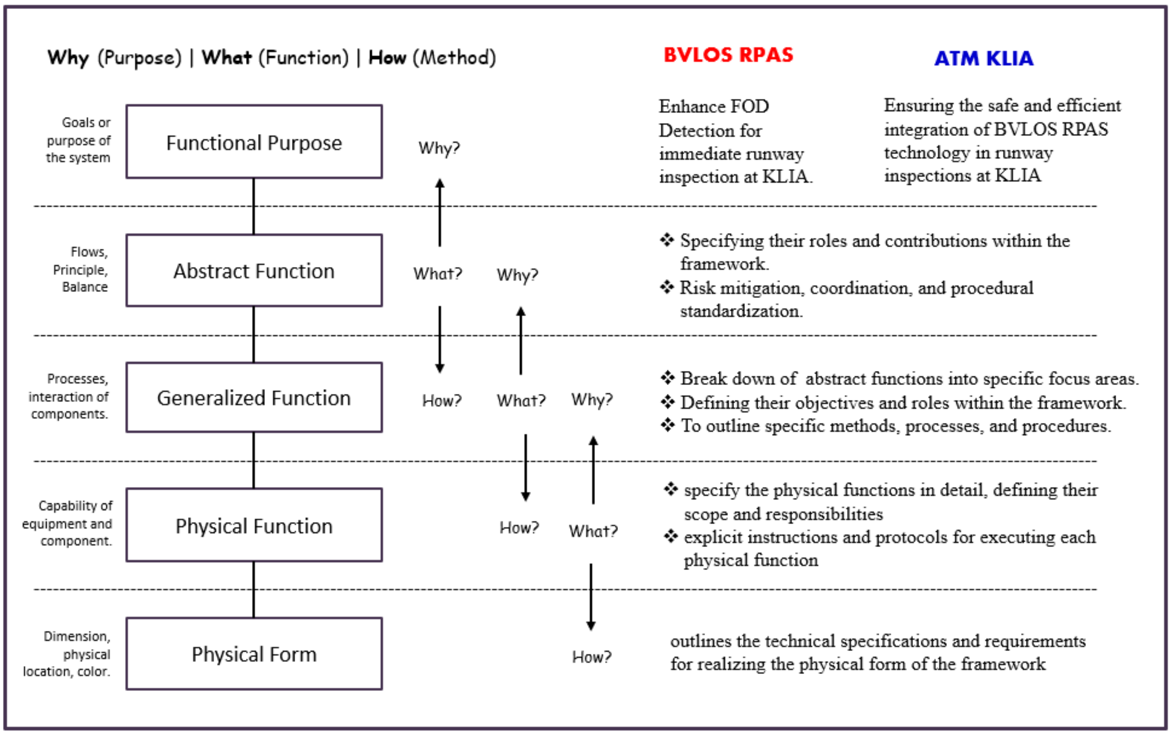

Figure 2: Schematic representation of the systematic identification of fundamental domains using Systematic Literature Review (SLR) based on the 'Why?', 'What?', and 'How?' aspects of the Abstraction Hierarchy level frameworks, contributing to the development of an integrated system architecture design

3. Results and Discussion

Figure 3 illustrates the fundamental domains identified through the combined analysis of SLR and Abstraction Hierarchy, as detailed in the methodology framework in previous Figure 1 and Figure 2. In brief, this investigation has unveiled 30 critical fundamental domains within the two major categories of core domains: BVLOS RPAS and ATM at KLIA. The findings have affirmed that the integration of the automated BVLOS RPAS technology, securely coordinated through the KLIA's ATM systems and procedures, holds the potential to significantly enhance FOD detection capabilities on runways.

The SLR has uncovered the pivotal capabilities of BVLOS RPAS that directly address limitations of current FOD detection methods. A notable limitation lies in the time required for manual inspection of lengthy runways, necessitating personnel travel and visual surface scanning. BVLOS RPAS efficiently overcomes this challenge through the rapid response, reduced inspection times and advanced sensors automating the FOD detection as highlighted by Ref. [16]. Among others, the identified key advantages include the following:

- Swift reaction and immediate response to FOD incidents, minimizing risks
- Shortened inspection and search times via wide aerial coverage and auto-pilot control
- Precision damage and FOD detection using digital imagery and advanced analysis like artificial intelligence (AI)
- Provision of live-feed data for real-time assessments by operators

The detailed insights into BVLOS RPAS technology and KLIA ATM Integration are tabulated in Table 1 and Table 2, respectively.

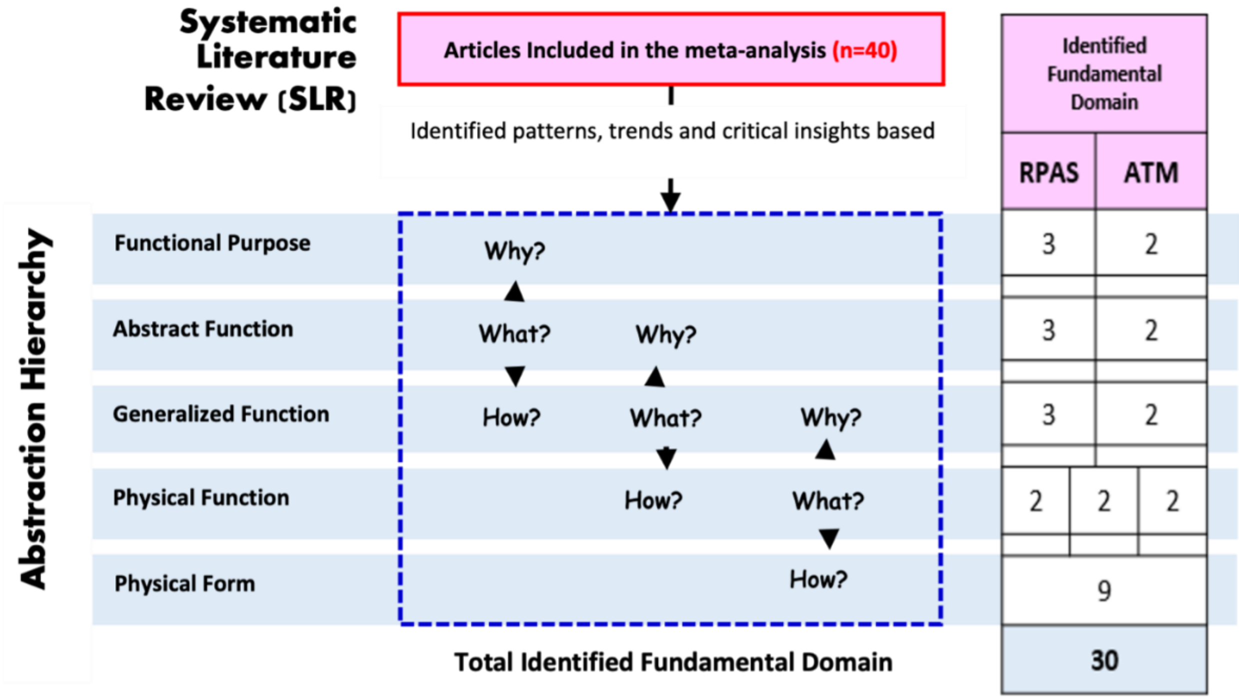

Figure 3: The recorded of fundamental domain for BVLOS RPAS and ATM KLIA

Table 1: BVLOS RPAS Technology

Findings	Implications
Swift Reaction	Rapid response to incidents, reducing assessment and mitigation times
Enhanced Efficiency	Improved runway inspections and FOD detection, minimizing closures
Precision	Detailed runway condition information for enhanced safety
Immediate Response	Swift response to FOD incidents, reducing aircraft damage risks
Reduced Inspection Time	Significant reduction in runway inspection and FOD detection time
Surface Damage Detection	Efficient detection of surface damage and FOD, enhancing runway safety
Remote Control Autopilot	Precise remote control and navigation features
Wide Field of View	Comprehensive aerial view coverage during inspections
Digital Image Analysis	Advanced analysis enhancing FOD detection accuracy
Live-Feed Data	Real-time data provision for operators, enabling timely decision-making
Flight Procedure Integration	Integration into instrument flight procedures for efficient and safe inspections
Geo-Fencing	Enhanced safety and control by restricting RPAS operations to specific areas

Table 2: KLIA Air Traffic Management (ATM) Integration

Findings	Implications
Safety Focus	Prioritization of airspace safety in aerodrome ATM procedures
Efficiency Focus	Avoidance of disruptions through coexistence with manned aviation
Situational Awareness	Necessary for safe and orderly air traffic flow, especially in mixed operations
Aerodrome Surveillance Display	Provides visual position display for ATCs, enhancing situational awareness
ATC Voice Coordination	Real-time communication between ATCs, manned aviation and RPAS operators
Report / Give Instruction	Facilitation of RPAS activities through reporting and instructions to aerodrome users
Visual RPAS Live Feed	Displays aid controllers with real-time runway condition information
Radio Communication	Ensures reliable contact between ATCs and aerodrome users

In the meantime, the Abstraction Hierarchy analysis has further delineated critical ATM integration requirements for safe and efficient BVLOS RPAS runway operations. Table 3 details the five hierarchy levels - Level 1: Functional Purpose, Level 2: What and Why, Level 3: How, What, and Why, Level 4: How and What, Level 5: How. It must be noted that a coordinated framework can provide situational awareness and communications between ATCs and remote pilots [17]. Several other elements including surveillance displays, radio voice communications, flight plans and also geo-fencing further facilitate a seamless integration. A significant finding is the efficacy of a nesting drone approach, which can enable immediate ATC activation of drones for faster FOD sites inspections as compared to traditional ground crews. Auto-pilot capabilities also precisely navigate pre-planned missions within geo-fenced areas.

Table 3: Abstraction Hierarchy Results

Level	Functional Purpose
Level 1	**BVLOS RPAS**: Promises fast reaction, increased efficiency and detailed accuracy **ATM KLIA**: Ensures safe coexistence and operational efficiency
Level 2	**BVLOS RPAS**: Immediate search response, shortened inspection time, surface damage detection **ATM KLIA**: Visual situational awareness, ATC voice coordination
Level 3	**BVLOS RPAS**: Digital data analysis, remote control autopilot, wide aerial view **ATM KLIA**: Aerodrome surveillance, report/give instruction, radio communication
Level 4	**BVLOS RPAS**: Robust communication, RPAS position, flight procedure design, geo-fencing, capture live feed **ATM KLIA**: Visual surveillance, radio voice communication
Level 5	**BVLOS RPAS**: Multiple nested drone units, geo-fencing, capture live feed images **ATM KLIA**: DPSD, Air to Ground Radio, collaboration, and communication for safety

In summary, BVLOS RPAS significantly improves the speed, accuracy and efficiency of the runway FOD detection. Integration with KLIA ATM safely coordinates their operation in active aerodromes. These findings have demonstrated that the proposed solution successfully addresses the limitations in current FOD detection practices.

4. Conclusion

This research is aimed to develop an integrated framework for BVLOS RPAS to enhance the FOD detection capabilities at KLIA airport. The limitations of current manual inspection methods include long detection times, visual scanning errors and delays responding to FOD incidents. The key findings demonstrate that an automated BVLOS RPAS integrated with KLIA ATM systems and procedures can effectively address these limitations. BVLOS RPAS can enable rapid and frequent inspection of runways with advanced sensors providing detailed damage and FOD detection data. Coordination through ATM elements like surveillance, communication protocols and flight plans is necessary to allow safe operation in active aerodromes. A major innovation is the proposed nesting drone approach, which allows ATCs to immediately dispatch drones to inspect FOD sites faster than waiting for ground crews. This reduces occupancy times and risks. The comprehensive framework integrates the strengths of BVLOS RPAS and KLIA ATM to optimize FOD detection capabilities.

In conclusion, this research lays a strong foundation for enhancing the airport's FOD management through leveraging BVLOS RPAS technologies and systems. The framework provides a valuable basis for guiding effective integration to maximize improvements in speed, accuracy and efficiency. Further research can build on these findings to quantify performance gains, optimize coordination procedures, and progress towards full operational implementation at KLIA and other airports. In addition, the long-term potential is a paradigm shift in runway safety management practices through use of BVLOS RPAS capabilities.

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