総合危機管理, No.8-10, 37-43, 2026

原著論文

Entropy-Based Evaluation of Disaster Information Quality in ICS Using Drone Observation

Masato Ebine[*1], Arief Wibowo[*2], Koseki Kenji[*3], Hitoshi Igarashi[*1], Tulus Yuniasih[*4], Fathin Aulia Rahman[*5], Ryota Iida[*1], Yohei Takano[*1], Mu'man Nuryana[*6], Yanuar Farida Wismayanti[*6]

Faculty of Risk and Crisis Management, Chiba Institute of Science [*1]
Faculty of Information Technology, Universitas Budi Luhur [*2]
Trajectory,Ltd. [*3]
Faculty of Social Sciences and Global Studies, Universitas Budi Luhur [*4]
Faculty of Economic and Business, Universitas Budi Luhur[*5]
The National Research and Innovation Agency of the Republic of Indonesia [*6]

Abstract

Effective disaster response within the Incident Command System (ICS) depends on rapid and diverse situational information. This study quantitatively compared disaster information obtained by a Human observation group and a Drone observation group using entropy-based metrics and an integrated information quality (IQ) score. A simulated disaster field experiment was conducted in Indonesia. The Human observation group (n=20) recorded events through on-site patrol reports, while the Drone observation group (10 flights) recorded events based on aerial observation. Detected disaster events were categorized and analyzed using Shannon entropy, entropy weight method (EWM), and a time-normalized IQ score. Group differences were tested using Welch's t-test. The Drone observation group detected more disaster events across all major categories and showed higher entropy values, indicating greater information diversity. The mean IQ score was significantly higher in the Drone observation group (10.6) than in the Human observation group (2.5) ($p < 0.01$, large effect size), indicating substantially greater operational information efficiency under aerial observation.

KEYWORDS: ICS, UAV, Information Quality, Disaster prevention, Risk management

1. Introduction

In recent years, the increasing frequency and severity of natural disasters such as earthquakes, floods, and fires have intensified the need for rapid and accurate situational awareness during the initial phase of disaster response[1]. Emergency operations must be conducted under strict time and resource constraints, and the quantity and quality of available information strongly influence the effectiveness of command decisions[2]. The Incident Command System (ICS) is an internationally standardized command and control framework widely adopted in disaster and emergency management, providing structured coordination through functional sections such as command, operations, planning, logistics, and information[3]. However, the operational performance of ICS depends heavily on the completeness, diversity, and timeliness of the information supplied to each section[2,3].

Conventional disaster information collection has largely relied on human visual observation and ground patrol, which are inherently limited by field of view, accessibility, and responder safety constraints[4]. As a result, collected information often becomes fragmented and spatially biased, particularly in complex or hazardous environments[4,5]. In recent years, unmanned aerial vehicles (drones) have attracted increasing attention as a tool for disaster assessment because they can rapidly acquire aerial imagery, wide-area visual coverage, and geospatial information, even in locations that are difficult or dangerous for responders to access[5,6]. Several studies have reported that drone-based mapping

連絡先：海老根　雅人　mebine@cis.ac.jp
千葉科学大学 危機管理学部 保健医療学科
Faculty of Risk and Crisis Management, Chiba Institute of Science
（2024 年 2 月 20 日受付，2024 年 3 月 11 日受理・掲載）

and aerial assessment can significantly accelerate damage evaluation and situational mapping in disaster zones[6,7]. Nevertheless, many of these studies focus on operational usefulness or technical performance, and relatively few have quantitatively evaluated the informational value contributed to structured command systems such as ICS.

From an information-theoretic perspective, Shannon information entropy provides a mathematical framework for quantifying information diversity and distribution balance[8]. Entropy-based approaches have been applied in fields such as disaster risk assessment, resilience measurement, and event detection in crisis-related information networks[9,10]. In addition, the Entropy Weight Method (EWM) has been proposed as an objective weighting technique in multi-criteria evaluation, enabling indicator importance to be derived from statistical dispersion rather than subjective judgment[9,11]. These approaches make it possible to quantify not only how much information is collected, but how structurally diverse and discriminative that information is.

Despite these methodological advances, limited research has compared human observation and drone-based observation within an ICS-oriented framework using entropy-based quantitative metrics. Few studies have examined how differences in observation modality affect the diversity, priority-weighted value, and reporting timeliness of disaster event information supplied to ICS decision processes.

Therefore, this study establishes a comparative framework between a no-drone condition (human observation) and a drone-assisted condition (aerial observation) and quantitatively evaluates the resulting disaster event data using entropy measures, entropy-based weighting, and an integrated Information Quality (IQ) score. Through this approach, the study aims to demonstrate how drone-based observation enhances the informational foundation of ICS and improves decision-support capacity in disaster response[3,6,8].

2. Objective

The objective of this study is to quantitatively compare disaster information obtained by human observation and drone observation within the Incident Command System (ICS) framework, using entropy-based metrics and an integrated information quality (IQ) score.

3. Methods

This study was conducted in a simulated disaster field environment in Indonesia. Within the experimental area, multiple disaster events were prearranged, including collapsed structures, fallen trees, debris, fire-related indicators, trapped victims, hazardous fragments, and fire-extinguishing equipment. Event categories were defined in advance, and all observations were recorded on an event-by-event basis.

3-1. Experimental Conditions

The comparative conditions in this study were defined as the following two groups.

Condition 1: Without drone (human observation group)

Twenty participants individually patrolled the field site and recorded visually confirmed disaster events using a tablet-based chat application.

Condition 2: With UAV (UAV observation group)

A drone was flown 10 times to observe the same field site from an overhead perspective. Five operators reviewed the drone video footage and recorded detected disaster events using a tablet-based chat application. The experiment employed a DJI Flip drone (DJI; 2.4 GHz Wi-Fi, maximum resolution 48 MP, sensor size 1/1.3 inch), which was flown over the simulated disaster field, and the captured aerial video was analyzed by the operators. Because one drone flight enables simultaneous wide-area observation compared with a single human patrol, the number of drone trials was smaller than the number of human observation trials. To address this imbalance, event-level normalization and variance-robust statistical testing were applied. The number of UAV trials (10 flights) was determined based on operational feasibility and the assumption that a single aerial flight enables wide-area simultaneous observation compared with one individual human patrol. To minimize environmental variability, all flights were conducted within a limited time window under stable daytime weather conditions without rainfall or strong wind. Although atmospheric conditions were not experimentally manipulated, no substantial visibility or wind fluctuations were observed during the data collection period.

3-2. Disaster Information Entropy

The data obtained under both conditions were organized as frequency distributions of categorized disaster events. Shannon's information entropy H (1) was then applied to quantitatively measure the diversity of the observed information, defined in terms of distribution balance and coverage.

$$H = -\sum p_i \log p_i \quad (1)$$

Here, pi denotes the occurrence probability of event category i, defined as pi, where Ni is the number of detected events in category i within a single trial, and m is the number of event categories.

Furthermore, the reporting time to ICS, denoted as T, was measured experimentally. Reporting time (T) was defined as the elapsed time from event confirmation (visual confirmation in the field for the human condition, and in the video for the drone condition) to successful posting of the event report message in the tablet-based chat application. T was recorded in minutes and aggregated per trial for IQ computation. In this study, Information Quality (IQ) was defined as a time-normalized indicator representing the operationally weighted amount of disaster information delivered to the Incident Command System (ICS). The IQ score was calculated as:

$$IQ = \frac{\sum_{i=1}^{m} w_i N_i}{T} \quad (2)$$

where wi denotes the weight coefficient of event category i derived from the Entropy Weight Method (EWM). Disaster IQ was defined as an operationally prioritized extension of IQ, emphasizing high-urgency categories (e.g., victims and fire) by applying ICS-priority coefficients in addition to wi.

category (6) and the weight coefficient (7) were obtained by normalization using the following equations.

$$d_i = 1 - e_i \quad (6)$$

$$w_i = \frac{d_i}{\sum_{i=1}^{m} di} \quad (7)$$

As a result, categories with greater variability in the observed data and richer informational content are assigned higher weights, whereas categories with more biased or uniform distributions receive lower weights. Because EWM emphasizes statistical dispersion, categories with lower detection frequency but higher variability may receive larger weights.

3-3. Entropy Weight Method

In this study, weight coefficients were calculated using the Entropy Weight Method (EWM) to objectively evaluate the informational importance of each disaster event category. EWM is a method used in multi-criteria evaluation to determine weights based on the information content (variability) of each indicator, and it enables objective weighting that does not depend on the subjective judgment of the researcher. In addition to entropy-based objective weighting, expert validation based on ICS operational priority was applied to ensure practical relevance. This hybrid approach integrates statistical variability and operational urgency.

First, for each disaster event category i, the observed values xij for each experiment (j = each trial) were used to compute the normalized proportion (3) according to the following formula.

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \quad (3)$$

Next, the information entropy of event category i was calculated using the following equation (4).

$$e_i = -k \sum_{j=1}^{n} p_{ij} \ln(p_{ij}) \quad (4)$$

$$k = \frac{1}{\ln(n)} \quad (5)$$

Here, n denotes the number of trials. A higher entropy value indicates a more uniform distribution and lower discriminative power of the indicator, whereas a lower entropy value indicates greater variability and higher discriminative power. Subsequently, the information utility of each event

3-4. Statistical Analysis

The primary evaluation outcome was the comparison of IQ scores between the no-drone condition (human observation group) and the drone-assisted condition (aerial observation group). As an independent two-group comparison, Welch's t-test was applied. Welch's t-test was selected because the two groups had unequal sample sizes and potentially unequal variances. The significance level was set at $\alpha = 0.05$ (two-sided). Effect size (Hedges' g) and 95% confidence intervals were also calculated.

3-5. Research Ethics

This study was approved by the ethics review board of Chiba Institute of Science (Approval

No. R07-22), and the experiment was conducted at UBL. The study followed the international ethical guidelines of the Council for International Organizations of Medical Sciences (CIOMS). Prior to participation, subjects were informed about the purpose and procedures of the experiment, that participation was voluntary, that responses were anonymous, and that no personal information would be collected. The experiment was conducted only after consent was obtained. Because no personally identifiable information was collected, the study posed no direct risk or disadvantage to participants. No personal identifiable information or biometric data were collected in this study.

4. Results

4-1. Event-Level Detection Results

In this study, multiple disaster events predefined in a simulated disaster field (Fig.1) including collapsed buildings and structures, fallen trees and debris, fire and smoke indicators, trapped victims, hazardous fragments, and fire-extinguishing equipment-were analyzed. Detection results from the human observation group and the drone observation group were recorded and compared at the event level. All observation data were collected through event discovery reports submitted via a chat application. Each detected event was individually counted based on confirmation either by direct human observation or by review of drone video footage, and these event-level counts were used for subsequent analysis.

Fig. 1 Simulated Disaster Field

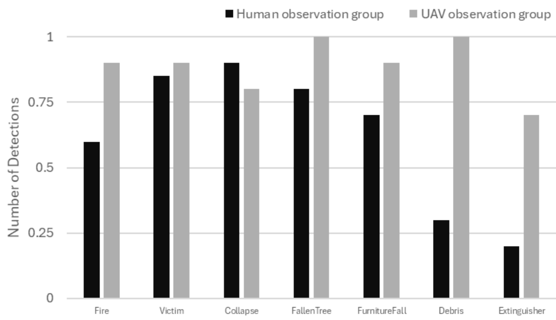

Fig.2 Mean Event Detections per Trial by Observation Method

As shown in Fig.2, the drone observation group recorded a higher number of detections than the human observation group across all event categories.
In particular, the differences were most pronounced for collapsed structures, trapped victims, and fire-related events, with the mean number of detections increasing by approximately 1.8 to 2.5 times. These events have high priority in the initial phase of disaster response and provide information that directly supports ICS operational and command decision-making.

4-2. Information Entropy Based on Event Distribution

Next, Shannon information entropy was calculated based on the distribution of disaster event categories detected under each observation condition (Fig.3). In this context, entropy represents not simply the total number of detected events, but an index that evaluates how many different types of events were detected in a balanced manner. In other words, the entropy value decreases when detections are concentrated in a limited number of categories and increases when events are more evenly distributed across multiple categories.

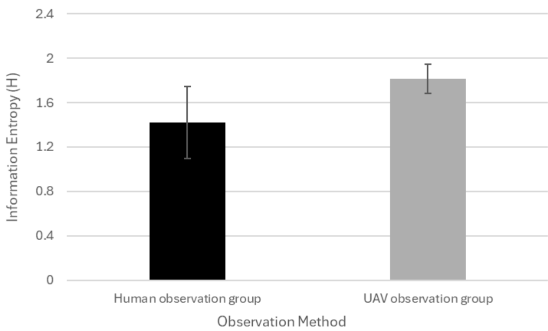

Fig.3 Comparison of Information Entropy Based on Disaster Event Distribution

4-3. Information Contribution Based on Entropy Weighting

Not all disaster events have equal informational characteristics; some categories exhibit greater variability across trials and therefore contribute more to discrimination between observation conditions.

In this study, weight coefficients were calculated using the Entropy Weight Method (EWM) based on the observed variance of each event category (Fig.4). As a result, categories such as Extinguisher and Debris received relatively higher weights due to their greater statistical dispersion across trials. In contrast, frequently detected categories with more uniform distributions received lower weights. By applying this entropy-based weighting scheme, integrated evaluation became possible based not merely on detection counts, but on the statistical informativeness of each event category.

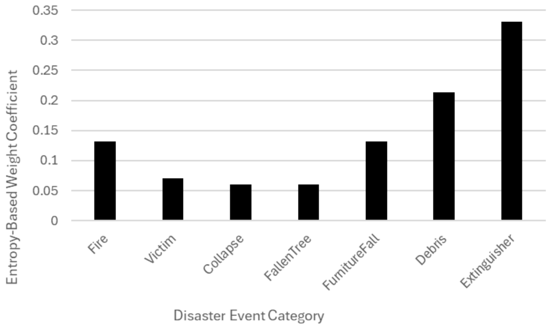

Fig.4 Entropy-Based Weight Coefficients by Disaster Event Category

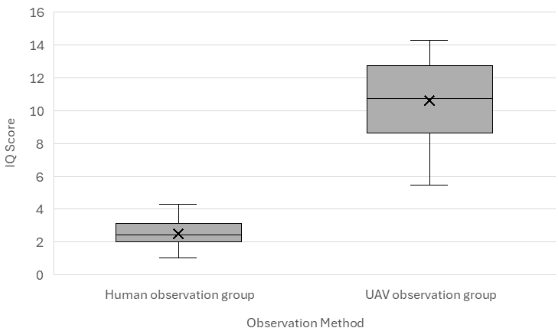

Fig.5 Event-based IQ Score Distribution by Observation Method

4-5. Summary of Results

Overall, the results demonstrate that drone-based observation, compared with human observation, not only increases the number of detected disaster events but also balances the distribution of information across ICS sections and simultaneously improves both information diversity and timeliness. Entropy-based and IQ score analyses quantitatively showed that drone observation strengthens the informational foundation supplied to ICS in both qualitative and quantitative terms.

4-4. Integrated Information Quality Index (IQ Score)

The integrated Information Quality (IQ) score was calculated by combining the event-level entropy values and weight coefficients and further normalizing them by the time required from event detection to reporting within the ICS framework. This index represents, in an integrated manner, how diversely and how rapidly high-priority events were identified. The analysis showed that the IQ score of the drone observation group substantially exceeded that of the human observation group. In particular, the early detection of high-weight events namely trapped victims and fire-related incidents contributed strongly to the increase in the score. As shown in Fig.5, the mean IQ score was approximately 2.5 in the human observation group, whereas it reached approximately 10.6 in the drone observation group, indicating a markedly higher level of integrated information quality under the drone-assisted condition. The IQ score of the drone group was significantly higher than the human group (Welch's t-test, $p < 0.01$), with a large effect size (Hedges' g), confirming the robust advantage of aerial observation.

5. Discussion

In the human observation group, detection rates decreased for events located inside buildings, confined spaces, or behind obstacles due to mobility and safety limitations[1]. In contrast, drone observation enabled simultaneous recognition of distributed damage from an aerial perspective, reducing blind spots caused by obstructions[2]. This difference in viewpoint likely contributed to variations in both total detected events and category distribution.

Event-level analysis demonstrated that drone observation increased detection counts and improved distributional balance across event types. These findings are consistent with previous aerial disaster mapping studies reporting improved coverage and detection capability[2,3]. Detection improvements were particularly notable for high-priority events such as collapsed structures, trapped victims, and fires, which are closely linked to ICS operational decisions[4].

Beyond detection quantity, drone observation increased event distribution diversity. Shannon entropy analysis[5] showed consistently higher values in the drone group, indicating reduced category bias. Because unbalanced information can influence situational assessment within ICS4), broader category coverage may support improved command awareness.

The application of the Entropy Weight Method (EWM)[6,7] enabled objective evaluation of event importance based on statistical dispersion. High weights assigned to victim- and fire-related events were consistent with their operational relevance4). Although categories such as "Extinguisher" and "Debris" showed high statistical variance and therefore received larger weights, this reflects dataset variability rather than life-saving priority. Hybrid weighting approaches incorporating expert-defined urgency may further refine evaluation models.

The IQ score integrates event volume, weight, and reporting time, enabling structured evaluation of weighted information delivery to ICS. The drone observation group demonstrated

Several limitations must be acknowledged. The study was conducted in a simulated environment and does not fully replicate real disaster complexity[8]. Trial independence may be limited due to repeated observations within the same field. The UAV sample size was smaller than the human group, although each flight provided wide-area coverage. Environmental factors and operator variability may also influence detection performance. Additionally, the current IQ framework emphasizes weighted event volume and reporting efficiency; future work should incorporate explicit correctness metrics (e.g., precision or recall) to strengthen robustness.

Future research should extend this event-based framework to real-time ICS systems, multi-drone operations, and diverse disaster scenarios, contributing to continued refinement of quantitative evaluation methods linking information acquisition and command decision-making[2,4,8].

6. Conclusion

This study quantitatively evaluated how different information collection methods-human observation and drone-based observation—affect the quantity, diversity, and transmission efficiency of disaster information supplied to the Incident Command System (ICS) in a simulated disaster environment. Evaluation metrics included Shannon information entropy, the Entropy Weight Method (EWM), and an integrated

significantly higher IQ scores with a large effect size, suggesting that drone-based reconnaissance may enhance ICS information acquisition processes. Timely information delivery is widely recognized as critical in emergency command performance[4,8].

Entropy-based evaluation has been applied in disaster resilience and information diffusion studies[5,7,9], but its explicit integration with ICS-oriented operational assessment remains comparatively limited. By linking entropy metrics with ICS structures4), this study provides empirical support for structured quantitative evaluation of disaster information quality.

This research was conducted in Indonesia, a disaster-prone country exposed to earthquakes, floods, and urban fires. Evaluating the framework in such a high-risk and infrastructure-diverse context supports its broader applicability.

Information Quality (IQ) score incorporating reporting time.

The results demonstrated that drone-based observation not only substantially increased the number of detected disaster events compared with human observation but also balanced the distribution of information across ICS sections and significantly improved information diversity. IQ score analysis with entropy-based weighting showed that the drone observation group significantly outperformed the human observation group, with large effect sizes. These findings indicate that drone observation is not merely a supplementary data collection method but a practical means to improve situational awareness and decision quality within ICS operations.

A key contribution of this study is the quantitative demonstration of drone effectiveness in disaster response using entropy-based and integrated metrics rather than qualitative assessments alone. By linking evaluation to the internationally standardized ICS framework, the results have both academic significance and high practical applicability.

In conclusion, drone-based observation is an effective approach for strengthening the disaster information foundation of ICS in both qualitative and quantitative terms and contributes to faster initial response and improved decision-making. The evaluation framework proposed in this study is expected to be applicable to real disaster training, multi-agency exercises, and expansion to different disaster types and regions.

7. References

1) United Nations Office for Disaster Risk Reduction (UNDRR). Human cost of disasters: An overview of the last 20 years 2000-2019. UNDRR; 2020.

2) Comfort LK, Boin A, Demchak CC. Designing resilience: Preparing for extreme events. University of Pittsburgh Press; 2010.

3) Federal Emergency Management Agency (FEMA). National Incident Management System (NIMS). 3rd ed. Washington, DC: FEMA; 2017.

4) Bigley GA, Roberts KH. The incident command system: High-reliability organizing for complex and volatile task environments. Acad Manage J. 2001;44(6):1281-1299.

5) Adams SM, Friedland CJ. A survey of unmanned aerial vehicle (UAV) usage for imagery collection in disaster research and management. 9th Int Workshop Remote Sensing for Disaster Response. 2011.

6) Nex F, Remondino F. UAV for 3D mapping applications: A review. Appl Geomatics. 2014;6:1-15.

7) Erdelj M, Król M, Natalizio E. Wireless sensor networks and multi-UAV systems for natural disaster management. Comput Netw. 2017;124:72-86.

8) Shannon CE. A mathematical theory of communication. Bell System Technical Journal. 1948;27(3):379-423.

9) Zeleny M. Multiple criteria decision making. New York: McGraw-Hill; 1982.

10) Sakaki T, Okazaki M, Matsuo Y. Earthquake shakes Twitter users: Real-time event detection by social sensors. Proc WWW Conference. 2010:851-860.

11) Wu J, Sun J, Liang L, Zha Y. Determination of weights for ultimate cross efficiency using Shannon entropy. Expert Systems with Applications. 2011;38(5):5162-5165.