

ABSTRAK

Sistem *multi-Unmanned Aerial Vehicle* (multi-UAV) dalam lingkungan *Flying Ad Hoc Network* (FANET) semakin banyak digunakan untuk misi pengumpulan data pada berbagai aplikasi seperti pemantauan wilayah, penginderaan, dan *Internet of Things* (IoT). Namun, sebagian besar pendekatan optimasi yang ada masih menggunakan fungsi objektif statik, seperti jarak tempuh, konsumsi energi, atau *coverage* semata, sehingga belum mampu merepresentasikan keberhasilan misi pengumpulan data secara *end-to-end* yang melibatkan proses penginderaan, penyimpanan data, komunikasi, serta keterbatasan energi secara terpadu. Penelitian ini bertujuan merumuskan dan mengimplementasikan Indeks Kualitas Misi multikriteria sebagai fungsi objektif kuantitatif pada misi pengumpulan data sistem multi-UAV dalam lingkungan FANET, serta mengembangkan dan mengevaluasi pendekatan optimasi yang diberi nama *Weighted Energy-aware Genetic Algorithm* (WE-Gen.A).

WE-Gen.A mengevaluasi setiap kandidat solusi melalui simulasi level misi yang memodelkan secara eksplisit pergerakan UAV, konsumsi energi, proses penginderaan, penyimpanan data pada *onboard buffer*, komunikasi berbasis *timeslot*, dan pengiriman data ke *Base Station* (BS). Fungsi *fitness* dirumuskan dalam bentuk Kualitas Misi yang mengintegrasikan lima metrik, yaitu efisiensi energi, *coverage completeness*, *data delivery ratio*, UAV *fairness*, dan *Point of Interest* (PoI) *fairness*. Kinerja algoritma dievaluasi melalui simulasi pada berbagai konfigurasi jumlah UAV dan distribusi PoI, kemudian dibandingkan dengan *Random Assignment*, *Greedy*, *Multi-Route Genetic Algorithm* (MR-GA), *Energy-Balanced Genetic Algorithm* (EB-GA), dan *Nondominated Sorting Genetic Algorithm II* (NSGA-II). Hasil eksperimen dianalisis dengan menggunakan (i) analisis kuantitatif berupa statistik deskriptif, uji Friedman, dan uji Wilcoxon *signed-rank* dengan koreksi Holm, (ii) analisis *trade-off* antar metrik, (iii) analisis sensitivitas, serta (iv) analisis visual lintasan UAV.

Hasil penelitian menunjukkan bahwa WE-Gen.A meningkatkan Indeks Kualitas Misi sebesar 2,74%–11,55% dibandingkan seluruh algoritma *baseline*. WE-Gen.A juga meningkatkan *coverage completeness* sebesar 4,72%–15,82%, UAV *fairness* sebesar 3,53%–9,26%, dan PoI *fairness* sebesar 4,51%–15,39%. Dalam kerangka simulasi level misi yang diusulkan, seluruh algoritma yang dievaluasi menghasilkan *data delivery ratio* yang secara konsisten tinggi. Selain itu, WE-Gen.A juga meningkatkan efisiensi energi sebesar 7,70%–22,47% dibandingkan NSGA-II, EB-GA, MR-GA, dan *Random*, meskipun lebih rendah 4,18% daripada *Greedy*. Meskipun demikian, WE-Gen.A mampu memberikan keseimbangan performa yang lebih baik pada seluruh komponen penyusun Indeks Kualitas Misi. Hasil uji Friedman menunjukkan bahwa perbedaan performa antar algoritma signifikan pada seluruh metrik utama ($p\text{-value} < 0,05$), sedangkan uji Wilcoxon menunjukkan bahwa WE-Gen.A secara signifikan mengungguli sebagian besar algoritma pembandingan dengan ukuran efek umumnya berada pada kategori sedang hingga besar. Kontribusi utama penelitian ini terletak pada pengembangan kerangka evaluasi *fitness* berbasis simulasi level misi, serta perumusan Indeks Kualitas Misi yang mengintegrasikan efisiensi energi, *coverage completeness*, *data delivery ratio*, UAV *fairness*, dan PoI *fairness* sebagai dasar evaluasi optimasi misi pengumpulan data secara *end-to-end*. Kerangka tersebut memungkinkan proses optimasi menghasilkan solusi yang lebih representatif terhadap karakteristik operasional sistem multi-UAV pada lingkungan FANET.

Kata kunci—Multi-UAV, FANET, Indeks Kualitas Misi, Algoritma Genetika sadar energi, Optimasi lintasan.

ABSTRACT

Multi-Unmanned Aerial Vehicle (multi-UAV) systems operating in Flying Ad Hoc Networks (FANETs) have been widely adopted for data collection missions in various applications, including environmental monitoring, remote sensing, and the Internet of Things (IoT). However, most existing optimization approaches still rely on static objective functions, such as travel distance, energy consumption, or coverage, and therefore fail to represent the end-to-end success of data collection missions that integrate sensing, onboard data buffering, wireless communication, and energy constraints within a unified framework. This study aims to formulate and implement a multicriteria Mission Quality Index as a quantitative objective function for data-collection missions involving multi-UAV systems in a FANET environment, as well as to develop and evaluate an optimization approach termed the Weighted Energy-aware Genetic Algorithm (WE-Gen.A).

WE-Gen.A evaluates each candidate solution through a mission-level simulation that explicitly models UAV mobility, energy consumption, sensing operations, onboard data buffering, time-slotted wireless communication, and data transmission to the Base Station (BS). The fitness function is formulated as a Mission Quality metric that integrates five performance metrics: energy efficiency, coverage completeness, data delivery ratio, UAV fairness, and Point of Interest (PoI) fairness. The proposed algorithm was evaluated through extensive simulations under various UAV fleet sizes and PoI distributions, and compared with Random Assignment, Greedy, Multi-Route Genetic Algorithm (MR-GA), Energy-Balanced Genetic Algorithm (EB-GA), and Nondominated Sorting Genetic Algorithm II (NSGA-II). The results were analyzed using (i) quantitative analysis consisting of descriptive statistics, the Friedman test, and the Wilcoxon signed-rank test with Holm correction; (ii) inter-metric trade-off analysis; (iii) sensitivity analysis; and (iv) visual analysis of UAV trajectories.

The results showed that WE-Gen.A improved Mission Quality Index by 2.74%–11.55% compared with all baseline algorithms. It also improved coverage completeness by 4.72%–15.82%, UAV fairness by 3.53%–9.26%, and PoI fairness by 4.51%–15.39%. Within the proposed mission-level simulation framework, all evaluated algorithms achieved consistently high data delivery ratios. Furthermore, WE-Gen.A achieved 7.70%–22.47% higher energy efficiency than NSGA-II, EB-GA, MR-GA, and Random Assignment, although it is 4.18% lower than Greedy. Nevertheless, WE-Gen.A provided a better performance balance across all Mission Quality Index components. The Friedman test indicated statistically significant performance differences among the evaluated algorithms across all major metrics ($p\text{-value} < 0.05$), while the Wilcoxon signed-rank test confirmed that WE-Gen.A significantly outperforms most baseline algorithms with effect sizes generally ranging from moderate to large. The main contribution of this research lies in the development of a mission-level simulation-based fitness evaluation framework and the formulation of a Mission Quality Index that integrates energy efficiency, coverage completeness, data delivery ratio, UAV fairness, and PoI fairness, as the basis for end-to-end data collection mission optimization. This framework enables the optimization process to produce solutions that are more representative of the operational characteristics of multi-UAV systems in FANET environments.

Keywords—Multi-UAV, FANET, Mission quality index, Energy-aware Genetic Algorithm, Trajectory optimization.