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Implementation of an Automata Mechanism for a Self-Organizing Swarm of Drones Platform

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Abstract

Drone technology has enabled major advancements in autonomous systems, particularly in swarm robotics. This paper presents a novel automation technique aimed at enhancing the efficiency, adaptability, and robustness of self-organizing drone swarms. The system uses decentralized control algorithms and robust communication protocols to enable real-time adaptive learning and decision-making among drones. Each drone acts as an autonomous agent, adjusting its behavior based on environmental inputs and interactions with other drones. A hybrid communication model blending peer-to-peer and cluster-based protocols ensures effective information sharing and coordination. To build a scalable and resilient architecture, multi-agent systems theory is integrated with advanced self-organizing strategies. Extensive modeling and real-world testing evaluated the systems performance in complex scenarios such as disaster response, environmental monitoring, and surveillance. Results demonstrate significant improvements in swarm efficiency, resilience to failures, and adaptability to dynamic environments. The incorporation of adaptive learning algorithms further optimized task allocation and execution in real time. This work represents a substantial advancement in autonomous aerial robotics, offering a comprehensive framework for deploying intelligent, self-organizing drone swarms and highlighting the transformative potential of automata-based approaches in future autonomous systems.

Keywords: Swarm of drones, Automata, Self-organizing system, Mathematical models.

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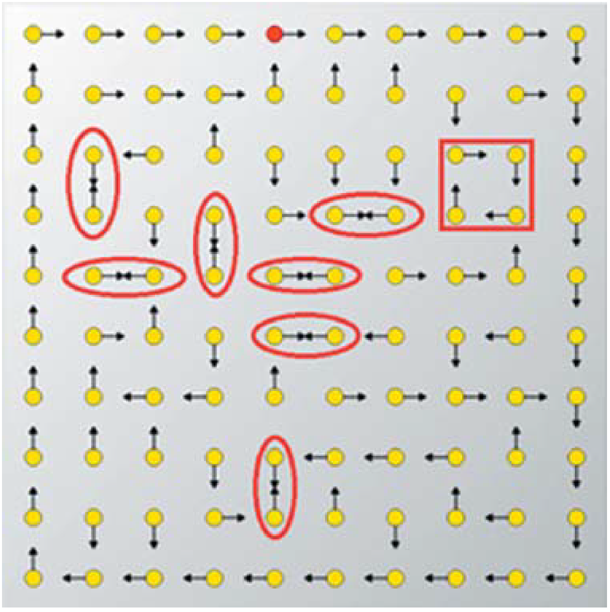
1. Introduction

Drone technology has improved dramatically in recent years, including benefits in agriculture, logistics, surveillance, and disaster response. Among these advances, swarm robotics has emerged as a particularly promising field of study and application. Swarm robotics draws inspiration from natural systems such as ant colonies and bird flocks to create decentralized, self-organizing groups of robots capable of performing complicated tasks more effectively than individual units [1, 2]. This technique uses the collective intelligence and collaborative skills of several robots to achieve goals that would be difficult or impossible for a single robot [3]. The application of an automata mechanism to a self-organizing swarm of drones represents a significant leap in the field of autonomous aerial robotics. In the context of drone swarms, an automata mechanism enables individual drones to operate independently while seamlessly coordinating with other drones in the group. This decentralized strategy enhances the swarm's ability to adapt to changing conditions, handle system failures, and optimize work distribution in real-time [4, 5]. This research focuses on the creation and implementation of decentralized control algorithms, resilient communication protocols, and adaptive learning techniques. Decentralized control algorithms enable each drone to make autonomous decisions using local data and interactions with its peers. This method is similar to that of social insects, in which simple individual norms evolve into complex and flexible group behavior. Implementing such algorithms allows the drone swarm to self-organize, distribute duties, and respond to environmental changes without the need for a central controller [6]. Robust communication protocols are required for swarm cohesion and coordination. These protocols ensure that drones can communicate data despite communication delays or breakdowns. Integrating peer-to-peer communication and clustering techniques allows the swarm to strike a compromise between efficiency and endurance. This hybrid communication architecture enables the dynamic formation of subgroups inside the swarm, resulting in more efficient task execution and resource allocation [7]. Adaptive learning techniques broaden the swarm's potential by allowing drones to learn from their experiences and improve their performance over time. Machine learning techniques, such as reinforcement learning and neural networks, can be linked to the automata process, allowing drones to optimize their activities based on environmental feedback. This continual learning process enables the swarm to adapt to new problems while improving its overall efficiency and effectiveness [8]. A self-organizing drone swarm has several potential applications. Drone swarms can be used in disaster response scenarios to quickly assess damage, find survivors, and provide crucial supplies. Swarms can collect data across huge areas for environmental monitoring, providing vital insights into ecosystem health and climate change. In surveillance and security operations, drone swarms may also cover large regions, monitor targets, and provide real-time situational awareness. The goal of this study is to give a thorough framework for implementing an automata mechanism in drone swarms while exhibiting the advantages of decentralized control, robust communication, and adaptive learning. By tackling the problems and opportunities connected with this technology, we hope to pave the way for future developments in autonomous aerial robotics and open up new avenues for a variety of applications.

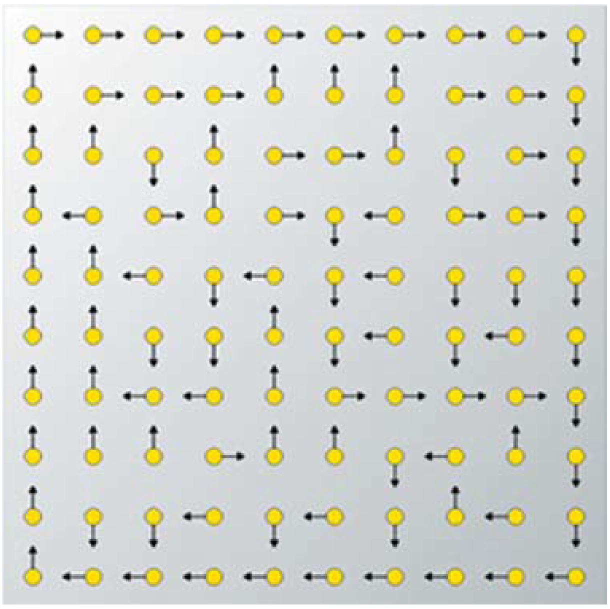
2. Self-Organized Systems and Gossiping Algorithms

Self-organization, also called spontaneous order in the social sciences, is a process where some form of overall order arises from local interactions between parts of an initially disordered system [9]. The process can be spontaneous when sufficient energy is available without outside control. Self-organization is often triggered by seemingly random fluctuations amplified by positive feedback. Self-organization is wholly decentralized and distributed over all the components of the entire system. As such, the organization is typically robust and able to survive or to self-repair from substantial perturbations. A narrower, still much closed concept related to self-organization is the phenomenon of self-ordering of systems. Complex dynamic systems are often self-organizing, and depending on the specified leading groups of properties, they are also called self-regulating, self-adjusting, self-learning, or self-algorithmizable systems. The Abelian sandpile model is the simplest and analytically tractable model of self-organized criticality [10]. In [11], a detailed overview of the known results about height probabilities and special correlation functions of the model is presented. In parallel, the research also focuses on the rotor-router model [12], where a one-to-one correspondence between the defined recurrent states and the graph spanning trees is observed. The rotor mechanism, first proposed in the theory of self-organized criticality under the name Eulerian walk, was rediscovered independently as a tool for the de-randomization of the random walk [13]. The dynamics of the rotor-router walk can be modeled over a square lattice with arrows attached to the sites, where arrows are directed toward one of the neighbors. A particle (a chip) performs a walk, jumping from a site to a neighboring site. Arriving at a given site, the particle changes the direction of the arrow at that site in a prescribed order and moves toward the neighbor pointed out by the new position of the arrow. Obviously, given an initial orientation of arrows on the whole lattice, the rotor-router walk is deterministic. The walk starting from uniformly distributed random initial configurations is called a uniform rotor walk. If the lattice is finite, the walk starting from an arbitrary site settles into an Eulerian circuit where each edge of the lattice is visited exactly once in every direction. When the walker is on the Eulerian circuit, the configurations of rotors associated with each site are recurrent. Graphically, the recurrent configuration representation is a unicycle. This is a specific state where the arrows form a spanning set of directed edges containing a unique directed cycle to which the particle belongs. Correlation between the Abelian sandpiles, Euler circuits and the rotor-router model is a subject to a rigorous mathematical survey [14]. The essential idea highlighted in the survey is the consideration of the rotor-routing action of the sandpile group on spanning trees in parallel with rotor-routing on unicycles. The rotor-router walk started from an arbitrary rotor configuration on a finite sink-free directed graph G, enters into an Euler circuit (Euler tour) and remains there forever (Fig. 1) after a finite number of steps.

In [13], the following property is proved: if at some moment, the rotors form a closed clockwise contour on the planar graph, then the clockwise rotations of rotors generate a walk which enters into the contour at some vertex, performs a number of steps inside the contour so that the contour formed by rotors becomes anti-clockwise, and then leaves the contour at the same vertex. This property generalizes the previously proved theorem for the case when the rotor configuration inside the contour forms a cycle-rooted spanning tree, and all rotors inside the contour perform a full rotation. We use this proven property for an analysis of the sub-diffusive behavior of the rotor-router walk. The suggested swarm algorithms and models have been designed based on the obtained results of the authors given below. The distinguishing characteristic of our approach against the existing solutions is that it meets all the classical requirements imposed on self-organizing systems, whereas the existing implementations each addresses the swarm construction and management specifically. Based on the analysis of available solutions and to best meet the requirements for UAV swarms construction, an optimally distributed software-hardware cloud system is suggested to manage self-organizing UAV swarms with the below mentioned capabilities. UAVs are loaded with basic schemes for information exchange. The development of decentralized and self-



(a) with cycle



(b) without cycle

Fig. 1. Cycle erasing illustration

organizing swarms of logically linked UAVs involved the design of optimal and fault-tolerant schemes (gossip/broadcast models). This enabled performing dynamic snapshotting and full exchange of captured images of the surveyed areas during the swarm quasi-random walk (rotor-router model). Essential definitions, concepts, and mathematical models of the construction are given below [15]. The gossip problem is formulated as follows: each of the participants within the group possesses distinct information. The goal is to distribute all the messages among all participants via phone calls. The minimum number of required calls is well-known: $\tau = 2n - 4$, $n > 4$. This problem can be modeled as a weighted graph, with vertices representing participants and edges representing the times at which peer communications occur. Unlike the existing methods, our approach enables communication between any two vertices (peers) to happen instantaneously, requiring only a single time tick. The utilization of k-fault-tolerant gossip graphs allows for the extension of the gossip problem to accommodate up to k arbitrary call failures. It is noteworthy that in the event of a call failure, no information exchange takes place. Subsequently, the subsequent objective was to determine the minimum number of calls required to achieve k-fault tolerance among n participants, denoted as $\tau(n, k)$, which remains an unresolved challenge. Presently, there exist only upper or lower bounds for

$$\tau(n,k) \leq \frac{n}{2}\log_2 n + \frac{nk}{2} \tag{1}$$

for n being a power of 2, and

$$\tau(n,k) \leq 2n\lfloor \log_2 n \rfloor + n\lceil \frac{k-1}{2} \rceil, \tag{2}$$

otherwise [16].

Definition 1. *A Knödel graph with* $n \geq 2$ *the vertices (*n *is even) and* $1 \leq \Delta \leq \lfloor log_2 n \rfloor$ *degrees is denoted by* $W_{\Delta,n}$*, where vertices are pairs of type* $(i, j), i = 1, 2; 0 \leq j \leq \frac{n}{2} - 1$*. For each of* j *and* $l, 0 \leq j \leq \frac{n}{2} - 1, l = 1, .., \Delta$*, there exists an edge weighted* l *between* $(1, j)$ *and* $(2, j + 2l - 1 - 1 mod \frac{n}{2})$ *nodes.*

3. Implementation of an Automata System Using Cloud Infrastructure and Physical Drones

This section discusses the automata environment provided by the platform, including dynamic scenarios and environmental variables (see Fig. 2).

3.1 Generate requests from QT

The Applications collection is produced utilizing the C++/QT library and Flask APIs. So, everything manages the toolset utilizing the QT environment. This section explains how to create requests from the QT environment to power the platform's functionality. An active server is required to start the preparation platform, and programs must automatically establish connections. Users upload location images to the server, which displays an input window displaying a map based on the image's coordinates. While users enter the appropriate coordinates, the system computes the real-world coordinates for each pixel, ensuring accuracy while configuring the simulation environment. The QT service layer protects against attacks by utilizing strong encryption while sending data to virtual servers in the cloud architecture over secure Internet TCP protocol communication channels. The drone map/automata graph module allows users to construct and manage maps for drone swarm navigation and task management. The JSON structure of all queries ensures that the platform and the QT environment communicate effectively and transparently. Users design a flight operation network for the drone swarm using the computed absolute coordinates of the pixels in the landscape image. The classification of vertices into Corner, Side Border, and Inner types facilitate precise drone operations planning. After that, users enter the drone's IP port to commence communication and select specific side vertices for drone installation. When the return router method completes any network cycles, the system generates coordinates and navigation data, which are then sent to the drone ground station. With the correct coordinates, the drones can travel the network without assistance from a person. Users can indicate target locations for drone strikes on a terrain image using internal geographic coordinates. Users can adjust the default network topology as needed. All changes are logged in a detailed log, which immediately alerts the cloud server and ensures that all users' graphical interfaces are consistent.

3.2 Cloud Infrastructure

The development of a cloud-based platform for mission preparation for self-organizing drone swarms using multi-agent systems, such as sandpile models, rotor-router models, and optimal gossip broadcast schemes, represents a significant innovation in the domain of logically interconnected and decentralized intelligent networks (see Fig 2.).

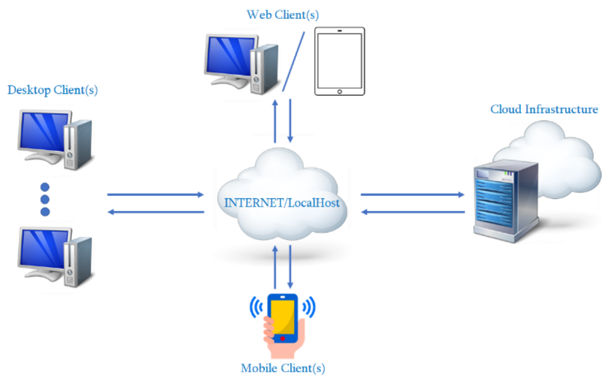


Fig. 2. Cloud infrastructure

The development of software toolsets for managing self-organizing drone swarms is both difficult and costly. As a result, combining virtual environments, cloud technologies, and computational resources into a single platform provides realistic solutions to these issues. The proposed platform seeks to enable autonomous mission execution across a wide range of activities and scenarios while lowering the time and cost associated with drone swarm missions. Our proposed and validated solutions for building high-performance computing infrastructures serve as the foundation for the design and implementation of this cloud platform, which adheres to modern standards and includes AI-powered collection, categorization, and processing of massive data, improved electronic infrastructure energy usage and cloud computing settings, efficient use of HPC resources for linear algebra computations, and cloud service disposal. Cloud computing has substantially improved the efficiency of image-processing for drones by leveraging scalable computer resources and large amounts of storage. Our proposed and validated solutions for building high-performance computing infrastructures serve as the foundation for the design and implementation of this cloud platform, which adheres to modern standards and includes AI-powered collection, categorization, and processing of massive data, improved electronic infrastructure energy usage and cloud computing settings, efficient use of HPC resources for linear algebra computations, and cloud service disposal. Cloud computing has substantially improved the efficiency of UAV image-processing processes by leveraging scalable computer resources and large amounts of storage. Our strategy makes use of a serverless cloud platform for high-performance computing (HPC), which has been precisely engineered to properly handle the drone swarm's HPC workloads, guaranteeing that swarm operations are completed on time. A server execution environment is created within the cloud architecture, with one server dedicated to swarm or single-drone flying operations. This server's IP address is documented in a functional log file that users can access via a graphical user interface. Each server is assigned a specific task, which involves initiating data processing and ensuring that results are visible and synced. This architecture facilitates the dispersed and efficient execution of drone flying operations and data processing.

4. Conclusion

This study effectively demonstrated the use of an automata mechanism to improve a drone swarm's self-organizing capabilities. The swarm functions efficiently and adapts to changing situations without central control by utilizing decentralized control algorithms, strong communication protocols, and adaptive learning processes. The use of cloud services enhances these capabilities by providing scalable computer resources and real-time data processing. Cloud-based infrastructure improves swarm communication and coordination, enabling more efficient information sharing and dynamic work allocation. The experimental results indicate considerable gains in task performance, resource utilization, and adaptability, demonstrating the system's usefulness in a variety of applications such as disaster response, environmental monitoring, and surveillance. Finally, the synergy between automata mechanisms and cloud services provides a solid foundation for future advances in autonomous drone swarms, paving the way for novel solutions in complex and dynamic circumstances.

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Ավտոմատների մեխանիզմի իրականացումը ինքնակազմակերպվող ԱԹՍ-երի երամի հարթակի համար

Ագիթ Ֆ. Աթաշյան, Արտյոմ Ա. Լազյան, Դավիթ Վ. Հայրապետյան
Վահագն Ս. Պողոսյան

ՀՀ ԳԱԱ Ինֆորմատիկայի և ավտոմատացման պրոբլեմների ինստիտուտ, Երևան, Հայաստան
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Ամփոփում

Անօդաչու թռչող սարքերի տեխնոլոգիան հնարավորություն է տվել զգալի առաջընթացի հասնել ինքնավար համակարգերում, մասնավորապես՝ երամային ռոբոտատեխնիկայի ոլորտում: Այս հոդվածում ներկայացվում է ավտոմատների նոր տեխնոլոգիա, որը նպատակ ունի բարձրացնել ինքնակարգավորվող անօդաչու երամի արդյունավետությունը, հարմարվողականությունը և հուսալիությունը: Համակարգը օգտագործում է կենտրոնազերծ կառավարման ալգորիթմներ և հուսալի հաղորդակցման պրոտոկոլներ՝ անօդաչու սարքերի միջև իրական ժամանակում հարմարվողական ուսուցման և որոշումների ընդունման ապահովման համար: Յուրաքանչյուր անօդաչու սարք գործում է որպես ինքնավար գործակալ՝ իր վարքը փոփոխելով՝ ելնելով շրջակա միջավայրի ներմուծումներից և մյուս սարքերի հետ փոխազդեցությունից: Հաղորդակցության հիբրիդային մոդելը, որը համատեղում է peer-to-peer և կլաստերային պրոտոկոլները, ապահովում է տեղեկատվության արդյունավետ փոխանակում և համաժամեցում: Մասշտաբային և կայուն ճարտարապետություն ստեղծելու համար բազմագործակալ համակարգերի տեսությունը ինտեգրվել է ինքնակազմակերպման առաջադեմ ռազմավարությունների հետ: Ընդգրկուն մոդելավորումը և իրական պայմաններում փորձարկումները գնահատել են համակարգի աշխատանքը բարդ սցենարներում, ինչպիսիք են աղետների արձագանքը, շրջակա միջավայրի մոնիթորինգը և հսկողության առաքելությունները: Արդյունքները ցույց են տվել երամի արդյունավետության, խափանումների նկատմամբ կայունության և դինամիկ միջավայրերին հարմարվելու ունակության զգալի բարելավում: Հարմարվողական ուսուցման ալգորիթմների ներգրավումը հետագա կերպով օպտիմալացրել է առաջադրանքների բաշխումը և կատարումը իրական ժամանակում: Այս աշխատանքը կարևոր առաջընթաց է ինքնավար օդային ռոբոտատեխնիկայում՝ առաջարկելով ինտելեկտուալ, ինքնակարգավորվող ԱԹՍ երամի տեղակայման համապարփակ շրջանակ և ընդգծելով ավտոմատների վրա հիմնված մոտեցումների փոխակերպող ներուժը ապագա ինքնավար համակարգերում:

Բանալի բառեր՝ ԱԹՍ երամ, ավտոմատներ, ինքնակարգավորվող համակարգ, մաթեմատիկական մոդելներ:

Реализация механизма автоматов для самоорганизующейся платформы роя дронов

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Аннотация

Технология дронов позволила добиться значительных успехов в автономных системах, в частности в роевой робототехнике. В этой статье представлена новая технология автоматизации, направленная на повышение эффективности, адаптивности и надежности самоорганизующихся роев дронов. Система использует децентрализованные алгоритмы управления и надежные протоколы связи для обеспечения адаптивного обучения и принятия решений в реальном времени среди дронов. Каждый дрон действует как автономный агент, корректируя свое поведение на основе входных данных окружающей среды и взаимодействия с другими дронами. Гибридная модель связи, сочетающая одноранговые и кластерные протоколы, обеспечивает эффективный обмен информацией и координацию. Для создания масштабируемой и устойчивой архитектуры теория многоагентных систем интегрирована с передовыми стратегиями самоорганизации. Обширное моделирование и тестирование в реальных условиях оценивали производительность систем в сложных сценариях, таких как реагирование на стихийные бедствия, мониторинг окружающей среды и наблюдение. Результаты демонстрируют значительные улучшения эффективности роя, устойчивости к сбоям и адаптивности к динамическим средам. Включение адаптивных алгоритмов обучения еще больше оптимизировало распределение и выполнение задач в реальном времени. Эта работа представляет собой существенный прогресс в автономной воздушной робототехнике, предлагая комплексную структуру для развертывания интеллектуальных, самоорганизующихся роев дронов и подчеркивая преобразующий потенциал подходов на основе автоматов в будущих автономных системах.

Ключевые слова: рой дронов, автоматы, самоорганизующаяся система, математические модели.