**VI SIMPOSIO DE LOGÍSTICA Y GESTIÓN DE LA CALIDAD**

**Automated Warehouse Processing with Autonomous Drones**

***Procesamiento automatizado de almacenes con drones autónomos***

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**Abstract:**

In this paper, a mathematical model and solution will be presented for performing the inventory tasks of a multi-user, mixed warehouse. After reviewing the literature on route planning and the use of drones in warehouses, we present a method that has been used to control drones movable in all directions and suitable for imaging and transmission. The proposed method consists of four main steps. In the first step, we provide the mathematical model and solution method required to determine the (optimal execution time) access routes required for processing the compartments of the warehouses. In the second step, based on the routes obtained in the first step, we control the real-time movement of the drones during the processing, which includes the movement of the camera and image recording. The third step is post-processing, i.e., the processing of QR code identification images, the interpretation of the QR code, and the recognition of empty compartments for inventory control. In the fourth step, the received data is transferred to the central system. The proposed model and solution method are suitable not only for inventory control, but also for solving other problems matching the model.

***Abstract:***

En este artículo se presenta un modelo matemático y una solución para realizar las tareas de inventario de un almacén mixto multiusuario. Tras revisar la bibliografía sobre la planificación de rutas y el uso de drones en almacenes, presentamos un método que se ha utilizado para controlar drones móviles en todas direcciones y aptos para la captura y transmisión de imágenes. El método propuesto consta de cuatro pasos principales. En el primer paso, proporcionamos el modelo matemático y el método de solución necesarios para determinar las rutas de acceso (tiempo de ejecución óptimo) necesarias para procesar los compartimentos de los almacenes. En el segundo paso, basándonos en las rutas obtenidas en el primer paso, controlamos el movimiento en tiempo real de los drones durante el procesamiento, lo que incluye el movimiento de la cámara y la grabación de imágenes. El tercer paso es el posprocesamiento, es decir, el procesamiento de las imágenes de identificación del código QR, la interpretación del código QR y el reconocimiento de los compartimentos vacíos para el control del inventario. En el cuarto paso, los datos recibidos se transfieren al sistema central. El modelo y el método de solución propuestos son adecuados no sólo para el control de inventarios, sino también para resolver otros problemas que coincidan con el modelo.

**Keywords:** *Drone, Genetic algorithm, Inventory, Mathematical model, Route planning*

***Palabras Claves:*** *Dron, Algoritmo genético, inventario, Modelo matemático, Planificación de rutas*

**1. Introduction**

The effective management of a company's products and stocks has become a crucial determinant of its operational capacity. Inventory management is a vital aspect of business operations, as including each item in the store contributes to the organization’s overall worth. Managers must know the value of the commodities inside their respective organizations. Hence, the implementation of effective inventory management procedures holds significant strategic importance. Effective inventory management entails some duties that necessitate a substantial allocation of human resources. Therefore, prioritizing the training of professionals is imperative, particularly in computer literacy (Hua-Gubán, 2014).

Currently, there is a fundamental shift occurring like work. Technological advancements have facilitated the integration of human-robot collaboration in various domains, including the business setting. The successful resolution of these difficulties necessitates the integration of robots, a factor notably impacted by multiple factors, including individual attitudes (Kiss et al., 2022).

Drones represent a significant advancement in warehouse inventory management, providing seamless real-time inventory monitoring, ensuring swift and precise tracking. Moreover, using drones in this context minimizes operational expenses for stakeholders involved in the supply chain. In addition, they provide safety advantages by mitigating potential harm to individuals. To minimize their environmental impact, the organization use rechargeable batteries to fulfil its everyday operating tasks. From an economic standpoint, implementing these systems enables almost uninterrupted monitoring of inventory levels and reduces labor expenses and operational disruptions associated with inventory management by enhancing operational decision-making (Karamitsos et al., 2021).

This essay aims to introduce a novel mathematical model and accompanying methodology. The present study elucidates the conceptual framework and procedural approach for managing a GPS-inaccessible high-altitude warehouse inventory. This involves utilizing several drones, equipped with a QR code system, to facilitate the inventory process.

**1.1. Literature review**

Inventory work is an essential link in the record-keeping system of industrial enterprises. To improve the current shortcomings of manual inventory (e.g., low efficiency and the possibility of error), drones equipped with high-accuracy portable radio frequency identification readers have been used in recent years. An important issue in using drones is the path the devices should follow during processing. Nowadays, many articles deal with drone routing, closely related to the inventory problem.

In the model given by Nan Pan and co-authors (2021), a hybrid differential evolution (DE) algorithm based on the life-cycle swarm optimization (LSO) algorithm was proposed. To reduce energy consumption and improve inventory efficiency, the lowest energy efficiency and the time efficiency ratio were used to form the objective function. A corresponding mathematical model for UAV route planning was established. For physical modelling, actual environmental data of a tobacco company's raw material and auxiliary material warehouse were used, and the simulation experiment was performed using the proposed intelligent optimization algorithm. In the same environment, compared with the other three leading-edge path planning algorithms, the experimental results showed that the path planned by the proposed algorithm can improve the efficiency of UAV warehousing.

Several articles deal with route planning based on a two-dimensional environment, which is unsuitable for practical applications since our system requires spatial route planning. The algorithms most used by researchers for inventory-appropriate route planning are the traditional squid algorithm (Chen et al., 2008), the genetic algorithm (Udvaros et al., 2019; Chen et al., 2022), the fast-expanding random tree algorithm (Wang-Yang, 2021), the traditional particle swarm optimization (PSO) algorithm, the ant eel algorithm (Huang et al., 2022), and neural networks (Albattah et al., 2022). Most researchers only consider the shortest flight path or the most minor energy consumption when generating the single-objective optimization model, and then apply the convex approximation strategy to determine the route. These solutions are of good practical use, and our research relies on these results, but our objective function will be a max-min time function, which does not allow the direct application of the given methods.

According to Yuhang Han et al. (2022), the key to drone route planning and efficient inventory management is to equip the drone with a high-accuracy portable radio frequency identification (RFID) reader to perform the inventory task. This paper proposes a method for route planning that uses a drone equipped with an RFID reader to inventory products stored in a warehouse. However, the particle swarm optimization algorithm (PSO) tends to become locally optimal when solving the route planning problem. PSO is improved, and an improvement method based on differential evolution is proposed.

To solve the inventory task, it is necessary to investigate which drones suit the task. Our previous study (Gubán et al., 2022a) shows that autonomous drones are needed for the job. For a drone to be fully independent, localization capability is essential. Adequate accuracy is achieved by using information sources from different locations. Eduard Mráz and colleagues (2020) used two sources of information in their research:

* Intel RealSense T265 tracking camera for continuous visual odometry calculation and
* The RGB color sensor was combined with ArUco's[[1]](#footnote-1) reference marker to minimize the error accumulated during visual odometry.

However, it is essential to acknowledge that these indicators include inherent limitations. Variance filtering is employed to mitigate the inaccuracies associated with ArUco markers. The system underwent multiple testing iterations utilizing an autonomous drone capable of indoor flight. The localization processes were successfully executed on the Nvidia Jetson Nano computer linked to the drone. The findings above collectively demonstrate the ability of autonomous drones to manage inventory control operations indoors without human involvement.

As stated in the scholarly work authored by Wawrla, L. et al. (2019), the primary objective behind the integration of an uncrewed aerial vehicle (UAV) system within a warehouse setting is to minimize operational durations and eradicate the need for human involvement in monotonous and straightforward duties. One of the domains above pertains to the inventory procedure, which encompasses utilizing diverse information-bearing mechanisms such as barcodes, QR codes, or RFID tags. The labor-intensive nature of this operation is most pronounced in high-bay warehouses, which house tens of thousands of products. Warehouses commonly conduct periodic inventory checks, typically monthly, quarterly, or other regular. Nevertheless, conducting stocktaking is a significant problem due to the necessity of temporarily suspending warehouse operations and involving the entire warehouse workforce in the stock control process, resulting in a time loss for the organization. Hence, there is a growing imperative to mechanize this procedure, with the dual objectives of diminishing the time required for execution and mitigating the occurrence of faults stemming from human execution.

Automated inventory management involves using a camera mounted on a drone to identify and locate products within a high-bay warehouse accurately. The autonomous aerial vehicle traverses a predetermined path within the warehouse premises. It conducts an inventory assessment using barcode or QR code scanning, specifically assigned to each product (Gubán et al., 2022b). In contrast to constructed warehouses, which typically employ bins with clearly defined shelves for load storage, products stored in open spaces generally lack a systematic arrangement. Efficient inventory management in the warehouse yard necessitates estimating QR code locations affixed to the products. In this scenario, a position estimation method that relies on a QR code segmentation model is deemed suitable. The segmentation approach is employed to identify areas inside a QR code that exhibit perspective distortion resulting from the angular disparity between the camera and the QR code. Following the identification process, the region containing the detected QR code undergoes shape correction and decoding. These methods can be employed to confirm the authenticity of the QR code and to approximate the location of the uncrewed aerial vehicle. The 3D coordinates of the QR code affixed to the product are determined by analyzing the drone images from two distinct perspectives. The warehouse can develop an effective inventory management system by implementing this approach. In the present scenario, we manage a pre-established intricate warehouse configuration. The design of the warehouse structure can be determined either through the utilization of a blueprint or by employing a pre-existing recognition algorithm for pre-built systems.

In their recent publication, Gubán et al. (2022a) introduce a novel conceptual framework incorporating a versatile drone equipped with imaging and transmission capabilities, allowing unrestricted movement in several directions. The paradigm under consideration has five primary phases. The system offers an optimal method for determining a passage pathway during the initial stage. This aligns with the architectural design and functional capacities of the facility. The second part of the procedure involves the assessment of the drone's real-time motion, encompassing both camera adjustments and image acquisition. The third stage requires post-processing, which entails processing images to facilitate QR code identification and interpretation and analyzing matches and inconsistencies for inventory control. One significant advantage for practitioners is that the desired outcome is attained without additional orientation tools, as the drone relies exclusively on its motions and a predetermined flight path. The present study employs the utilization of a drone as a means to demonstrate a model and propose a solution strategy for effectively accessing fixed-roster shelving systems.

Based on the comprehensive assessment of existing literature, it is evident that no prior approaches to inventory management similar to the one proposed in this study have been encountered. Therefore, as presented in this research, the model and solution method for inventory management with drones is a pioneering advancement in the field.

**2. Methodology**

Determining the precise whereabouts of stored products poses a challenge within the expansive and heavily utilized warehouses of logistics centers. This scenario commonly occurs when automated forklift trucks do not perform storage operations or when commodities are erroneously selected from an incorrect place during the picking process. In addition to exacerbating the situation, GPS-based identification within these warehouses is highly challenging and unattainable in certain instances. The absence of time-of-flight (ToF) cameras makes placing automated equipment unfeasible. This study presents a conceptual framework that may be universally applied to various warehouse configurations, enabling the utilization of drone technology for inventory record updates.

The warehouse is where loading, unloading, order picking, unit load design, and labelling occur. The warehouse employs a dual shelving arrangement. The wide aisle between the twin shelves provides ample space for the drone to navigate. The frame is partitioned into separate compartments. The vertical dimensions of each case may exhibit variation. The commodities housed in the rooms are identified by a QR code, which provides all the required data for handling.

From the center of the corridor, a drone equipped with a mid-range camera can capture a superior quality photograph. The dock is manually positioned at the terminus of the gallery, serving as a location for recharging and replacing the battery. However, the specific positioning of each drone must be provided.

Multiple drones can be simultaneously utilized for processing operations within the warehouse setting. In this particular scenario, each drone will operate autonomously. However, it is essential to note that a single drone can only process each aisle. This means that two separate drones cannot process two distinct compartments within the same corridor within the same processing cycle. Furthermore, drones will navigate across aisles at varying altitudes to mitigate collisions. To arrive at a solution, it is satisfactory to delineate the operational sequence for a single drone and then apply the same procedure to the remaining drones. The known data for the model includes representing the warehouse's structure and shelving system. The distinctions above can be unambiguously delineated by referring to the design documentation of the warehouse, which can be further augmented by conducting an on-site inspection utilizing drones to enhance the accuracy and precision of the data.

The model's functionality remains unaffected by the specific location of the docks, as it solely necessitates awareness of the dock's placement within the vast warehouse expanse.

**2.1. The research study prompted the formulation of the subsequent research questions:**

1. How can warehouse stocking be automated with drones?

2. Can the process of drone inventory be mathematically modelled?

2. If it can be modelled, can a solution method be provided for the problem associated with the model that answers the four sub-questions below:

3.1. How can we optimise (minimise) stocking time with drones?

3.2. The corridors in which each drone should start its inspection,

3.3. which route to take, i.e. the order in which compartments are visited during processing and

3.4. - if necessary - when should I visit the charger?

All this must be done so the drones can carry out their tasks without colliding.

**2.2. Outline of the proposed solution**

Processing consists of five main processing stages.

Phase 1: define the warehouse design and provide the model's necessary warehouse and drone data.

Phase 2: Determining the optimal routes to be followed by each drone and the times for charging/changing batteries.

Phase 1: Inventory is carried out using the drone program based on the route plan provided by Phase 2.

Phase 1: perform the photo processing and extract the QR code data.

Phase 2: transmission of the processed photo data to the Central Application.

This paper aims to present a mathematical model and algorithm in the initial phase, which addresses the research issues and proposes a feasible approach for automating warehouse inventory processing. Furthermore, the algorithm for the second phase is provided.

**2.3. Outline of the model for Phase 1**

The initial stage of the modelling process involves clarifying notations and their corresponding substance. A comprehensive inventory of parameters was conducted to accomplish this. The data set was established in collaboration with professionals in the field. The collected data was categorized based on its role inside the model. The parameters are extensively elucidated in the publication authored by Miklós Gubán et al. (2022a). In the subsequent stage, a mathematical model was developed to represent the manufacturing parameters of the warehouse and the drones intended to be utilized, along with incorporating variable data. A tractable and simplified motion and velocity model was developed by Gubán et al. (2022a). Subsequently, the subsequent course of action was to formulate a pragmatic positioning plan.

The mathematical model was constructed taking into account:

1. the operating time of drones and the necessary in-flight charges accordingly.

2. Safe corridor changes, avoiding collisions.

In the processing, the path of a drone is broken down into several stages that are important for modelling:

1. The safe way to take your drone from the charger to the front compartment.

2. The drone's path to the next compartment to be processed. This compartment to be processed can be

a. another case of the same shelving system,

b. a point of the shelving system opposite (camera rotation),

c. another room in another corridor.

The model is designed for one-way or two-way traffic in the corridors. The model is described in detail in Miklós Gubán et al. (2022a).

Figure 1. The processing flow for each drone



*Source: own editing*

The first two research questions can be answered affirmatively by describing the procedures and presenting the mathematical model encompassing the automated processing and the drone path.

**2.3.1. Method of solving the problem related to the model**

The proposed technique employed a genetically modified algorithm to identify the most efficient way for drone access minimizing distance travelled. In this study, we offer an optimization approach for determining the path of a drone with the longest processing time. However, it is essential to note that our proposed method also aims to maximize the operation time of the remaining drones. The inclusion of supplementary algorithms is necessary in this context:

* *The objective function generator algorithm*

The algorithm gives the time of operation for a given route for one drone, but you can set up the function for all drones in a similar way. The algorithm returns the value of the objective function for the current assignment.

* *Checking compliance with the restrictive conditions*

The algorithm of nonlinear constraint conditions checks for a given path whether the model's set of conditions is satisfied.

All subsidiary inquiries about research question 3 have been effectively addressed by explicitly delineating the algorithms employed. The methodology provides each drone's comprehensive and time-efficient trajectory, encompassing the initial intersection and the duration required to reach the charging station.

**2.4. The processing flow of Phase 2**

The unmanned aerial vehicle transitions from the loading area to the initial compartment of the primary aisle for further processing. The drone systematically traverses the hall, sequentially inspecting the bays before capturing photographic images, which are subsequently transmitted to pre-processing equipment. During the pre-processing stage, the initial scan is conducted to assess the quality of the picture. The drone remains stationary until it receives instructions from the pre-processing program to alter its position. In the event of an unsatisfactory image, the pre-processing application will prompt the drone to capture an additional embodiment, with a maximum allowance of three attempts. The drone will proceed with its trajectory if the image quality is satisfactory. During the image processing phase, the pre-processing system assesses to determine the presence of a QR code within the photograph. If this is the case, the content is being read. Upon achieving success, the information inside the QR code is transmitted to the central application, resulting in the adjustment of the processing status indication to reflect the successful outcome. If the specified condition is not met, the processing status of the compartment will be changed to Failed. A notation indicating an empty room is recorded if a QR code cannot be detected. Notably, the absence of a QR code does not necessarily imply that the compartment is genuine. The determination of whether the room is empty or if the processing has encountered an error will be made by the central application. In this scenario, the drone is consistently dispatched to the subsequent compartment. The execution of additional operations is always performed within the core application and exclusively relies on the functionalities offered by the central application. The elucidation of the procedures involved in the main application falls outside the purview of this scholarly publication.

Upon processing each compartment, the pre-processing application transmits relevant data to the central application, including the compartment's location, processing status, and QR code information.

Based on the model, the pre-processing system possesses precise knowledge regarding the drone's exact location within the warehouse. In other words, the 3D data about the warehouse is specified. In conjunction with this information, the provided QR code enables the inventory management model to determine the product's location accurately. If no QR code is detected, the specified place lacks inventory.

The pre-processing program incorporates pre-established optimal routes for individual drones, primarily optimized to maximize the drone's operational duration. This optimization considers the time required to recharge or replace batteries if the drone's power level is depleted.

The programming of the solution method for phase 2 is contingent upon the outcomes of the initial phase and is to be implemented within the pre-processing application.

**3. Results and discussion**

The authors of this study have devised an innovative methodology for the automated inventory management of high-altitude warehouses by utilizing drones. The authors have established a comprehensive mathematical framework by examining multiple warehouses to elucidate the underlying problem. Additionally, the authors presented techniques that address the difficulty connected with the model, facilitating the implementation of the acquired results in practical scenarios. Simultaneously, the researchers examined the drone configuration's influence on resolving the logistical challenges encountered within the warehouse. The utilization of this model and the subsequent resolution of the associated problem enable the comprehensive examination of the effects of employing drones for automated warehouse processing on various sustainability factors, with specific emphasis placed on energy usage.

The primary contribution of the article is in its demonstration of the feasibility of mathematically modelling the problem at hand, hence enabling a general solution through the utilization of said model. Furthermore, an additional benefit is that the proposed method dramatically influences warehouse operations' automation, velocity, and energy efficiency while considering all pertinent restrictions associated with the problem.

This paper makes a significant scientific contribution to researchers studying the application of drones in warehouse processes. It achieves this by systematically mapping the critical components of the problem, generalizing previously observed elements, developing a novel mathematical model, and establishing time functions that determine the most efficient processing path. The paper also presents a solver algorithm and its associated auxiliary algorithms. The findings further validate the fundamental assumption that the problem is solvable.

The findings possess generalizability due to the inclusion of various components in the model, such as the utilization of multiple drones, potential variations in start times, diverse shelving arrangements, and unidirectional and multidirectional traffic. These elements may not be present in every individual warehouse or may only be present in certain sections. Consequently, the model and its solution can be applied to any system, not exclusively to warehouses, as long as the concepts and definitions align with the given context. Consequently, the findings can be utilized to tackle effective processing routes in a broader context, encompassing various additional forms of drone-related services.

The findings of this study have the potential to inform managerial decision-making, as the stated methodology enables the investigation of specific processes within automated warehouse management and facilitates strategic decision-making through the examination of several factors. This will allow the identification and implementation of a warehouse management system that optimally aligns with the logistical objectives established.

One of the model's limitations is its ability to address improper aperture processing in photography automatically. While the incidence of this phenomenon is relatively low, it is imperative to conduct a thorough investigation to mitigate the need for manual processing of apertures. Furthermore, the stability of the solving method gives rise to inquiries, as it appears to be highly sensitive to parameters upon initial examination. Consequently, it is advisable to do sensitivity analyses and enhance it through additional research. Furthermore, exploring a broader spectrum of solution methodologies is imperative, potentially integrating them with contemporary approaches to improve the solution algorithm's stability.

**4. Conclusions**

The advent of the information society has brought forth many digital options that have revolutionized various domains, offering innovative and clever solutions that were previously inconceivable. The proliferation of Industry 4.0 can be attributed to the rise of sensor-based intelligent devices that facilitate enhanced automation in manufacturing, production, and service sectors. Furthermore, these devices often offer autonomous decision-making capabilities, particularly in high-stakes or contentious scenarios. These solutions, along with the increased digital maturity of the organization, may now function with enhanced efficiency and, significantly, with a greater emphasis on environmental consciousness.

Uncrewed aerial vehicles (UAVs), also known as drones, have the potential to contribute to critical technical operations inside various industries significantly. Using uncrewed aerial vehicles, also known as drones, has expanded the scope of functions beyond just production to encompass logistical and economic dimensions. Nevertheless, the warehouse under investigation lacked the conventional infrastructure for drone management, necessitating the development of a bespoke three-dimensional control system. Simultaneously, it is imperative to consider that the energy supply utilized for propelling the equipment possesses a limited capacity to sustain power for a brief duration. To maximize the processing of compartments in a single charge, it was necessary to calculate the optimal course of movement meticulously. Naturally, this alignment is congruent with environmental considerations, as the execution of economic operations with consistent energy input leads to a reduction in specific emissions.

In conclusion, a 5-stage solution has been successfully developed to enable the drone to execute the inventory control work efficiently. This solution entails the drone doing various processes, such as finding, identifying, and interpreting one or more identifiers on the unit loads, all within the lowest possible timeframe. The acquired data is transferred to the organization’s enterprise resource planning (ERP) system via an interface tool and application.

The model and optimization method that we have derived have undergone a rigorous evaluation. The comprehensive review of efficiency and sensitivity remains pending, as it necessitates field testing and analysis of actual operational outcomes. The produced tool offers practical, expeditious, precise, and almost ideal real-time answers.

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1. ArUco - Augmented Reality University of Cordoba - is a square marker consisting of a wide black border and an inner binary matrix. [↑](#footnote-ref-1)