Multi-UAV System for Inventory Automation

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***Abstract*—This paper discusses the high-level design considerations and implementation challenges of an RFID-reader-equipped multi-UAV (unmanned aerial vehicle) system to aid inventory automation in a warehouse. A preliminary simulation, employing probabilistic-like algorithm for navigation decision, was also conducted to visualize the feasibility of the system.**

***Index Terms*—Algorithms, Design, Performance, Probability, Reliability Simulation**

I. Introduction

In supply chain flow, inventory shrinkage due to unaccounted stock is not uncommon. Accuracy of inventory can help reduce the profit loss due to this form of inventory shrinkage [1] [2]. While early adopters have started employing RFID technology in their supply chain flow, many are still questioning the return-of-investment of RFID technology. Over-the-air signal interference and the potentially high velocity of moving RFID tags when stock first arrive or leave the warehouse may affect the performance of RFID readers [3].

This paper proposes an automated system to certify the inventory amount recorded during stock arrival or stock shipment by deploying mobile RFID-readers. These readers are carried by unmanned-aerial-vehicle (UAV) to perform inventory checking after stock has been transferred to shelving areas. This will reduce the probability of unaccounted stock based on Eq. 1.

$$Pr(ie) = Pr(rd) * Pr(sd) * Pr(sa) \tag{1}$$

Pr(ie) represents the probability of inventory error, Pr(rd) represents the probability of missed RFID readings at receiving dock, Pr(sd) represents the probability of missed RFID readings at shipping dock and Pr(sa) represents the probability of the mobile RFID-readers' failure to discover the stocks at shelving area. Since each probability is always less than one, the proposed system will decrease the probability of inventory error. Moreover, with constant monitoring from the UAVs, the proposed system will also provide inventory visibility.

While there are existing robots designed to cover two-dimensional space such as iRobot's Roomba, none has been designed to cover three-dimensional space which is required for inventory tracking. Uneven terrain in a warehouse and items stored at higher places, unreachable to a grounded robot, trigger the need for a flying system. However, the capability to traverse a 3D path is not sufficient to perform inventory.

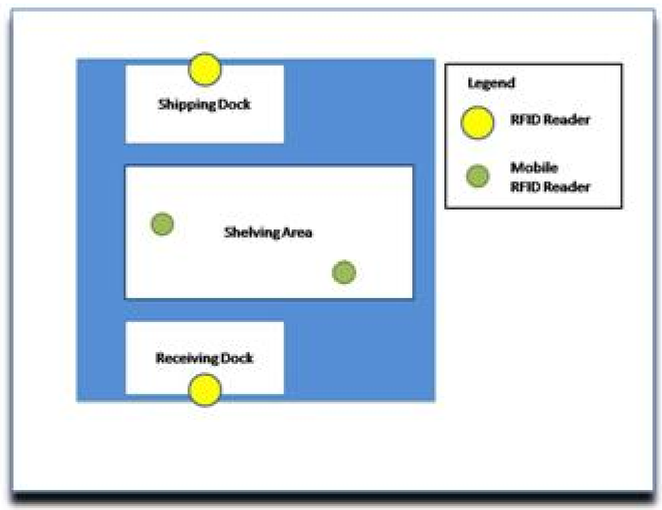

Fig. 1. Proposed inventory method with mobile RFID-readers.

An exhaustive method would require the multi-UAV system to cover all possible spaces to determine the correct number of items in a warehouse. Equipped with a RFID reader that has a limited reach range, the UAVs may be required to retain information of its trajectory and not just programmed to reach a destination. Moreover, dynamic obstacles have to be taken into account when designing the UAV system.

Nevertheless, the multi-UAV system is not the sole solution to this three-dimensional problem. Warehouse can deploy many RFID readers around the warehouse such that the RFID-reader read-range can cover the entire warehouse. There has also been new technology that allows many antennas to connect to one RFID-Reader. The multi-UAV system however, provides flexibility to accommodate changing warehouse layout which static RFID-reader deployment does not. Apart from performing inventory, the multi-UAV system will also allow spatial tracking of items in a warehouse. Once deployed, the helicopters can also perform other tasks such as security, survey and other sensing such as air pressure and room temperature.

This remainder of the paper is organized as follows. Section 2 summarizes previous work that can be leveraged for this project. Section 3 details the simulation conducted as a preliminary analysis of this problem. Section 4 describes the high-level design consideration and potential challenges that may arise while Section 5 concludes the finding of this paper and a brief description of future work to follow. Overall, this paper discusses the high-level design considerations of a multi-UAV system to aid inventory-automation.

II. Previous Work

Previous work in the field of autonomous flight control, artificial intelligence, self-localization, machine learning, and RFID hardware simulation has made the project more viable and manageable.

The Aero-Astro Controls Laboratory at Massachusetts Institute of Technology (MIT) has been working on autonomous helicopters that are capable of tracking a moving radio-controlled car in coordinated swarms [4]. In this project, stable flight control and swarm-like communication was achieved.

Omead Amidi from Carnegie Mellon University's Electrical and Computer Engineering department has also integrated cameras into his UAV system to develop vision guided autonomous helicopter [2]. Work in these areas can be leveraged to quickly setup a group of autonomous helicopters.

Literature in artificial intelligence and machine learning will also be a helpful resource when designing the three-dimensional path-decision algorithm.

Studies have also been done on RFID-Reader collision problem by Auto-ID Center at MIT [3] and other research institutes. These studies can be used to analyze RFID-Reader behavior and determining simulation parameters when modeling a RFID-reader apart from solving the RFID reader collision problem.

III. Preliminary Simulation

A. Motivation

Autonomous flight control is not trivial; to avoid unwanted hardware destruction during testing, a simulation framework has been setup to analyze any algorithms to be implemented. Moreover, this initial simulation will also provide a benchmark for future work to improve on. Due to the three-dimensional nature of the problem, a three- dimensional graphical simulator framework has been designed using Microsoft XNA framework to represent a real warehouse.

B. Units and Simulation Parameters

Real world measurements are translated to simulation units using the dimension of the DraganFly radio controlled helicopters as a reference. A 3D model representing the DraganFly helicopter can be bounded by a cube of 42 units.

Representing the Draganfly helicopter which has real dimension of approximately 82 cm by 82 centimeters, 1 simulation unit corresponds to approximately 1.95 centimeters. Thus, a 60 x 60 x 60 unit box in the simulation would correspond to a 1.17 x 1.17 x 1.17 meter box in the real world. Velocity of the simulated UAV is set at 3.9 m/s or approximately 8 mph. The Draganfly RC helicopter is claimed to have a maximum speed of 20 mph.

XNA framework keeps track of the total real time elapsed since the start of the program and the time elapsed after each update cycle, up to one millisecond accuracy. The simulation time is conveniently based on XNA framework's game time parameter.

C. Simulation Assumptions

For simplicity, the RFID reader attached to the simulated UAVs are assumed to have a 100% read-guarantee when EPC tags are within the read-range of the RFID reader. It is also assumed that RFID collision between readers are being handled using time division multiple access (TDMA) [3]. The simulated RFID-readers are centrically placed and have a read-range of 3.9 meter radius.

Sensors are also modeled as an abstraction of their functions. Probability of signal drifts and noise are not taken into account in the initial simulation.

Even though there are more than one UAV deployed in some of the initial tests, the UAVs navigate independently and do not communicate with each other. However, the UAVs can detect other UAVs when in proximity and will avoid any collision. Based on experiment results, these assumptions will be changed accordingly in future iterations.

D. Semi-Probabilistic Navigation Algorithm

In the initial simulation, the UAVs are programmed to move in a vertical zigzag motion to cover three-dimensional space. The UAVs are also programmed to navigate using probabilistic-like or randomized algorithm when encounter an obstacle. The UAV will also change its direction when the RFID reader it carries has not read any EPC for more than ten seconds. The direction decision is shown in the formula below.

$$Yaw_y = Random(-175, 175) \tag{2}$$

The UAV will rotate at any integer angle value ranging from -175 degrees to +175 degrees. The integer value is generated using .NET's Random class, which generates a pseudo-random number. For simulation purposes, we will assume this pseudo-random number as random. The probabilistic algorithm will approximate an expected performance or runtime for this system. The finite state diagram in Figure 2 shows the states that each UAV will iterate when in autonomous mode.

E. Initial Simulation and Results

A series of test, recording task-completion statistics and the trajectory of one of the UAVs were executed to determine the expected runtime. The simulation scenario sets up a 195 x 66.5 meters warehouse containing twelve five-tiered shelves, measuring 50 meters wide and 5 meters deep, arranged in a layout shown in Figure 3.The RFID-reader carried by the UAV has a read-range of 3.9 meters or approximately 12 feet. 616 boxes, measuring 1.17 x 1.17 x 1.17 meters, were randomly placed on all the shelves.

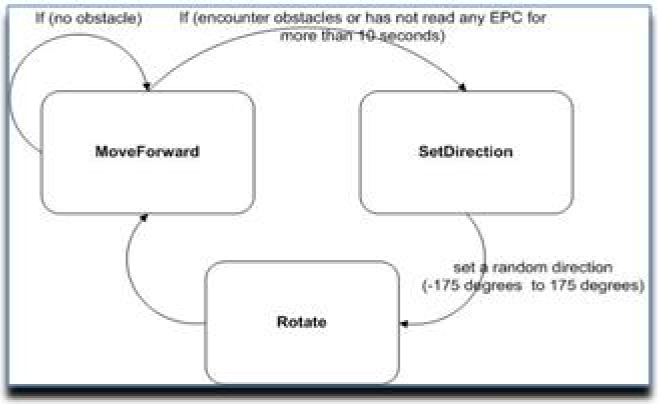

Fig. 2. UAV FSM implementing probabilistic algorithm.

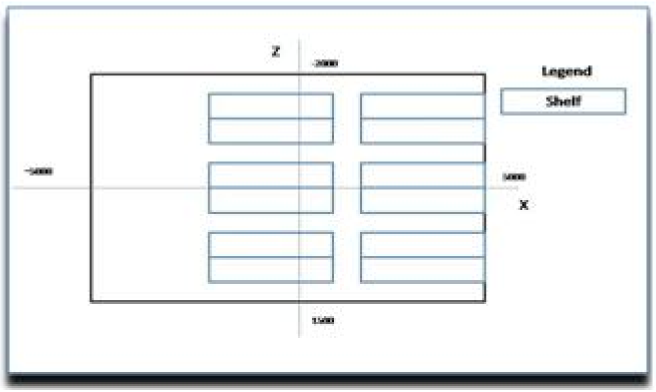

Fig. 3. Simulated warehouse layout.

The first series of test were bounded within a time limit of 12 minutes, the average flight time of commercial radio-controlled helicopters. Six independent UAVs were deployed. The UAVs collectively fails to complete the task of finding all the EPCs in the warehouse within the 12 minute duration.

The progress (fraction of EPCs tags read) shown in Figure 4 below can be modeled as a logarithmic function. It is intuitively obvious that the rate of finding new tags will decrease as time progresses given a probabilistic navigation algorithm.

Another series of tests, but with a time limit of 60 minutes and six independent UAVs deployed, were executed. All three tests in this series show that the group of six UAVs successfully found all the EPCs after a minimum duration of 27 minutes. The rate of completion versus time is plotted in Figure 5.

Five more series of tests were then executed, with a decreasing number of UAVs deployed in each series. Six tests were run in each series and an average completion (fraction of total EPCs read) in twelve minute duration were calculated. With only one UAV deployed, the average completion rate is 54.83% while when five UAVs were deployed, an average of 90% completion rate was achieved. Surprisingly, even though there was no cooperation between the UAVs, the increase in completion rate with number of UAVs is almost linear.

Fig. 4. Completion versus Time (6 UAVs deployed).

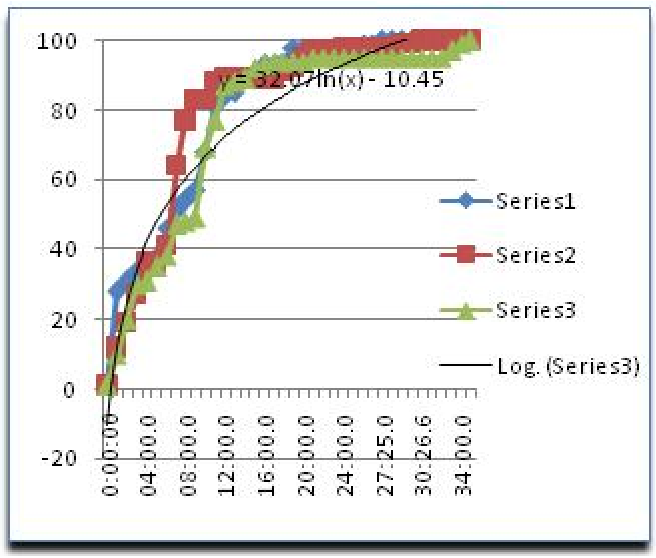

Fig. 5. Completion versus Time (Unbounded).

Figure 7 shows a two-dimensional trajectory of one of the UAVs during a twelve-minute duration operation. Even though the UAV may repetitively end up in the same location on the graph, its vertical position may be different each time. Thus, the redundancy may not be as much as it appears.

However, as more UAVs are deployed, the probability of one UAV going to a spot that has been covered by another UAV increases. It has not been determined if this redundancy is unfavorable since a UAV may fail to read an RFID tag even though the tag is within the RFID-reader read-range.

F. Result Summary and System Viability

From initial analysis, it appears very promising that given a more clever design and/or the right number of UAVs deployed, a group of UAVs will be able to complete its task of covering

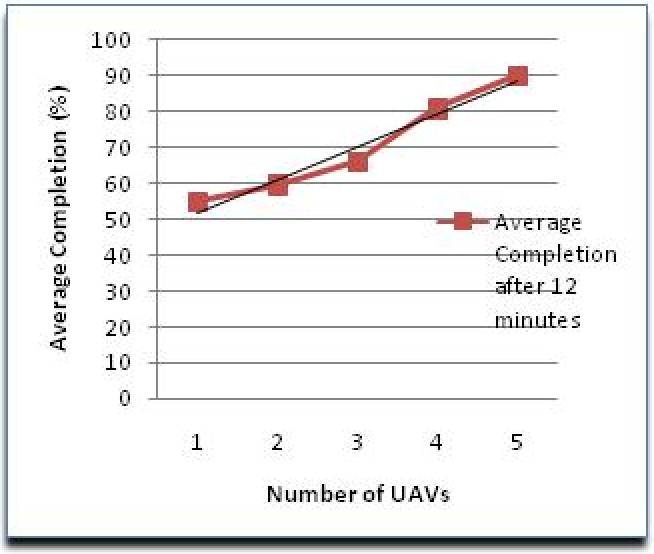

Fig. 6. Average completion versus number of UAVs.

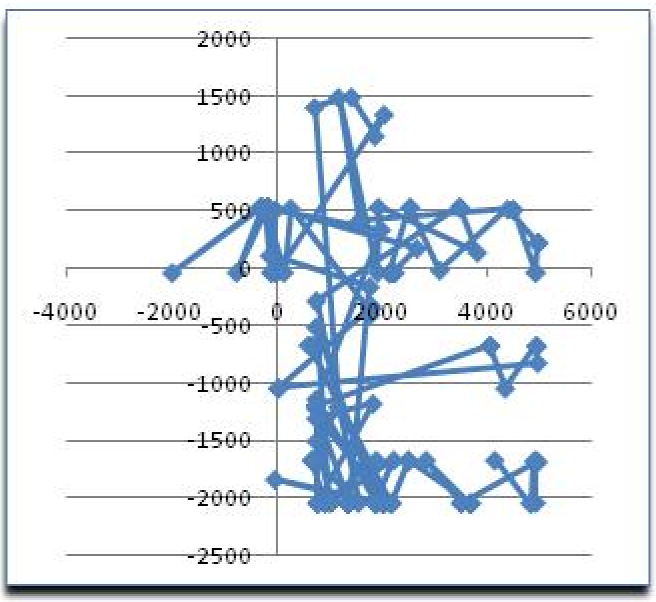

Fig. 7. Two-dimensional trajectory of one of the monitored UAVs.

a warehouse within one flight cycle of 12 minutes. Using helicopters that have a longer flight time, the number of helicopters needed can be reduced.

Even though the initial simulation provides an insight of the viability of creating a multi-UAV system to cover a three-dimensional space, the simulation assumptions are overly optimistic. Thus, we should expect a decrease of performance when accounting all other simulation variables such as signal drift and RFID reader's fail-to-read probability.

IV. High Level Design and Challenges

A. General Issues

1) Measuring performance and determining task completion: Even with an extremely clever design, it is not guaranteed that the system will be able to detect all the EPCs within the warehouse. RFID-reader collision, non-guarantee of reads, and other unpredictable variables such as dynamic obstacles will contribute to the probability of fail positives.

Since the main goal of this system is to reduce the probability of a lost item in supply chain flow, we can model a performance metric as a conditional probability. The probability of a loss item during supply chain flow depends on the probability of accurately shipping the right number of items per-shipment. It is possible during a transaction that items are over-shipped or under-shipped. Consequently, knowing the probability that an item is no longer in a warehouse given that it should have been shipped can give us an insight on how an item is lost in the supply chain flow.

Thus, a good system is a system that can guarantee the highest probability that its inventory report is absolutely accurate. An example performance formula is shown below where X is the number of EPCs found by the system and x is the real number of EPCs in the warehouse.

$$Performance = Pr(X = x|x) \tag{3}$$

However, the method of determining the value of x, the real number of EPCs in the warehouse will have to be addressed since our problem stems from the fact that we cannot determine the actual number of items in a warehouse in the first place.

Thus determining a performance-metric for this system is non-trivial and may require a business-rule model.

2) Task Distribution: Size of target space and the maximum velocity a UAV determine the minimum number of UAVs is required to cover the target space. Consider this simple scenario; a warehouse has a dimension of 200 meters by 60 meters, and a UAV travels at 4 m/s, carrying a RFID-reader with 2 meter read range.

It takes at least twenty five minutes and twenty five seconds to cover this two dimensional space. Thus it is impossible for one UAV to cover a three-dimensional space within one flight cycle of 12 minutes. From initial simulation, it is observed that performance (percent completion given time duration) increases almost linearly with the number of UAVs even under probabilistic algorithm navigation. To further increase the efficiency of the system, the UAVs can cooperate and communicate to distribute their coverage more efficiently.

Three possible UAV-distributions will be considered for the design of this system: zone distribution, swarm distribution and zonal swarm distribution. The potential trade-off between each distribution is efficiency versus simplicity. For instance, it may be more efficient to deploy the UAVs as a three-dimensional swarm. However, swarm coordination will require constant communication between the UAVs and hence a more sophisticated design.

3) Localization and Navigation Reference: Meaningful cooperation between UAVs to distribute area-coverage will require self-localization. Even though GPS technology typically has very poor indoor performance, a lot of work of has been done on utilizing GPS for indoor localization. One such technology is called Pseudolites [3] which provide up to centimeter accuracy.

An alternative to using GPS for localization is to place static benchmarking tags in a warehouse which the UAVs can relate to as a point of reference. By keeping track of its velocity and orientation, the UAV can deduce its position with reference to the benchmarking tags. The placement of these benchmarking tags and the amount to deploy will have to be addressed in the design.

Another alternative is to use the RFID tags on stock items as a navigation reference. This design will assume that the stock items are static during the UAV operation. This design however may prevent the UAVs from performing machine learning based on its trajectory history since the navigation reference will change frequently depending on the warehouse stock flow.

B. Hardware Challenges

1) Helicopter Payload and Power Consumption: One of the major design problems for the system is to determine the right flight hardware. A hobbyist radio controlled four-rotor helicopter, commercially sold as DraganFly, has been chosen as the starting hardware to build the UAV. With the ability to hover, a helicopter provides an easier flight control than a radio controlled airplane.

However, most hobbyist radio-controlled helicopters are not designed to carry a heavy payload. The design has to take helicopter payload into account when determining navigation sensors, on-board processor choice, and RFID-reader type.

Moreover, with more devices, it is more likely that more power will be needed. The DraganFly battery allows a flight time of about 12 minutes. If other devices such as sensors and RFID reader share the helicopter's power supply, the flight time will be shortened. At the same time, the weight of an extra power supply will further reduce the payload of the helicopter.

2) Navigation Sensors: Due to the limited payload of a helicopter, sensor choice is critical to the viability of a UAV. At minimum, the helicopters will need sonar sensors and altimeters to detect obstacles and to avoid crashing when landing.

Other helpful sensors for autonomous flight control include digital compass for navigation and MEMS sensors which include gyroscopes and accelerometers for balancing and determining velocity.

3) RFID-Reader Constraints: It is obvious that a low-powered and lighter RFID-reader is preferred. However, other RFID-reader's parameters such as reads-per-second and read-range also affect UAV flight-control and algorithm. A low reads-per-second will slow down the velocity of the UAV to ensure RFID tags can be read by the RFID-reader. Short read-range will also force the UAV to fly nearer to the shelves, which increases the probability of unwanted contact with obstacles.

Moreover, swarm movement of UAVs may also create RFID-reader collision where one RFID-reader radio signal will interfere with another's due to the shared space of their coverage [1]. Thus, depending on the RFID-Reader read-range, asymmetrically placed RFID-Reader on the UAV will probably perform better than a centrically placed RFID-reader.

The distance between shelves in a warehouse typically ranges from 6 feet to 10 feet [9]. Unless, the RFID-reader read range is more than 18 feet (assuming each shelf is 4 feet in depth), the UAV will never be able to read the items on two opposite shelves simultaneously. Thus, a centrically placed RFID-reader is only helpful in balancing the UAV.

C. Software Challenges

1) Machine Learning and Artificial Intelligence: Robots are often associated with artificial intelligence. While, the UAVs are assigned a very specific task of covering a warehouse searching for RFID tags, the UAVs cannot be programmed to follow a specific path because different warehouses have different layouts. Warehouses may also change their layouts periodically based on business needs.

Thus, machine learning and artificial intelligence is required to allow the UAVs to make clever path decision and adapt to unfamiliar environment and dynamic obstacles. Artificial intelligence can also help the UAVs optimized their path decisions to minimize the amount of time used to complete the task based on previous trajectory pattern.

2) Multi-threading Programming: The UAVs will be required to process all its sensor data in parallel to avoid any crashes. Apart from processing sensor data, the UAVs will also need to make other calculations to determine the navigation direction and communication with other UAVs. Thus, multi-threading programming is needed in designing the UAV system.

However, not all threads are equally important in terms of processor-time allocation. Intuitively, sensor data management should be prioritized to avoid UAV crashes and to maintain stable flight control.

To regulate the complexity of multi-thread programming, the design will most likely utilize Microsoft's Coordination and Concurrency Runtime (CCR) framework. Microsoft has also provided a robotic programming platform called Microsoft Robotic Studio with utilizes the CCR framework.

3) Data Management and communication Protocol: Each UAV will be reading a lot of data particularly from its sensors and RFID-reader during operation. RFID readers do not filter repetitive reads; duplicate filtering is usually done at the software level. Thus, the UAVs will probably need to send RFID-reads to a database, such as an EPCIS (EPC Information Services) server, periodically to handle a potentially massive amount of data collected.

The design of this system should also consider what data the UAV should keep, to be used for navigation and path decision, and which data to transfer to a database.

The system will probably implement an 802.11 wireless communication protocol to relay data back to a database and as a channel to communicate to other UAVs if necessary.

V. Conclusion

The preliminary simulation shows the feasibility of the multi-UAV system and that coordinated distribution of the UAVs is probably required to complete the task of inventory checking due to the short flight time of currently available commercial helicopters.

In future iterations, the three-dimensional path decision algorithm can be optimized by taking trajectory history heuristics into account. Moreover, future simulation should also provide a simple model of the RFID reader collision problem to provide a fairer representation of the probability of fail-positives from the RFID readers.

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