Delivery by Drone: A Command and Control Analysis of the Unmanned Aerial Vehicle's Role in Package Transportation

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***Abstract*—In the past five years, the concept of delivery systems based on unmanned aerial vehicles (UAVs) has progressed from a futuristic concept to a reality. With new FAA regulations published less than a year ago, the field of UAV-forward delivery systems has begun to blossom with new ideas, innovation, and novel implementations. With such a lofty goal comes a great deal of complexity. This paper seeks to analyse and model a UAV-based delivery system using command and control principles as the forefront of the design process. An analysis of the four domains and seven function of C2 is provided to outline the complexities that must be considered in the design process. Furthermore, the concept of requisite variety is taken into account to develop a trajectory synthesizer with automatic obstacle avoidance features. The model and simulation are then utilized to simulate a three-dimensional UAV delivery system with a varying capacity. The process loops involved in the system are mapped to demonstrate the data flow of the system, and relevant standards for autonomous vehicle communication are discussed. Overall, the nuances of the C2 approach to UAV delivery systems are used to show the variety and usefulness of such a system once all necessary considerations are properly accounted for.**

I. Introduction

The recent introduction of unmanned aerial vehicles (UAVs) into the commercial sector has brought about a host of challenges and opportunities. Over the past decade, the possibility of package delivery by UAV has progressed from a futuristic proposal to a work in progress. With the FAA's newest UAV regulations in place as of December 2020, companies like Amazon, Walmart, and UPS are ready to take their experimental package delivery systems into the air [1], [2], [3]. While corporations show eagerness to fill the skies, the FAA has exhibited restraint as it seeks to maintain safety in the national airspace system (NAS) without stifling innovation [4].

The introduction of many UAVs into the skies comes with a great challenge in command and control (C2). This paper seeks to provide an analysis of methodologies by which a package distributor may execute UAV deliveries while accounting for the many factors at play. Factors such as communications procedures, risk reduction, and failure recovery must all be accounted for to ensure a seamless delivery process. A three-dimensional simulation is provided to better visualize and evaluate the variations at play as UAV traffic increases. The simulation is designed to account for obstacle avoidance and is designed to produce a realistic and simple flight path for each UAV using its adaptable trajectory synthesizer. With aid from the simulation and applicable research, an analysis of the command and control domains is performed to provide a set of guidelines by which a UAV-based packaged delivery system may be designed.

II. Project Description

This paper seeks to outline the C2 aspects of an autonomous UAV delivery system and to describe a Python simulation by which the aerial delivery process can be modeled. The simulation is designed to model suburban airspace congestion during peak and non-peak delivery times. By modeling air traffic scenarios with the quantity of UAVs as the primary variable parameter, congestion can be evaluated so as to better predict the challenges that will be faced in the physical domain as UAV delivery expands in popularity. The results of the simulation process are discussed and evaluated with regards to the C2 challenges faced by the delivery process.

In addition to simulating the delivery process, this paper outlines past progress made with UAV delivery, current and future plans made by existing delivery companies, and the C2 principles that must be applied to produce a successful system. The process loops and system architecture are reviewed with an outline of the sysem of systems (SoS) considerations. Additionally, relevant standards and regulations are discussed to articulate the considerations that must be taken into account when designing an FAA-approved commercial UAV delivery system.

III. History of Autonomous Delivery Systems and Autonomous Machines

A. *The evolution of delivery systems*

Traditionally a package would need to be taken to the post office to be mailed from one individual to another. This process could take several days to weeks complete depending on how far the package needed to travel. Companies wanting to get packages to customers were interested in a more efficient method. In 1907 UPS was formed with the intent of delivering packages from stores to customers [5]. This revolutionized the process of getting a package shipped from a store to the customer. Again in 1971 FedEx was formed to try and expedite this process even further [6]. Their plan was to be able to deliver packages in the quickest way that was possible. They believed that important packages needed to be shipped across the country faster than traditional methods. FedEx introduced their fleet of planes in order to move packages across the country in record time. When Amazon was founded, they used the delivery methods that were already in place with most of their packages being delivered by UPS. Amazon later introduced their own delivery vans so that they would not have to contend with all the other packages that were being shipped through these external companies. This drastically reduced the time it took for packages to be delivered to customers.

Now Amazon is looking to take this process a step further with the introduction of a UAV delivery system. With this new method of delivery, a package will be shipped directly from the warehouse to the customer. This has the potential to reduce delivery time drastically. The first successful autonomous UAV delivery was completed on December 7th, 2016, in Cambridge, UK [7]. This was the first step in an effort to get this method into the delivery process. When this test was conducted, the participants needed to be in close proximity of the Amazon warehouse and also needed to have a relatively large yard. The promise from Amazon is that they will be able to deliver their packages to customers in 30 minutes or less [8]. As of August 2020, Amazon was able to win approval from the FAA to have a UAV fleet [8]. This will allow for greater testing so that they can incorporate their final design.

B. The changing landscape of autonomous vehicles

While the concept of autonomous vehicles only recently came to practical fruition, its sector has grown dramatically in recent years. As autonomous and semi-autonomous automobiles have begun to gain traction, relevant regulations and standards have been created to improve the continuity of systems from diverse suppliers [9].

As autonomous automobiles began to increase in popularity, some researchers began to apply the same principles to other autonomous vehicles such as UAVs. While the technology is still in its infancy, early adaptations of a wireless vehicular ad hoc network (VANET) have stemmed from these standards [9], [10], [11]. The IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) standard is one such standard designed to allow vehicles like automobiles or UAVs to communicate in a "rapidly varying environment" where communication speed is critical [12], [13]. By making use of a system similar to the IEEE 802.11 standard, UAVs at close range can communicate with one another to ensure collision avoidance (one of many varieties that must be accounted for).

In addition to applying standards from the automotive world, researchers have begun to extend the conceptual layers of Internet of Things (IoT) systems to UAV fleets. In [9], the authors explain the process by which specialization of the IoT led to the creation of the more specialized class "Internet of Vehicles" (IoV). Furthermore, they note that the IoV is now bringing forth a new concept dubbed the "Internet of Autonomous Vehicles" (IoAV). The authors decompose the system concept into broad layers. These include the application later, network layer, and data-link/physical layer. They then further break the system down into a more detailed structure involving greater complexity and variety. Additionally, they highlight the importance of incorporating existing standards such as IEEE 802.11p and and cellular technology (e.g. LTE) into the IoAV so as to facilitate a well-defined system with ample considerations taken into account [9].

In December 2020, the FAA issued a press release announcing the establishment of its long-awaited regulation update for UAVs [1]. With the announcement came a description of remote ID broadcasting requirements. All UAVs weighing over 0.55 pounds that are not flying in a designated exception zone are required to continuously broadcast status updates over the air [14]. This requirement is designed to aid law enforcement and air traffic regulators in identifying UAVs in any given area. Applicable UAVs must broadcast information about UAV ID, geographic coordinates of both the UAV and control station, altitude, velocity, emergency status, and message timestamp [14]. This enables surrounding UAVs to better understand the whereabouts of other obstacles, thus helping to avoid a collision.

Due to the recency of these regulations, the means by which these communications occur are yet to be standardized. The FAA's summary explains that the broadcast methodology would likely be implemented by means of "Wi-Fi or Bluetooth technology" [14]. This aligns well with the goals of the IEEE 802.11p standard which is designed for a fast-paced environment. According to the FAA's rule summary, "anyone can create a means of compliance" so long as the system receives approval from the FAA [14]. While achieving FAA approval for a broadcasting system may come with challenges, the open-ended nature of the new regulations helps to promote innovation in both the private and public sectors. As many delivery companies race to be the first with widespread UAV delivery, many potential solutions will likely be developed in the near future.

With new standardization comes new challenges to surmount. As the commonality of UAVs has increased, the variety of obstacles has grown. In 2011, researchers explored the concept of UAV formations and interactions with their proposal of a new decision-making system [15]. While a UAV-based delivery system would overwhelmingly consist of UAVs acting with individual agendas, the concepts employed in such formation layouts translate well when ensuring that UAVs are aware of each other's presence using standards such as IEEE 802.11p [11], [15]. By drawing on past work with both UAV formations and wireless vehicle communication standards, a proper grasp on both the physical and information domains can be gained to ensure that all relevant variety is considered in the design process [16].

IV. Core C2 Functions in Autonomous UAV Delivery

To better understand the role that C2 will play in the UAV delivery process, the system must be analyzed in terms of the functions of C2. Alberts and Hayes define seven essential functions of C2 that must be accounted for [16]. These functions are given as: establishing intent; determining roles, responsibilities, and relationships; establishing rules and constraints; monitoring and assessing the situation and progress; inspiring, motivating, and engendering trust; training and education; and provisioning [16].

A. Establishing intent

The objective of this system is to deliver packages utilizing autonomous UAVs. This will help to decrease the time it takes for Amazon to deliver packages to customers. There is a risk to the general public because these UAVs will be flying overhead. All possible precautions will be taken in an effort to eliminate these risks.

B. Determining roles, responsibilities, and relationships

In the implementation of this system there will be different responsibilities. There will be operators who are monitoring the UAVs that are out on delivery. This way if something does begin to go wrong, they have a chance to step in and intervene.There will be programmers that are responsible for making sure that the code the UAVs are operating on is capable of performing in all conditions. Amazon is also going to be responsible for not only the delivery of the package to customers, but also the safety of the general population.

C. Establishing rules and constraints

This system will only be permitted to operate if all of the safety guidelines are met. This will ensure a safe delivery process. If any one condition is outside of the acceptable range than the system will not operate. Amazon will only operate the autonomous UAVs in clement weather[7]. Amazon will also not allow UAVs to operate after dark. Both of these guidelines are included in order to protect the public. In the event that unpredicted inclement weather occurs the UAVs will cease operations. This will prevent harm to the public. They will also not allow UAVs to fly beyond their specified range to deliver packages. Amazon will also work with local governments if no-fly zones need to be established.

D. Monitoring and assessing the situation and progress

Operators will be standing by to ensure that the autonomous UAV delivery system is able to complete its function safely. This way if something were to go wrong an operator is able to step in to address the situation. Amazon will work with local weather agencies to ensure that flight conditions are within the acceptable ranges. Each UAV will send performance data back to operators. That way if a UAV has a issue it can be taken out of the delivery process until the problem is resolved.

E. Inspiring, motivating, engendering trust

Amazon will encourage their employees to generate new ideas that will help to make this system operate at maximum efficiency. There will be rewards within the organization that will help to keep employees motivated.

F. Training and Education

Amazon will provide training to employees to prepare them to operate this system beyond any schooling they may have previously received. There will also be addition training modules that are required to maintain operational status within the program.

G. Provisions

Amazon will be responsible for the delivery of the packages to their customers. They will need to maintain not only the storage of the packages that need to be delivered, but also the fleet of UAVs used for the deliveries. This also includes maintaining a supply of the necessary utilities for maintenance and repair of the UAV fleet to ensure maximum system uptime.

V. Simulation Design

The concept of the model is to analyze the visual view of UAVs simultaneously leaving an Amazon warehouse and delivering a package to the customer. Considerations to take into account include: no fly zones, obstacle avoidance, trees, obstacles, and weather. In addition, the maximum distance available for a UAV to fly given a certain battery life before needing to come back to recharge and deliver the following package must be considered. Scheduling each UAV to optimally deliver a package in coordination with a UAV returning to avoid collision with each other on departure and return was analyzed.

A. Trajectory Synthesis

A UAV is modeled to have a parabolic ascent assuming no obstacles when leaving the amazon warehouse. Once the UAV reaches maximum altitude, it maintains the altitude until it is directly over the delivery point. In this situation, the UAV would vertically descend and then reascend to avoid as many obstacles as possible. The parabolic ascent in the beginning is synthesized to optimize power, speed, and delivery time by taking the Pythagorean hypotenuse rather than ascending in the up-direction and then moving in the east/north-plane.

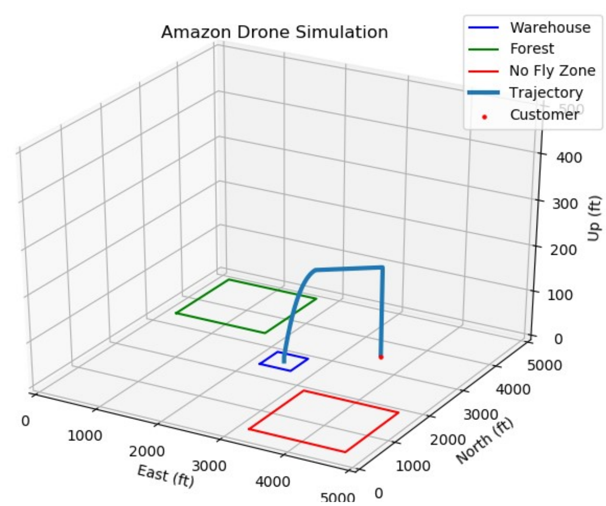

Fig. 1. Trajectory 1 UAV

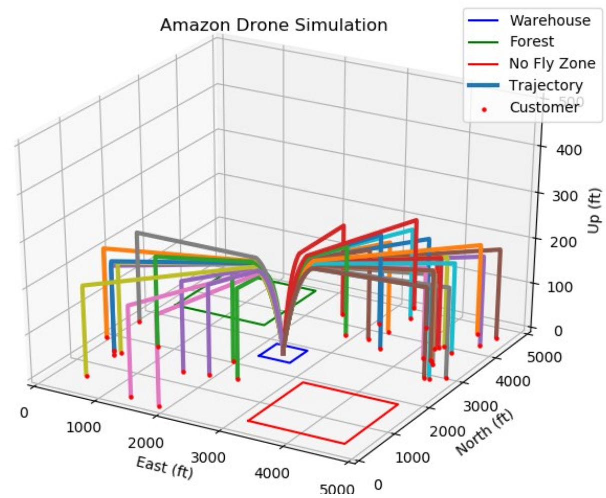

Fig. 2. Trajectory 36 UAVs

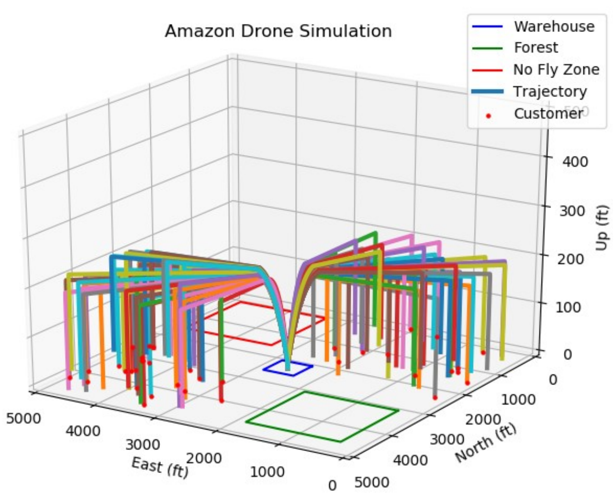

Fig. 3. Trajectory 100 UAVs

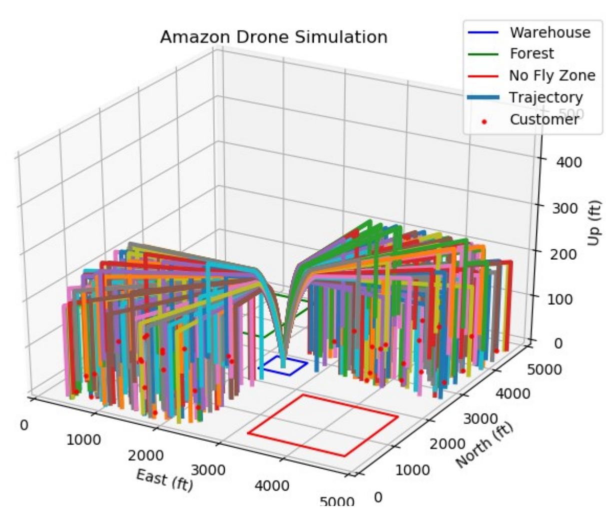

Fig. 4. Trajectory 500 UAVs

Figures 1, 2, 3, and 4 illustrate the simulation of various numbers of UAVs leaving the Amazon warehouse and delivering packages to the customer. The various number of UAVs include: 1, 36, 100, and 500. The maximum legal altitude a UAV can fly is 400 feet and the maximum legal velocity for commercial UAV is 100 miles per hour [17]. The altitude designed here is set at 200 feet high and then remains at that height. The blue square in the middle of the simulation space is the warehouse, the red square is a no fly zone, the green is the forest, the blue line is the UAV trajectory, and the red dot represents the location of the customer.

Notice that as the number of UAVs increases, the congestion increases highlighting the need for a maximum number of UAVs to be able to deliver a package at one instance. The coordinate frame is in ENU delivering packages between 500 to 5000 feet away. If a UAV is delivering a package to a customer under a mile away traveling at an average velocity of 50 miles per hour and approximately 1 mile away, then $v = \frac{d}{t}$ can be used to solve for average round trip time for one UAV. Time, t, would be $\frac{1*2}{50}$ or 2 minutes 24 seconds. If a UAV has a max flight time of 30 minutes round trip, then $d = 50 * \frac{0.5}{2}$, $d = 12.5$ miles for max distance at 50 miles per hour maximum average velocity. As the distance increases, however, the more optimal communication systems need to be to communicate with hundreds of UAVs simultaneously. When analyzing Shannon's theorem, a high bandwidth will be needed to allow the UAV to communicate quickly with the control center during flight.

B. *Obstacle Avoidance*

When synthesizing a trajectory, one cannot assume an obstacle-free environment. The creation of a three-dimensional trajectory must be preceded by a study of applicable variety. In the case of trajectory modeling, a great amount of variety comes from obstacles such as buildings, trees, and no-fly zones. As Ashby explained decades ago, "variety can destroy variety" [18]. To account of the great presence of obstacles, an object-avoidance algorithm was developed to synthesize trajectories between two points while avoiding obstacles that would intersect a straight path between the origin and destination of the UAV. The obstacle avoidance algorithm was first developed as a two-dimensional system prior to being implemented in three-dimensional space.

During the operation of a UAV delivery system, the environment around each warehouse will be different and will constantly be undergoing changes. Some of these changes will include areas which the UAV will not be permitted to enter such as construction areas, large structures, government buildings, etc [19]. The ability to accurately map and navigate the areas of an environment is essential for the UAV delivery system to conform to a multitude of different environments and regions. To account for the variety of obstructions and restrictions, the UAV delivery system would need to be updated each time one of these areas is added, removed, or altered in order for the system to perform to the best of its abilities without causing issues. Another method of obstacle avoidance is a sensor placed on the UAV that can detect objects that are in its immediate path and attempt to maneuver around the object. If this technique were to be combined with the pre-loaded list of all known obstacles and no-fly-zones, it would produce the most efficient trajectory synthesis algorithms to deliver a package.

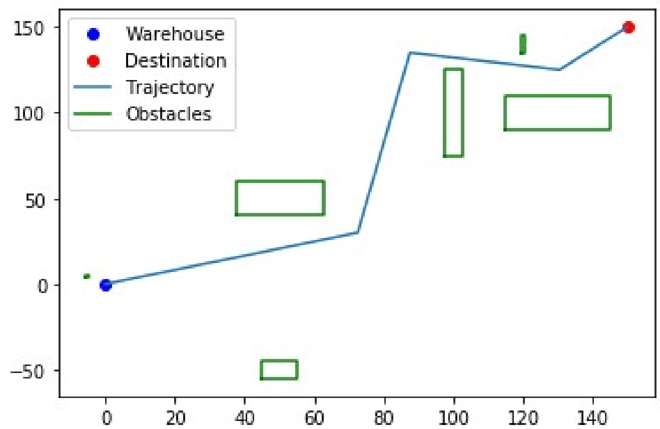

Fig. 5. Obstacle Avoidance Simulation Result

The simulation starts by collecting the locations of the warehouse where the UAVs will be launched from and the delivery destination of the package and mapping them on a plot. It then automatically accounts for every known obstacle, simplifies them to rectangular shapes, and maps them onto the same plot. It then maps the path between the start and end point and looks to see if it intersects with any of the listed obstacles. If an obstacle is in the way, a point is selected off of one of the corners of the obstacles for the UAV to travel to before the destination and checks the path from that point to the destination for more obstacles. This process is repeated until a clear path free of obstacles is set between the warehouse and the delivery location. This path is finally plotted on the same plot to give a top-down view of the area. As seen in Fig. 5, the trajectory of the UAV is synthesised successfully avoiding all obstacles in its path so that it safely reaches its destination.

Another important result of a simulation of this system is whether the detour around certain areas would lead to insufficient battery power. If the distance the UAV would travel is greater than the distance than the battery life can handle, the package would need to be delivered another way, just as if the destination resided in an area that has been sectioned off inside one of the no-fly areas. The importance of the pre-loaded list of obstacles is to accurately measure the amount of power required for the UAV to reach the destination and return. If the UAV were to simply rely upon an on-board sensor, it could possibly take too much time to reach the destination and would not have enough power to complete the journey and crash, which can cause serious damage.

VI. System of Systems Overview

The system we are designing is a directed system of systems (SoS), with the warehouse, UAVs, package handling, and flight pathing are completely integrated. Furthermore, all of the systems within the UAV delivery system will need to be controlled by a central management, due to the need of high accuracy in both inventorying and delivering. By separating the systems, the potential room for error in increased. However, it is worth noting that the UAV delivery system will most likely be within an acknowledged SoS, as Amazon is continually expanding the different industries it branches into. The delivery system will most likely be kept connected but separate from the streaming platform.

As for the properties of this SoS, one can utilize the five characteristics of SoS as defined by Boardman & Sauser [20]. The first characteristic is probably the strongest for Amazon, which is autonomy. Each system in this SoS will most likely operate fully autonomously, as long as the packages are transported to a predetermined, specific location. From there, the constituent systems can independently move packages and deploy UAVs as necessary. The systems comprising the UAV delivery system also are vital to the system's success, which contributes to the belonging of the SoS, however, some parts of the system are more vital than others. An example would be the warehouse, which has additional purposes other than just the UAV delivery system.

The next characteristic is connectivity, which while very important to this SoS, it is also a very linear connectivity. Each subsystem needs to direct and precisely connect to each other, but there is not a significant need for interconnect outside of that in this SoS. Finally, there is the diversity characteristic, which this SoS does not perform quite as strongly in. Since the warehouse is part of another larger delivery system, and the UAVs are the primary system, this system's capabilities are still a sum of its parts, but it is not as diverse as the average SoS. Of course, there is the fifth characteristic of emergence, however, emergence acts as a result of the other four characteristics. Furthermore, it would be affected by how the SoS behaves with the Amazon umbrella, and this project is observing the UAV delivery system in a vacuum to reduce the number of unknown variables.

VII. Process Loop Mapping

For this particular system, there are two primary control loops: the route planning control system and the autonomous UAV flight control loop. The first and larger scale of the two would be the route planning control. This is where the system will not only have to find an optimal route, but must also consider natural obstacles, man-made obstructions, and unique conditions that would affect the flight path. Now on an individual level, and within our simulation, this is as simple as a singular function. However, in a real application this system that plans the routes would need manage potentially hundreds of delivery UAVs depending on the area. This factors in which UAVs are available, how many loading and unloading locations are in the warehouse, the delivery locations, current local air traffic, and other factors that would effect the system's ability to perform.

The reason it is better to have one central system to control this entire process is because it has higher command and control potential, and it helps to alleviate processing from the individual UAVs. The system has access to local, strong computation resources to do the large scale command information processing and control peripherals. As for the specifics of the system, it is unfortunately not feasible to map since not only would it rely on how the Amazon warehouses functions, but it would require more research into how this system should operate as a whole and what factors would need to be considered. The most complex part of this system are accounting for "real world" factors such as resources, personnel, and space that aren't applicable to our simulation.

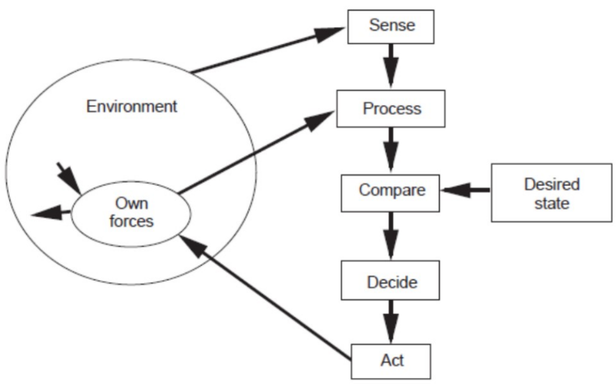

Fig. 6. Lawson model for C2 loop structures

However, this does mean that we have a relatively defined control loop for the autonomous UAV during the flight, which only needs to focus on maintaining homeostasis while progressing along the predetermined flight path. This requires a GPS module to track that it is following the flight path, a barometer to monitor altitude, and a smaller subset of sensors to monitor the safety of the UAV and the immediate environment. Some examples would be if the GPS position deviates away from the course further than the maximum expected error, it should first move to reach the flight path before continuing. Additionally, there could be sensors to detect the wind speed, which would most likely fluctuate at the flight altitude. Having the UAV monitor the wind speed means it can counteract it to better follow the flight path.

Since this is meant to just sustain homeostasis in the system, this type of system should most likely follow the Lawson model which is shown in Fig. 6. The simplicity of Lawson's model in [21] lends to its broad usefulness in characterising system such as the UAV delivery system. Since the Lawson model is centered around a desired state, the UAV would focus on maintaining the GPS location and altitude that exists along the flight path while moving forward along it. These processes are shown in the UAV operational loop concept in Fig. 7. This model focuses on the general command and control flow of the system, rather than detailing how the drone would specifically operate (for example how the package carrier would actuate). While these would be necessary for the real system, this was not implemented in the model due to the fact that in the simulation there is never a reason for the UAV to deviate from the intended flight path once obstacles are taken into account.

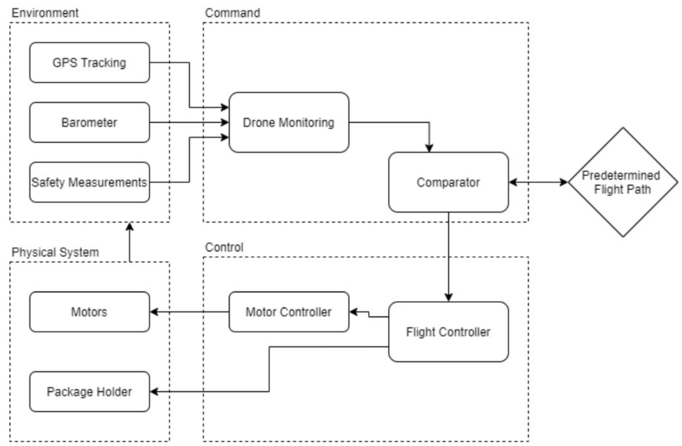

Fig. 7. UAV operation control loop

VIII. Conclusions

Overall, the complexities and nuances of a UAV-centric delivery system were analyzed in relation to the fundamental principles of C2. During the analysis process, it was found that a great amount of complexity arises during the consideration of the physical domain principles involved in the delivery process. Such a complexity stems form the three-dimensional aspect of the delivery system. While a ground-based delivery system would only need to account for a two-dimensional route, the UAV-based system must account for altitude as an additional parameter.

By taking into account the cybernetics principles of variety, a trajectory synthesizer was designed to not only produce a realistic path from the warehouse to the customer, but also to optimally avoid obstacles during the entirety of the delivery process. A mathematical analysis was performed to better understand the variations experienced when accounting for speed, distance, and altitude. The simulation also showed the increasing complexity that arises as the number of active UAVs increases within a given airspace sector.

Ultimately, the C2 approach that was applied to the UAV delivery system helped to better demonstrate the complexities that must be accounted for when designing such a system. The model was constructed such as to produce requisite variety by which to counteract obstacles within a basic UAV delivery system. Although many more rules and constraints must be established to produce a fully functional UAV delivery system, many companies have made great strides within the past five years. While it may take time for UAV-based delivery to take off in all parts of the US, one thing is certain: C2 principles only become more essential as technology progresses to new heights.

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Christopher Juan will be a electrical engineer at Lockheed Martin upon graduation in spring 2021. He has worked on the NASA BIG Idea Challenge of Lunar Dust Mitigation. And the Spaceport America Cup with the goal of designing a rocket to reach 30,000ft in his time at Rowan University.

C. Neeve Kadosh

Neeve Kadosh is an Electrical and Computer Engineer with a Certificate of Undergraduate Study in Combat Systems Engineering graduating Rowan University with *Magna Cum Laude*. His focus is in the sub field of Artificial Intelligence called Reinforcement Learning (RL). He is returning to Lockheed Martin as an Associate Member of the Engineering Staff to pursue RL opportunities in Directed Energy and Fire Control teams.

D. Robert Mullin

Robert Mullin will be an Electrical and Computer Engineer upon graduating from Rowan University in spring 2021. He has participated in competitions organized by NASA regarding their BIG Idea Challenge of creating a Lunar Habitat design and by Spaceport America to design a model rocket capable of reaching 30,000ft with a desired payload.

E. David Sheppard

David Sheppard is a system integration and test engineer at Leidos. His work focuses primarily on the verification and validation process of air traffic management system development as part of the FAA's NextGen portfolio. He graduated *summa cum laude* from Rowan University with a bachelor's degree in electrical and computer engineering in 2020 and is currently pursuing a master's degree in the same field.