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TOWARDS AIRSPACE RULES FOR FUTURE UAS-BASED DELIVERY

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ABSTRACT

The growth of the nascent UAS industry will be affected by the airspace coordination rules between drones because these rules can impact business profitability. Few analyses have been reported to support design of commercial UAS operations in low-altitude commercial urban airspace. Analysis of minimum horizontal separation is critical for designing safe and efficient UAS delivery systems. In this paper a constructive simulation model is used to analyze and evaluate proposed UAS airspace traffic. A high density of delivery drones could create a bottleneck in a drone-based supply chain very quickly, especially when a high minimum horizontal separation standard is required. This paper proposes a simple idea on how to organize low-altitude UAS traffic, and evaluates the idea using a simulation model. Additional implications and future work needed in relation to UAS-based delivery are also discussed.

1 INTRODUCTION

This paper is concerned with the lower portion of Class G airspace, which includes elevations up to 1,200 feet above the surface where there is no Air Traffic Control (ATC) designated to manage that airspace (FAA 2015). Current Federal Aviation Agency (FAA) regulations do not facilitate pro-business climate for UAS-based low-altitude delivery systems. FAA requires aircraft to be 1,000 feet above the highest obstacle within a horizontal distance of 4 nautical miles from the course to be flown and does not provide enabling guidance for the use of autonomous UAS in this airspace (FAA 2015). The lack of FAA rules does not allow for explicit description of future UAS-related businesses operations, but this indicates an opportunity to investigate management options by using simulation models that can inform the FAA about business perspectives related to this endeavor. More well-defined system and structural rules are needed to both guarantee safety and provide economic justification due to potential crowding of future low-altitude urban airspace. For instance, a mix of centralized and decentralized controls of UAS could offer both resilient and redundant operation.

Infrastructure that could enable safe and widespread use of low-altitude airspace for UAS operations does not yet exist; therefore, NASA has initiated research, within the 2014-2020 timeline, that should lead to the development of a prototype UAS traffic management (UTM) solution (Kopardekar 2014). Low altitude UTM could provide services such as dynamic configuration, dynamic geo-fencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning and re-routing, separation management, sequencing and spacing, and contingency management (Kopardekar 2014). Initially, the UTM system is expected to support low-altitude airspace delivery of goods and services via UAS operations in remote areas and then migrate to increasingly denser areas, eventually managing airspace over urban areas (Kopardekar 2014).

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Mohammed et al. (2014) discussed several UAS-based related business and technical challenges in the context of smart cities. Foina et al. (2015) proposed a UTM that consists of three main components: electronic identification plate, ground identification equipment, and a Traffic Routing System (TRS). It introduces an air parcel model dividing low altitude airspace into a 3-D air parcel map. TRS calculates efficient and collision free trajectory assuming straight flying path between waypoints. This proposed system considers a pilot-operated UAS, which can be a major drawback to achieving cost efficient delivery system.

This paper builds upon the research reported in Balaban et al. (2016), where concepts of the future UAS business delivery operations were introduced and a theoretical constructive simulation model was used to analyze selected factors.

2 ORIGINATION OF SIMULATION STUDY

A general concept of a future low-altitude UAS delivery system is provided by Amazon (2015a). Four airspace classes below 500 feet access were proposed: basic, good, better, and best. The "basic" access has only radio control, allowing for flying within the line of sight (LOS) in predefined low risk locations. The "good" access should be considered in suburban areas at less than 200 feet daytime LOS and includes, in addition to the basic access, a collaborative vehicle to vehicle (V2V) communication, an on-vehicle internet connection, GPS and Wi-Fi, an ability to receive traffic information, and proximity alerting. The "better" access adds autopilot de confliction, and it should be considered at altitudes of less than 400 feet for suburban areas and limited urban areas. Finally, the "best" access should be considered for urban areas. It adds a non-collaborative sense-and-avoid (SAA) technology and 4D trajectory planning. Amazon provided some UAS delivery business specifications. For instance, drones weighing less than 55 pounds would carry up to five pounds in 30 minutes or less and fly under 400 feet. NASA identified a standard of minimum 1 mile horizontal separation for low-altitude UAS airspace (Kopardekar 2014). This constraint within a given geographic area could cause a bottleneck rather quickly, hence an alternative perspective on horizontal separation is analyzed in this work. Amazon (2015b) proposed an airspace design for small drone operations where two velocities are considered: low velocity transit at altitudes below 200 feet and high velocity at altitudes between 200 and 400 feet.

This research looks at how to effectively maintain horizontal separation between drones during horizontal transition, proposes a simple idea on how to organize low-altitude UAS traffic related to the future use of UASs for the delivery of products, and evaluates it using a simulation model. The first simple rule is for all drones within a single layer to maintain a single velocity and to move using straight paths from point A to point B. This can help in designing more complex rules based on estimated trajectories. The next concept is to divide a single velocity layer of airspace into 4 altitudes. The movement within each sublayer would follow strict rules determined by direction/bearing of a drone. Each layer with altitudes separated by 25 feet covers 90 degrees of horizontal motion range. For instance, four altitudes for low velocity airspace would include 100, 125, 150, and 175 feet, with the assigned bearing from $0\ to\ \frac{\pi}{2};\ \frac{\pi}{2} to\ \pi;\ \pi\ to\ \frac{3}{2}\pi; and\ \frac{3}{2}\pi\ to\ 2$ for each altitude, respectively. Additionally, each layer can be described using four geographic directions: northeast, southeast, southwest, and northwest.

This division constrains the angle at which drone trajectories can intersect to less than or equal to 90 degrees. While moving using the GIS coordination system, bearing can change along the horizontal trajectory which can cause the crossing angle of two trajectories to sometimes go a little above 90 degrees. However, this should not have a large impact on trajectory because potential problems occur at angles close to 180 degrees. Using this rule, this system operates similar to that of a street intersection. The vehicle closest to a 'virtual' intersection between trajectories will move first, while the rest of the vehicles within considered range will wait. To illustrate the proposed idea Figure 1 displays a virtual crossroad where 3 drones with headings $h1, h2,$ and $h3$ are flying at altitude 175 feet in a northwest direction ($\frac{3}{2}\pi\ to\ 2\pi$) and must determine rights of way. The following distance relations between drones occur $D1D3 < D1D2 < D2D3 < D3D2 < D2D1 < D3D1$. It is assumed that at any time within a virtual crossroad there can be only one drone that is closest to another drone. Because drone 1 is the closest one to the intersection with another drone (drone 3), it will go first leaving the virtual crossroad. Because $D2D3 < D3D2$ drone 2 goes next, and finally drone 3 leaves.

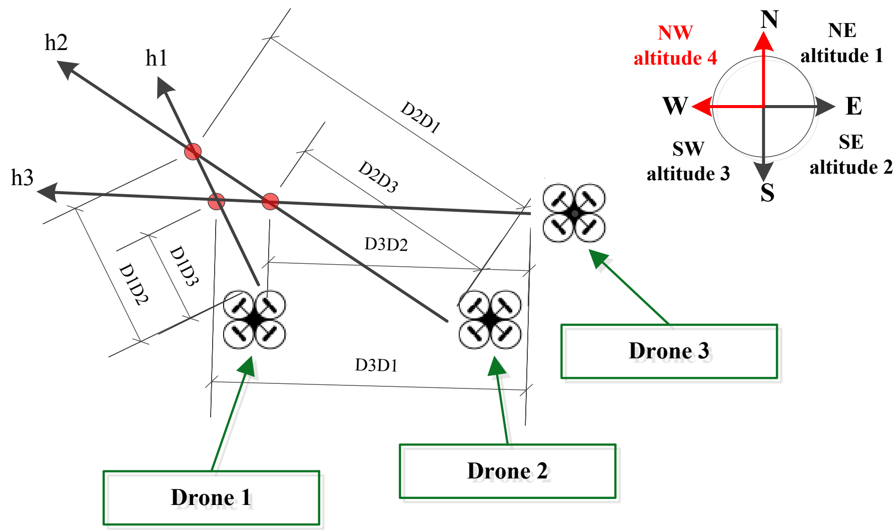

Figure 1: Right of way rule for drones.

In this approach, one must handle a situation where two or more drones are at similar distances to their intersection points. This can be realized at 'better' of 'best' access levels, according to the classification proposed by Amazon (2015a), using collaborative V2V communication and a de confliction mechanism.

3 SIMULATION MODEL

The initial simulation model developed in Balaban et al. (2016) is expanded and used to investigate horizontal separation traffic rules between drones during transit. In a realistic scenario, businesses could potentially operate multiple UASs at the same time within a shared geographic airspace.

3.1 Independent and Dependent Variables

This section introduces the variables used for conducting an analysis of the proposed system. The independent variables consist of a number of available drones (ND), product demand (D), separation range (SR), and the separation algorithm (SA). SR is a distance to a horizontal trajectory crossing between drones at which the SA determines right of way based on the GIS location of the relevant drones and their heading/bearing. This must be supported by appropriate technologies, e.g., SAA and V2V communication. SA describes two options, using or not using the separation algorithm.

The dependent variables include the observed minimum distance (MD) between drones, the average minimum distance (AMD) between drones, and the percentage of average drone lost time (PTADLT) due to the separation algorithm. MD is a minimum value of the shortest distances between two drones observed for the same input configuration, e.g. a minimum of the shortest distance out of multiple iterations using the same input values for the independent variables. AMD is defined as the average of the shortest distance between two drones within a considered set of iterations. Finally, PTADLT is expressed as $100 * (\sum_{i=0}^{n} \int_{0}^{T(m)} \frac{LT_i(t)dt}{T(m)})/\, n$, where n is a total number of drones, $LT_i(t) = \begin{Bmatrix} 1\ if\ drone\ waits\ at\ time\ t \\ 0\ if\ drone\ moves\ at\ time\ t \end{Bmatrix}$ is the drone wait time during horizontal movement due to congestion, and $T(m)$ is the time spent observing the airspace during m intervals.

3.2 Simulation Model Structure and Assumptions

Figure 2 presents the main components of a simulation model and the Modeling and Simulation (M&S) methods used. Agent-based Modeling (ABM) is used to represent the overall multi-level model structure that allows for embedding processes, behaviors, and interactions of actors (i.e. delivery businesses, customers, orders, and drones). Discrete Event Simulation (DES) represents product deliveries that involve processing orders and utilize UASs to represent the resources required to process the orders. Orders and UASs combine properties of both agents and entities because they are (1) part of DES processes and (2) include internal behaviors that trigger other agents or monitor conditions triggered by other agents. State charts (SC) represent drone states during operations and their transactions with customers. Figure 3 shows a graphical overview and a simulation model screen capture for UAS delivery involving four businesses, including markups that point out the main components within the figure.

While the experimental design will use independent and dependent variables, several assumptions are made in our hypothetical scenario, including variable values. Businesses are located at four diagonals, half-way between the center of the map and each corner as shown in Figure 3. Each business offers a specific product that can be ordered by customers, which are randomly generated within the area of operations. Orders are fulfilled using delivery drones, thereby allowing for the possibility of situations where drones can cross each other's paths during flight. The airspace implemented in the model covers a single velocity layer, e.g. a low-velocity localized traffic layer as proposed by Amazon (2015b), which is further subdivided into four altitudes. Each altitude is assigned one of four direction ranges, 90 degrees each, starting at the north direction as shown at the bottom of Figure 3. Drones are assigned altitudes twice during a single order flight, first assigned based on the heading towards a customer location, and then assigned based on the heading towards the home business location.

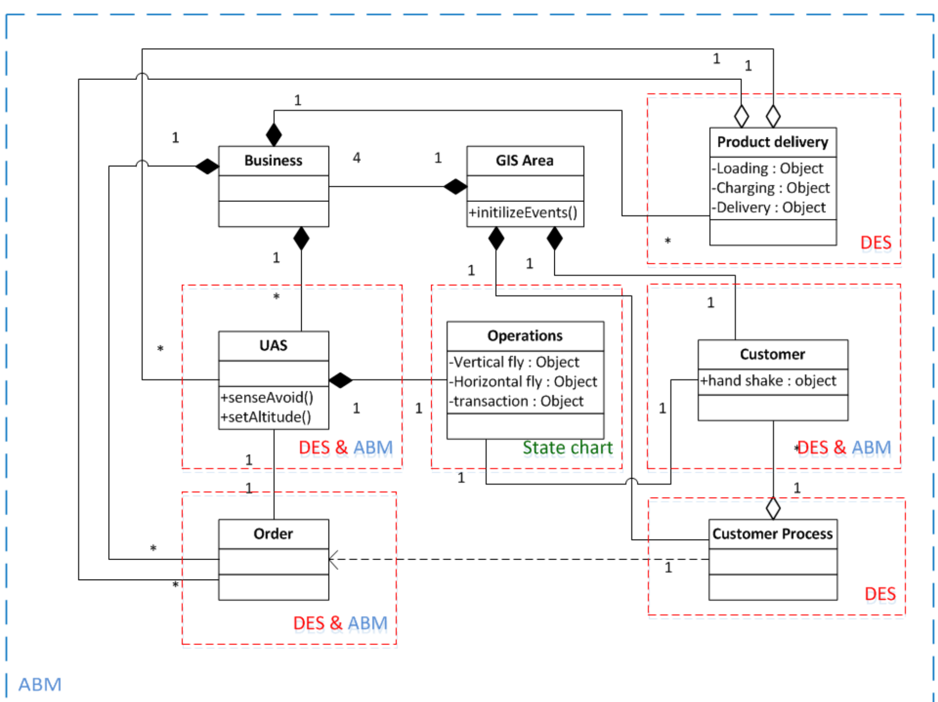

Figure 2: Structure of the simulation model.

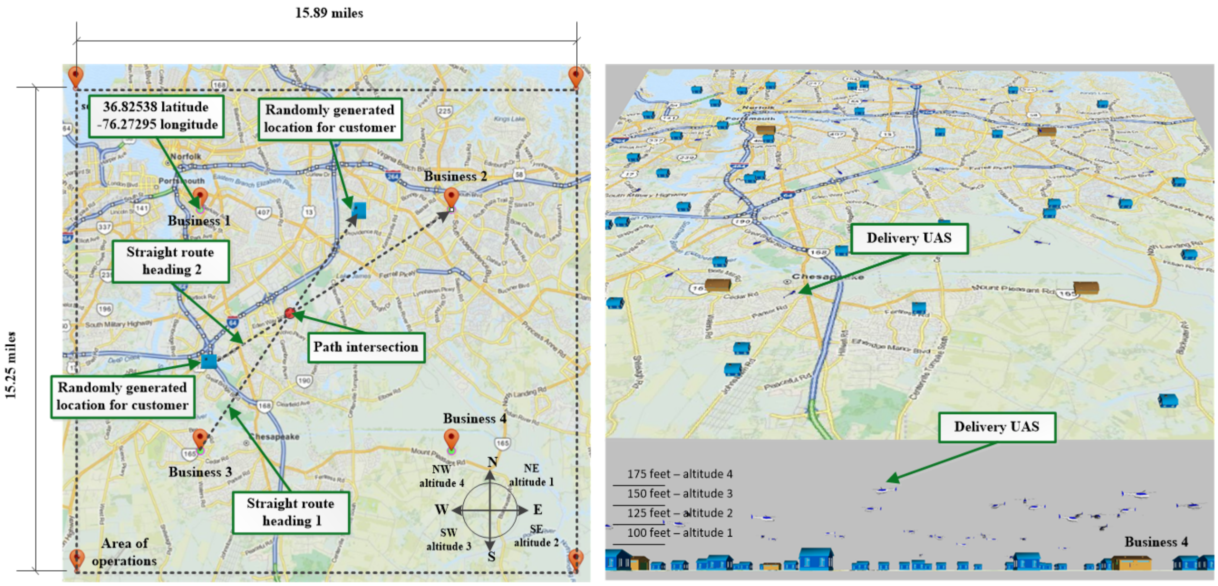

Figure 3: UAS delivery with four businesses.

Drone velocity (DV) is set to 55 mph, the four altitude levels are set to 100, 125, 150, 175 feet. Maximum drone fly-time (MFT) is set to one hour, batteries swap (BS) after finishing order is set to take three minutes, and route type (RT) is set to straight paths. It is assumed that drones move following perfect vertical and horizontal trajectories and that they maintain constant velocities. UAS ascending velocity is 10 mph. Time to load a drone is represented using a triangular distribution with minimum, maximum, and most likely values at 1, 3, and 2 minutes, respectively. A business takes orders for 10 hours daily, and finishes all the orders already placed before closing for a day. This business setting converts into a terminating simulation. Customer balking is not represented, i.e. situations when customers cancel orders or decide not to place orders due to excessive delivery wait times. For more detailed description of the drone delivery process please refer to Balaban et al. (2016).

In order to ensure both sufficient precision and reasonable simulation time, two internal frequency modes representing UAS scanning the surroundings were used. A frequency of 1 Hz is used for detecting situations where the separation algorithm should start, while a frequency of 30 Hz is used for monitoring and de confliction until exiting a contingent area. The sensing error is 80.7 feet for 1 Hz and 2.7 feet for 30 Hz while at 55 mph velocity. This was assumed sufficient when considering the scope of the simulation model at this stage of the research. A minimum safe SR value is assumed as 200 feet due to precision limitations. This means that in the worst case the 30 Hz scanning will start at least 119.3 feet away from the intersection point between drone paths.

The implementation of the separation algorithm in the GIS coordinate system is an important part of the model. In order to specify which drone should proceed and which one should wait, the distances to the intersection point must be known. In GIS, this requires knowing the latitude and longitude values of the intersection point as well as the location and headings of both drones. While the heading and distance can be obtained using the GIS API provided within the Anylogic software, the latitude and longitude of the intersection point is calculated using a modified algorithm for the intersection of two radials provided by Williams (2016). The vertical rules for separation of drones during ascending and descending was conceptualized, but not implemented and will be developed as part of the future work. In order to minimize recording of MD values associated with the lack of implemented vertical separation, the areas 200 feet or less from the base or customer location do not log MD values. This does not guarantee eliminating 100% of biased values, but will eliminate most except in situations where two drones take off from the same base or from two nearby located customers at the nearly the same time and using the same or very similar headings. Increasingly accurate representation of trajectories, and acceleration and deceleration of drones will also be part of the future work.

4 SIMULATION ANALYSIS

This section discusses the design of experiment (DOE) and the results of the simulation analysis.

4.1 Design of Experiment

The DOE for the simulation model requires identifying the dependent and independent variables that are of interest to the study and then specifying value ranges for the independent variables. As such, high and low values were chosen for ND, the D factor is varied at four levels, the SR factor is varied at three levels, and the SA factor has two options as indicated in Table 1. The values of input factors are usually estimated by subject matter experts or study sponsors (Law 2007); however, because this is a non-existent system, the values for independent variables were chosen based on results from initial runs. Values for the independent variables were spread sufficiently far apart in an attempt to observe a difference in the dependent variable and to avoid nonsensical configurations. The lowest SR level was set at 200 feet because of a precision constraint, while the highest level is set to 5280 feet (1 mile). The understanding of how SR affect minimal MD and AMD is important for evaluation of the proposed airspace traffic rules. A full factorial design with four factors and 30 iterations per level required a total of 1440 (2^2 x 3 x 4 x 30) simulation runs. Table 1 summarizes the DOE factors and levels.

Table 1: Input values of the independent variables and the metrics for both independent and dependent variables.

Independent variable	Input values	Metric	Dependent variables	Metric
Number of available of drones (ND)	10, 15	Quantity	Minimum distance (MD) between drones	Feet
Delivery demand (D)	20, 40, 60, 80	Orders per hour	Average minimum distance (AMD)	Feet
Separation range (SR)	200, 1000, 5280	Feet	Percentage time average drone lost time (PTADLT)	Percent
Separation algorithm (SA)	No, Yes	N/A		

4.2 Results of Simulation

A total of 1,440 simulation runs were conducted using the input values described in Table 1. From these runs, 175 runs where no trajectory crossing was observed were eliminated leaving a total of 1265 runs for the analysis. Analysis of Variance (ANOVA) p-values display if there exists a systematic difference between group means or if differences are due to chance (Iversen and Norpoth 1987). As shown in Tables 4 and 5 in the Appendix, the ANOVA test resulted in significant p values of less than 0.001 for D, SR, and SA, for both AMD and TAPDLT. ND was not significant for AMD and TAPDLT at p values of 0.8 and 0.94, respectively. ANOVA is not applicable to MD. PTADLT values for SA = No are zeros and are skipped. Table 2 provides the average values obtained across all levels.

The separation algorithm worked, although the minimum value of MD was 7.4 feet, which is very low. Considering the error due to the precision is 2.7 feet, the worst possible scenario that could occur would have less than 5 feet of actual separation between drones, and that does not include high wind conditions. The lowest MD value recorded without SA was 1.5 feet, which could result in a collision. Using a paired two sample t-test between all SR levels MD was below the t critical value (0.068, -0.92, and -0.73; two-tail t critical 2.13 for df = 15); hence, longer SR did not guarantee better MD values even if it is significant for AMD based on the ANOVA results mentioned above.

Table 2: Resulting average values for DOE at all levels.

		SA = No				SA = Yes					
ND		10		15		10			15		
D	SR	MD	AMD	MD	AMD	MD	AMD	PTADLT	MD	AMD	PTADLT
20	200	13.5	119.9	99.3	129.0	74.7	117.3	0.001	66.4	126.4	0.001
	1000	22.8	320.6	37.8	376.2	116.4	483.6	0.008	134.5	549.8	0.007
	5280	1.5	362.3	67.3	320.6	386.0	1178.7	0.221	149.8	996.9	0.230
40	200	2.4	96.4	2.7	80.9	90.5	132.8	0.001	42.2	123.7	0.001
	1000	28.5	121.8	15.3	132.9	67.8	311.6	0.016	25.6	284.3	0.015
	5280	28.6	134.3	5.5	125.2	93.3	404.8	0.479	15.1	360.7	0.498
60	200	13.4	81.5	13.1	76.6	62.1	121.0	0.001	66.3	120.5	0.001
	1000	14.7	72.8	13.1	59.2	82.0	197.4	0.023	29.3	223.1	0.021
	5280	12.4	84.1	18.0	91.0	60.0	247.2	0.731	7.4	294.5	0.711
80	200	8.5	45.3	10.3	63.7	31.7	97.2	0.001	43.6	98.2	0.001
	1000	4.2	48.9	5.6	43.8	16.4	140.6	0.029	18.1	133.5	0.029
	5280	6.5	39.6	7.0	45.7	9.4	181.2	0.942	20.3	216.9	0.948

Table 3 show a 95% confidence boundaries of expected effects, upper and lower for each level. The 'zero' column displays numerical level dependency if the difference between the two level boundaries does not contain zero, and 0 otherwise. For instance, examining D within the minimum distance between drones of Table 3, a value of '14' is shown under the final column. This is because the difference between confidence boundaries at level 1 and level 4 does not contain '0'. Red color indicates significant negative relations and green color indicates significant positive relations. Because of the different number of levels used for the independent variables, N/As are filled in Table 3 for SR at level four and for ND and SA at levels three and four.

Table 3: Analysis based on confidence boundaries.

	upper 1	lower 1	upper 2	lower 2	upper 3	lower 3	upper 4	lower 4	zero
	Minimum distance (MD) between drones								
ND	71.7	32.3	48.2	28.0	N/A	N/A	N/A	N/A	0
D	162.6	32.4	55.4	14.2	49.7	15.6	22.7	7.5	14
SR	70.0	49.4	86.0	36.6	161.2	24.1	N/A	N/A	0
SA	24.4	13.3	90.6	51.8	N/A	N/A	N/A	N/A	21
	Average minimum distance (AMD)								
ND	273.7	154.7	263.9	158.8	N/A	N/A	N/A	N/A	0
D	642.4	204.4	264.7	120.1	189.9	88.3	134.3	58.1	13, 14
SR	124.0	110.3	372.4	208.6	688.7	281.5	N/A	N/A	21, 31
SA	154.0	102.0	366.1	229.1	N/A	N/A	N/A	N/A	21
	Percentage time average drone lost time (PTADLT)								
ND	0.28710	0.12200	0.28770	0.12260	N/A	N/A	N/A	N/A	0
D	0.15065	0.00511	0.32612	0.01063	0.48086	0.01492	0.63058	0.01991	0
SR	0.00081	0.00061	0.02327	0.01401	0.74768	0.44270	N/A	N/A	21, 31, 32
SA	0	0	0.28560	0.12410	N/A	N/A	N/A	N/A	21

Additionally, the 30 lowest separation distances from all runs for SA factor were used to conduct a paired two sample t-test. A significant difference was observed when the separation algorithm was used: t stat = 13.35; df= 29; and two-tail t critical = 2.04. Mean and confidence values for SA = 'Yes' was 33.4 ± 4.9 feet and for SA = 'No' was 8.7 ± 1.2.

5 FUTURE WORK ON UAS-BASED DELIVERY SYSTEM

Future work includes developing vertical rules for separation of drones during ascending and descending and conducting an in-depth analysis of SA for parallel or near-parallel drone headings to determine the worst case scenarios. Balaban et al. (2016) reported analyses based on multiple business factors and observing causal relations between independent and dependent variables as shown in Figure 4. The development and analysis of simulation models of UASs delivery system offered insights into various UAS business considerations. Moreover, in that same paper the authors proposed multiple business UAS models as summarized in Figure 4. Future work should also investigate the effects that traffic separation constraints have on different UAS business delivery models.

The extended simulation model aims to support the ability to quickly integrate models and to create scenarios for optimal route planning, scheduling, and cost-volume-profit (CVP) analysis. Future work is also required to improve our representation of drone trajectories. The Dynamic Systems (DS) method will be considered. Moreover, the next step needs to involve calibration and validation of the model using data obtained from actual drone testing. Ultimately, the commercial potential of the ideas presented in this paper should be tested and evaluated using real systems. This can involve a combination of real time operations and simulated system to provide additional information to the FAA about the potential benefits and risks of different strategies for the use of drones by commercial entities.

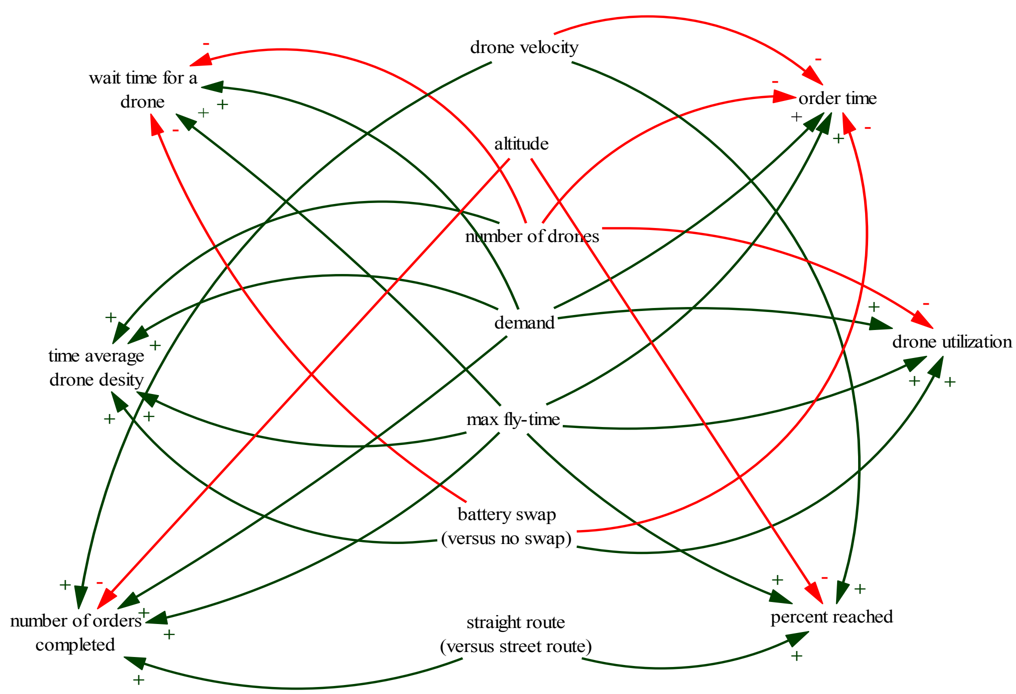

Figure 4: Causalities observed based on a simulation model of business deliveries (Balaban et al. 2016).

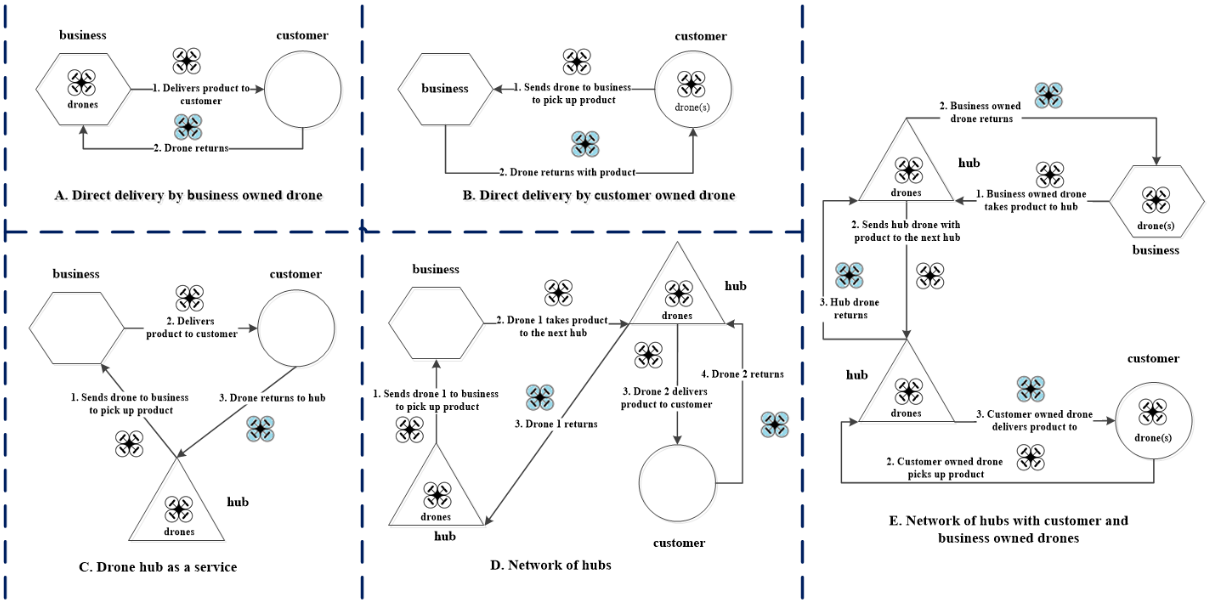

Figure 5: Summary of UAS business models (Balaban et al. 2016).

A APPENDIX

Table 4: ANOVA results for AMD.

AMD	Df	Sum Sq	Mean Sq	F value	Pr(>F)
ND	1	3577	3577	0.061	0.804
D	1	26238465	26238465	450.956	<2e-16 ***
SR	1	4932595	4932595	84.776	<2e-16 ***
SA	1	11327027	11327027	194.676	<2e-16 ***
	1261	73370200	58184		

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 5: ANOVA results for PTADLT.

PTADLT	Df	Sum Sq	Mean Sq	F value	Pr(>F)
ND	1	0	0	0.006	0.804
D	1	1.93	1.934	60.666	1.4e-14 ***
SR	1	27.08	27.08	849.447	< 2e-16 ***
SA	1	17.34	17.341	543.956	< 2e-16 ***
	1261	40.2	0.032		

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

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