Design of a Drone Lead-Follow Control System

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Abstract— **A Drone Light Show (DLS) is visual entertainment in which multiple autonomous drones form complicated flight patterns. As drones become smaller and more efficient due to technology advances, a DLS can replace fireworks for cheaper and reduced risks.**
This paper describes the design of a control system to create drone trajectories using a "Lead-Follow" Control System in a Cartesian coordinate. The simulation was created through a Matlab subprogram called Simulink and studies the trajectory behavior of the two drones with optimal Proportional, Integral and Derivative (PID) control gains to determine the separation between the drones. Based on the optimal separation, risks of fatality, injury and property damage are assessed. With a proportional gain of 6, derivative gain of 0.3, and a 0.1 integral gain, separation distances of 10 ft, in the X and Y axes and a 0 ft separation in the z axis, a 5% error margin was achieved.

I. INTRODUCTION

As technology continues to progress in a very fast rate, the uses of small unmanned aerial vehicles (Drones), have also increased in the same rate because of their versatile use, small size, ease of access and increased efficiency in the software and hardware they use. This project focuses on the design of a Drone Lead-Follow separation control system, which is the major part of our parent project called a "Drone Light-Show Production System," which uses multiple drones to fly simultaneously in coordinated and synchronized patterns all while emitting different colored lights to produce light shows. Operation of these light shows require systems that shall meet very high operational and safety standards. The separation between adjacent drones is vital to produce a functioning Drone Light-Show production system with minimum Near Midair Collisions (NMACs); which could pose potential fatality, injury and property damage risks. In addition, a falling drone poses even a bigger treat for audience members and/or a nearby property. This paper focuses on the Control component of this system, specifically, the Drone Lead-Follow separation control in a cartesian coordinates system in the first section and the risk analysis in the second section.

II. CONTEXT

In 2012, the total revenue which was generated from the U.S. entertainment and media market industry was $479.23 billion. This was 29.2 percent of the total global industry revenues which was estimated at $1.639 trillion in that year [1]. By the end of 2017, the industry in the United States is expected to generate $632.09 billion, which is equivalent to 29.4 percent of the global revenue which is approximated to be more than $2.152 trillion[1]. In the category of light show entertainment, fireworks are the most dominant alternate followed by Laser light shows. The demand for fireworks has been growing over the years as shown by the increased revenues, which jumped from $284 in 1998 million to $536 million in 2010 and again to $755 million in 2015 [2].

However, safety and health concerns remain a major issue when it comes to fireworks and laser light show entertainment options. The major risks associated with fireworks include the risk of injuries and fatalities to the public and the risk of fires. A report by National Fire Protection Association indicated that in 2013 alone, fires emanating from firework displays were estimated at 15,600 [4]. In 2015, Consumer Product Safety Commission (CPSC) reported 11 deaths and 11,900 injuries that were caused by fireworks [5]. Due to the health and safety concerns which are associated with fireworks and potential eye damages in relation to laser light shows,the demand for Drone Light-Shows have increased in recent years as shown in the 2017 Super Bowl halftime show.

III. STAKEHOLDERS ANALYSIS

The stakeholders for the Drone Light-Show production System are divided into 3 main components and are shown in different colors in the stakeholder interaction diagram (figure 1): The stakeholders that fall on the sky blue background are stakeholders that are directly or indirectly involved with the money flow to allow the show to run (Insurance Companies, Venues and Manufacturers), those who seek satisfaction from the industry are presented in green (Entertainment industry, viewers, sponsors, and competitors), and lastly, those who provide safety for the viewers are shown in the red background (FAA/OSHA, Law Enforcement).
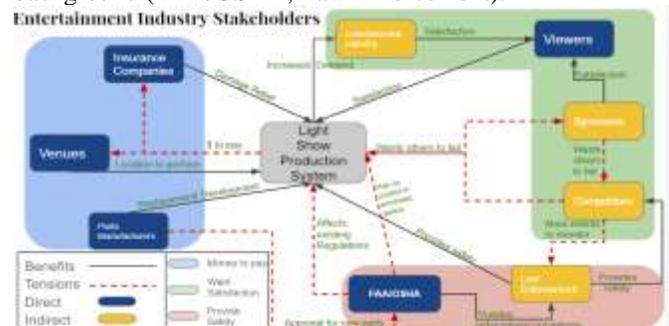

Figure 1: Entertainment Industry Stakeholders

For a win-win outcome, the tensions between the stakeholders must be addressed to satisfy the objectives of the stakeholders, whether direct or indirect, in a fair manner. The tensions in figure 1 are shown in dotted red lines.

IV. PROBLEM STATEMENT

The entertainment industry in the United States is one of the key industries with substantial impact on the economy. For instance in 2012 alone, the total revenue which was generated from the U.S. entertainment and media market industry was $479.23 billion. This figure is expected to grow in the year

2017. But there are no adequate alternatives when it comes to light shows in contributing to the existing revenue generating lines of the entertainment industry. In addition, the risks involved with the existing light show alternatives, have hampered the potential revenue that could be generated from light shows. As a remediation, there is a need for a system which can contribute to the growing gap between the supply and demand in the industry. Which can be accomplished by building a system which is safe for the people, safe for the environment, superior in entertainment to the current alternatives, cost effective and renewable.

V. SIMULATION

Simulation Requirements

 SR.1. The system shall model the Separation Distance between an adjacent Lead-Follow drone pair.
 SR.2. The system shall model Cohesion of the Drones.
 SR.3.The system shall model the risks associated with drifts from target positions during flights.

Simulation Objectives

The objectives of system verification using simulation for the DLS is to ensure that the system is working according to design specifications and the set requirements that the system have to meet. For the DLS system, the following are the simulation objectives:

The simulation will be used to evaluate:

 i) The alignment of drones relative to each other in the x,y and z cartesian coordinate axes.

 ii) Cohesion between drones to evaluate how long the lead-follow pair maintain their separation.

 iii) The Risks associated with the drones' inability to follow their target trajectories.

 Stage 1
   ● Lead-Follow Control Model

A mathematical model that defines the flight trajectories of the two drones is simulated to demonstrate the manoeuvrability of the drones with varying control variables. The model will evaluate the relative position of a Lead-Follow pair according to target trajectory patterns and predetermined separation requirements.

Stage 2
   ● Risk Simulation Model

The Risk model uses the relative position of the drones from the Lead-Follow control model to derive their velocities and calculate the kinetic energy of a drone when it makes contact with an audience member or a nearby property in case of a failure.

VI. LEAD-FOLLOW CONTROL MODEL

For the Lead-Follow Control model, the user defines a configuration in which the initial and final positions of the Lead drone in three coordinate axes are fed into the simulation model. Based on the position of the Lead Drone, the initial position of the Follow drone and the target separation between the pair, their trajectories will be traced to check whether the target separations are kept on the course of their flights. Based on the observed preliminary results, the proportional, derivative and integral control gains are adjusted to decrease the errors and bring the separation between the pair as close as possible to the target values. The outputs from each coordinate axis is then plotted as Lead -Vs- Follow on an XY plot to show their relative positions throughout the course of their flights.
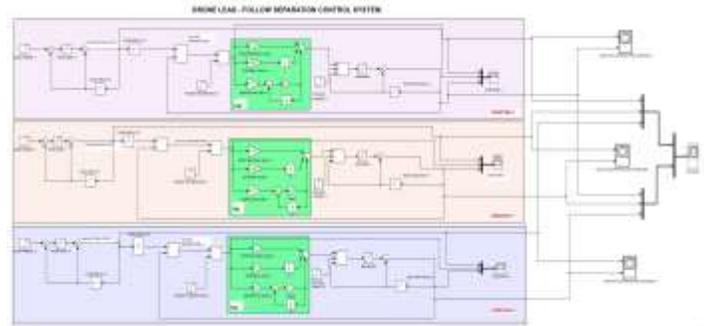

Figure 2: Drone Lead-Follow Control System

The simulation was created through a Matlab subprogram called Simulink. Simulink was used due to its' visually progressive functionality in order to show all the physical components that are necessary for the "lead-follow" drone control law parameters. To better understand each portion of the system, the model is divided into three sections. The first section shows the inputs and outputs of the Lead drone, the second section shows the controller portion and the third section shows the input and outputs of the Follow Drone.

The first subsystem is the lead drone, or the drone that will be leading the flight. First, a saturation block was placed so the limit of the lead drone could not fly any faster than what is physically possible. Since we are using an Asctec Hummingbird drone for our system, the maximum air speed is 15 meters per second and that number is the inputted to limit this scenario. Next, there was an included delay so the lead and follow drones would not collide. This value is a dependent variable in order to find the optimal delay that will not cause a collision between the drones.

The second subsystem is the Proportional controller, integral controller, and derivative controller. The gains for the PID subsystem were all altered during verification testing to find the optimal separation.

The output of the PID, which is equal to the input to the Follow Drone plus possible disturbances in the time-domain is given by.

$$C(t) = K_p\, e(t) + K_i \int e(t)\, dt + K_d\, d(e)/d(t) \quad (1)$$

Where: C(t) is controller output ; e(t) is the separation error; Kp, Ki and Kd are the proportional, integral and derivative gains respectively.

The variable e(t) represents the difference between the desired (target) input position to the Lead drone L(t) minus the actual output of the Follow f(t).

When e(t) is sent to the PID controller, the controller calculates both the integral and derivative of this error signal. The control signal C(t) is equal to the proportional gain (Kp) times the magnitude of the error plus the integral gain times the integral of the error plus the derivative gain times the derivative of the error.

Figure 3. Lead-Follow Control Block Diagram
The control signal C(t) is sent to the Follow drone, and the new output F(t) is obtained. This new output F(t) is then fed back and compared to the reference(target) position of the Lead to find the new error signal e(t). The controller takes this new error signal and computes its derivative and its integral again, throughout the duration of the flight.

The transfer function of the PID controller can be obtained by taking the Laplace transform of equation (1).

$$Kp + (Ki)/S + Kd*S = (Kd*S^2 + Kp*S + Ki)/(S) \qquad (2)$$

Where Kp, Ki and Kd are the proportional, integral and derivative gains respectively.

Our third subsystem is the Follow Drone. This subsystem is similar to the Lead Drone in that it has a saturation block in order to limit how fast the drone can physically fly, but past the saturation block is where the model starts to differ. First, the follow drone goes through the PID controller to be able to correct the flight trajectory error in order to stay synchronized to the lead drone. Additionally, the follow drone has its' own delay to be able to start moving after the follow drone moves. This value was varied in the verification testing to see what time would work best for the results of the model.

VII. METHOD OF ANALYSIS
The method of analysis for the Lead-Follow control model focuses on the trajectory tracing of the Lead-Follow pair and verifying the target separations are met according to control gain parameters. Simulation is done in two stages: the first stage is a Lead-Follow model and the second is a Risk model. The results of the Lead-Follow model are used as input for the risk model. Simulation modeling in two stages helps in to reducing the the number of runs for the simulation models during the verification process of the system design. In regard to the verification of the Lead-Follow Control system, the models are run through simulink software with the aim of quantifying the separation during the trajectory tracing. The process also seeks to quantify the risks of fatality, injury and property damage to study and mitigate the potential collision of the drones with audience members and/or nearby property.

VIII. SIMULATION RESULTS
A.Lead-Follow pair in the X , Y and Z axes.

Figures 4, 5 and 6 show the relative position of the Follow drone with respect to the position of the Lead drone in X-Y plots. The X axis shows the position of the Lead drone and the Y axis shows the position of the follow drone in all three cases. As the initial and final positions in the X and Y axes and the target separation as well as the control parameters are the same, figure 4 and 5 are identical.
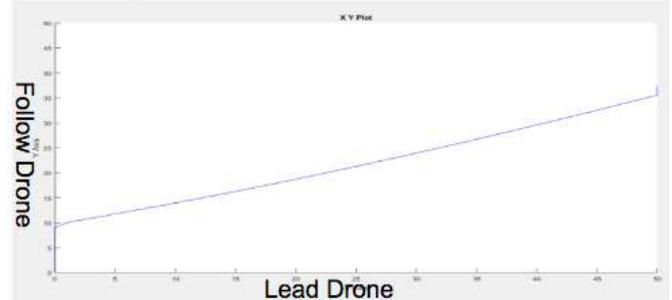

Figure 4. Lead Vs Follow relative position in the X axis. The Y Axis is the change in distance (m) and the X axis is time (S)

As the values in the graphs show, the follow drone does not move until the lead reaches 10 meters and the final values are 50 and 40 for the Lead and Follow respectively which are consistent with the target values.
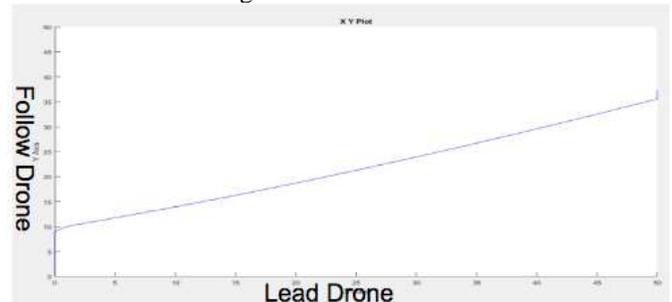

Figure 5. Lead Vs Follow relative position in the Y axis. The Y Axis is the change in distance (m) and the X axis is time (S).
As it can be seen on figure 5 below, the trajectory tracing of the Lead-Follow pair in the Z axis has a different pattern than the ones shown for the X and Y axes because of the pair differ only in delay times and their initial and final positions are the same as set in the target input values.
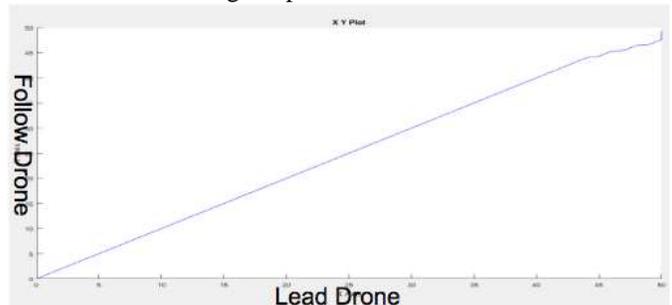
Figure 6. Lead Vs Follow relative position in the Z axis.The Y Axis is the change in distance (m) and the X axis is time (S)

This simulation output diagram on figure 6 illustrates the the difference between the lead (yellow) and follow drone (in green). The blue and orange lines represent the actual separation and separation error respectively.
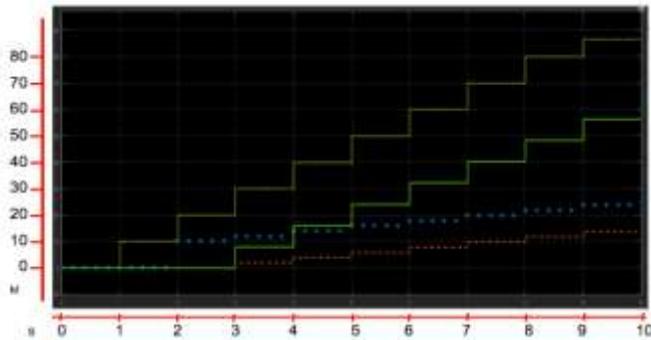

Figure 7. Screenshot of Lead-Follow control System signal tracing in the X and Y axes. The X axis is the time (s) and the Y axis is the separation between drones.

The vertical gap between the lines representing the lead and follow indicate the separation between the pair in a given axis. The control parameters used to get the output shown on figure 6 are, Kp=1.43, Kd=0.09 and Ki=0.022 which give an optimal separation pertinent to the set targets.

RISK MODEL

In order for our risk model to be effective it needs to produce kinetic energy less than 120J. In the figure 7, the kinetic energy and associated speeds illustrate the three critical areas for human injuries.
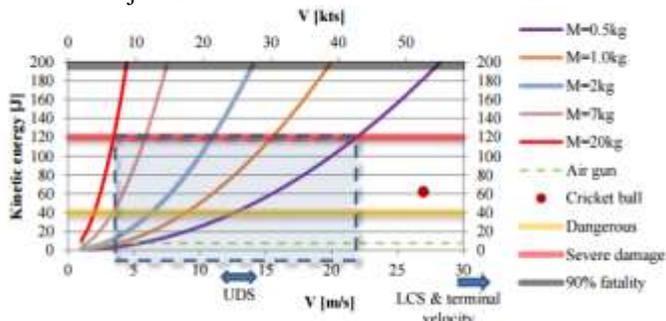

Figure 8. Screenshot of the injury model developed to address risk areas for drones.

In the risk model shown below, the velocities in the X,Y and Z axes were derived from the Lead-Follow Control model discussed above on this paper.
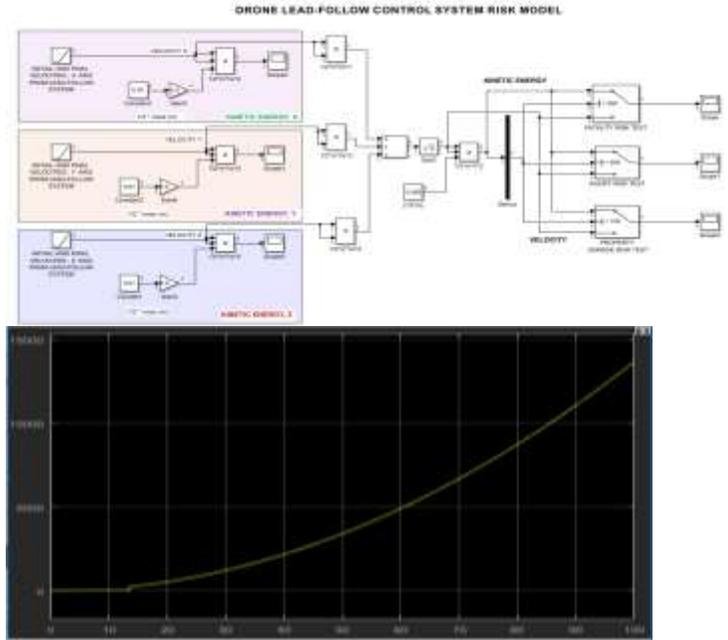
Figure 9. Risk Model

Figure 10. Risk Model output. The X axis shows the velocities and the Y axis shows the associated kinetic energies.

The risk model will attempt to control the kinetic energy of the drone to limit injuries. It will be using figure 8 as limit guide to do so. Based on the drone model the DLS uses, the Aztec Hummingbird, which has a maximum velocity of 15 m/s, with a rate of change of 1 m/s, it takes only 15 seconds to reach the 250 Joule kinetic energy that poses a potential fatal accident if an audience member is hit on the head by a falling drone.

IIX. BUSINESS CASE

As this project's end goal is to create a functional Drone Light Show within the entertainment industry, the business case is one of the most pivotal components of the Drone Light Show Production System. If the DLSPS can not profit or even break even on costs, then the show would not be able to run.

The business case is divided into 3 components in order to minimize cost and boost revenue all while maintaining the integrity of the product:
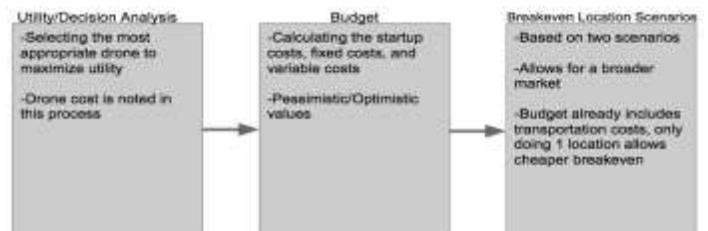
    a.   Utility/ Decision Analysis for different drone types
    b.   Budget Costs
    c.   Location Scenarios

    A.   *Utility/Decision Analysis for different drone types*
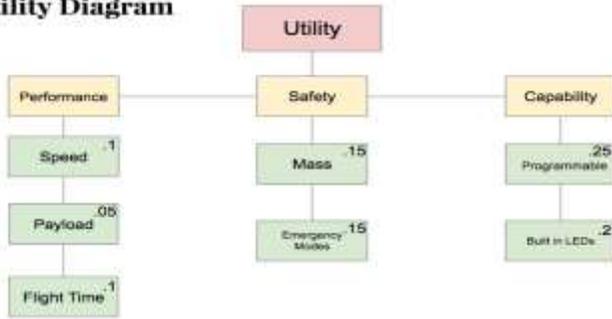
Utility Diagram

Figure 10. Utility Diagram

In order to decide which drone would be the most effective within the DLSPS system, 5 drones were compared by utility versus cost based on their performance, safety, and capability as shown in figure 10.
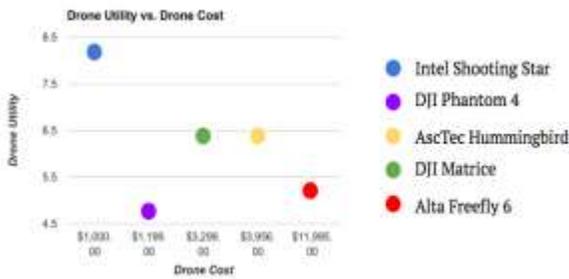

Figure 11. Utility Vs. Cost Diagram

Although the Intel Shooting Star was the most fitting drone to work with, it is not yet able to be purchased for production and may stay a prototype. As a result, the AscTec Hummingbird is the next best drone for utility while also having a low price.

B. Budget

The budget is decomposed into several sections in order to be able to calculate how to break even for the different scenarios as shown in section C. First are the fixed costs for year 1, which includes all the drone purchases, construction costs, and initial drone transportation to move the drones to the venue locations. Next are the year 1 variable costs, which allow us to run 1 show and set up for the show. After that comes the variable costs after year 1 that may incur once the show has been running for an extended period of time, including maintenance costs, repair costs, and drone replacements.

Using these sections, the budget was able to be calculated with a 10% buffer which included optimistic and pessimistic costs. (Figure 12) The budget does not include income.

Figure 12. Overall Budget for Asctec Hummingbird

This project had been divided into two scenarios: Eagle Bank Arena (Scenario A) and Mason's Center for Performing Arts (Scenario B). Eagle bank Arena is unique in that the stadium has a capacity for 10,000 people. With such a large attendance, tickets can be cheaper which could attract more viewers. For the Center for Performing Arts (CPA), the center is smaller with an attendance of 1935, however boasts the ability to be able to have an orchestra playing with music to synchronize to the drones.

Figure 13.

For Scenario A, with an initial cost of $40,000 to gain access to the stadium, and an additional 4$ per ticket including $3,000 for insurance, the total cost would be $83,000 assuming a full house. With our sum budget being around $890,000, that would mean a break even as shown in figure 13.
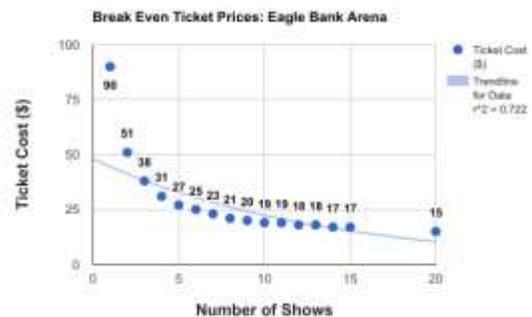

Figure 14. Break Even for Scenario A

If one light show were to be performed, a break even point for ticket price would only be $90 before profit would be made. Contrarily if a low ticket price would be more feasible, 7 shows would break even for the DLSPS for less than 25$ per ticket.

$$\left(\sum Budget\right) + ((30000 + 80000) * (Sq - 1)) - ((Sp * 10000) * Sq)$$

Equation 1

In order to break even for Eagle Bank Arena, the equation shown in equation 1 would be used. In equation 1: ∑Budget= Sum of the drone expenses, S_q=Show Quantity, and S_p=Show Ticket Price. $3,000 is inputted for the insurance costs per show, $80,000 is the cost of the venue fees, and 10,000 is the number of tickets sold.

Figure 15. Break Even for Scenario B

The CPA has a much smaller attendance capacity, and thus the cost of the tickets would have to be much more, however with an orchestra playing at each show as well the premium price comes with more value. At 5 shows, the ticket price would only have to be $125, but after 5 shows the price would have to increase to break even because of hiking insurance costs.

$$\left(\sum Budget\right) + ((Sq - 1) * ((20200 * Sq)) + 1500)) - (1935 * Sq * Sp)$$

Equation 2

The CPA costs are due to the equation shown above which calculates the break even cost dependent on how many shows are performed. In equation 2: ∑Budget= Sum of the drone expenses, S_q=Show Quantity, and S_p=Show Ticket Price.

References:

[1] Bond, P. (2013). Study: Global Entertainment Industry Poised to Top $2 Trillion in 2016. Billboard.com. Retrieved from http://www.billboard.com/biz/articles/news/global/1565728/study-global-entertainment-industry-poised-to-top-2-trillion-in

[2] American Pyrotechnics association. (2015). U.S. Fireworks Industry Revenue Figures Breakdown by Industry Segment 1998 – 2015. Retrieved from http://www.americanpyro.com/assets/docs/FactsandFigures/fireworks%20revenue%20by%20industry%20segment%201998-15.pdf.

[3] National Fire Protection Association. (2016). *Fireworks.* NFPA. Retrieved from http://www.nfpa.org/news-and-research/fire-statistics-and-reports/fire-statistics/fire-causes/fireworks

[4] Gouder, C. & Montefort, S. (2014). Potential impact of fireworks on respiratory health. Lungindia.com. retrieved from http://www.lungindia.com/article.asp?issn=0970-2113;year=2014;volume=31;issue=4;spage=375;epage=379;aulast=Gouder

[5] http://www.ll.mit.edu/mission/aviation/publications/publication-files/ms-papers/Kuchar_2005_ATM_MS-19102_WW-18698.pdf

[6] Cheung, N. (2016). Intel-Shooting Star- Drone debits first drone designed for arts, entertainment and light shows. Intel. Retrieved from https://newsroom.intel.com/newsroom/wp-content/uploads/sites/11/2017/01/Intel-Shooting-Star-Tech-Fact-Sheet.pdf

[7] Milassius, R. (2016). Drones in Manufacturing and Supply Chains. Intouch manufacturing Services. Retrieved from https://www.intouch-quality.com/blog/drones-in-manufacturing