Autonomous Quadcopter Research, Systems, and Global Impacts

by

Ryan Covey Skeele

A THESIS

submitted to

Oregon State University

in partial fulfillment of the requirements
for the degree of

Bachelor of Arts in International Studies in Mechanical Engineering

Presented on March 17, 2014
Commencement March 2014

AN ABSTRACT OF THE THESIS OF

Ryan Covey Skeele for the degree of Bachelor of Arts in International Studies in Mechanical Engineering presented on [March 17, 2014].
Title: Autonomous Quadcopter Research, Systems, and Global Impacts

Abstract approved: ______________________________

Geoffry A. Hollinger

Recently, interest in autonomous quadcopters for a variety of international markets has dramatically increased. The main sectors can be narrowed to military, business, and humanitarian services. Remote control quadcopters have already begun making appearances during disaster relief, and future systems have the potential to take a more interactive role in delivering needed supplies. Major companies have announced plans to utilize autonomous quadcopters for delivery services. Military and law enforcement agencies are using the technology for tactical surveillance and they are pursuing systems for searching hostile indoor environments. Such tasks require systems capable of precision navigation, which are currently being developed by the research community.

The demand developing in these areas has created a lot of interest in autonomous quadcopters. However, no thorough overview of the systems and their impact has been presented. This paper will examine the developing technologies in autonomy, specifically for quadcopters. An overview of autonomous vehicles and quadcopter systems will be presented. Corresponding research is focusing on the problems of perception, navigation, coordination, mapping, and flight control. This paper will first discuss the state-of-the-art research and development in these fields before analyzing the market demand, developed systems, and the implications of market realization. Through this analysis it will be established that the development of autonomous quadcopters will lead to transformative changes across a wide range of industries.

Bachelor of Arts in International Studies in Mechanical Engineering thesis of Ryan Skeele presented on March 17, 2014.

Approved:

Geoffry A. Hollinger (Department of MIME)

Rob Stone (Head of MIME)

Nick Fleury, Head Advisor (International Degree Program)

I understand that my thesis will become part of the collection of Oregon State University. My signature below authorizes release of my thesis to any reader upon request. I also affirm that the work represented in this thesis is my own work.

Ryan Covey Skeele (Author)

Acknowledgements

I would like to thank all the people that have supported me and my pursuit of robotics. Without your continued encouragement I would not have made it to this point. Thank you for your love and kindness.

Contents

1 Introduction **1**

2 Background **3**

2.1 Autonomous Vehicles . . . 3

2.2 Quad Specific Systems . . . 4

3 Related Work **6**

4 Methods **6**

5 Literary Survey **7**

5.1 Perception . . . 7

5.2 Flight Control . . . 10

5.3 Navigation . . . 12

5.4 Mapping . . . 14

5.5 Coordination . . . 16

6 Analysis **18**

6.1 Military . . . 18

6.2 Business . . . 19

6.3 Humanitarian . . . 21

7 Conclusion **23**

References **25**

List of Figures

1 Diagram of a basic quadcopter. [1] 2

2 Descriptive diagram of yaw, pitch, roll on a quadcopter. [2] 5

3 Ascending Technologies Pelican. [3] 6

4 Illustration of optical flow. [4] 8

5 Hough transform filtering lines and showing vanishing point with monocular vision. [5] 9

6 Diagram of two cameras (stereo vision) locating a common point, and calculating its position in 3D space. [6] 10

7 Descriptive plot of an MPC controller. [7] 12

8 Point cloud map of indoor environment with color corresponding to height. [8] 14

9 Illustration of an octree. [9] 15

10 Large octomap of building with color corresponding to height. [10] 16

11 Aerovironment's military grade quadcopter. [11] 19

12 DHL test quadcopter. [12] 20

13 Aeryon Scout for structural inspection. It also has thermal imaging capabilities. [13] 22

14 Rendering of Matternet quadcopter aid delivery system. [14] 23

1 Introduction

The field of autonomous robots (more specifically, quadcopters) has dramatically grown in recent years. With the reduced cost of sensor technology and the development of efficient algorithms, these systems have become more commonplace. While fixed winged aircraft previously were targeted platforms [15], recently large efforts have gone into vertical takeoff and landing (VTOL) systems capable of precision navigation. Research demands [16] have shifted to systems capable of maneuvering tight, cluttered spaces, which quadcopters are well suited for. Fields of study have developed into navigation, perception, coordination, flight control, and mapping.

In the face of an ever changing global market, a demand for these systems has emerged. The need spans military, business, and humanitarian efforts. Opportunistic companies have begun development of autonomous quadcopters capable of everything from cinematography [17] to package delivery [18, 19]. Efforts to bridge the gap between market demand and current technology has led to the shift in research funding. Aerial vehicles have used the largest amount of Department of Defense (DoD) funds of any other unmanned systems [20]. While there have been significant development of UAVs in recent years, there has been a slow response in corresponding regulations. The ethical, phylosophical, and legislative impact of unmanned systems is beyond the scope of this paper and will not be discussed.

Autonomous quadcopters will soon reach the market in mass and there will be global impact; this paper will present the research developments and discuss real world implications. Following a technical overview of an autonomous quadcopter system and a literature survey regarding current research, the potential impact on developing markets will be examined. It will then be established that the development of autonomous quadcopters will fundamentally lead to transformative changes across a wide range of industries.

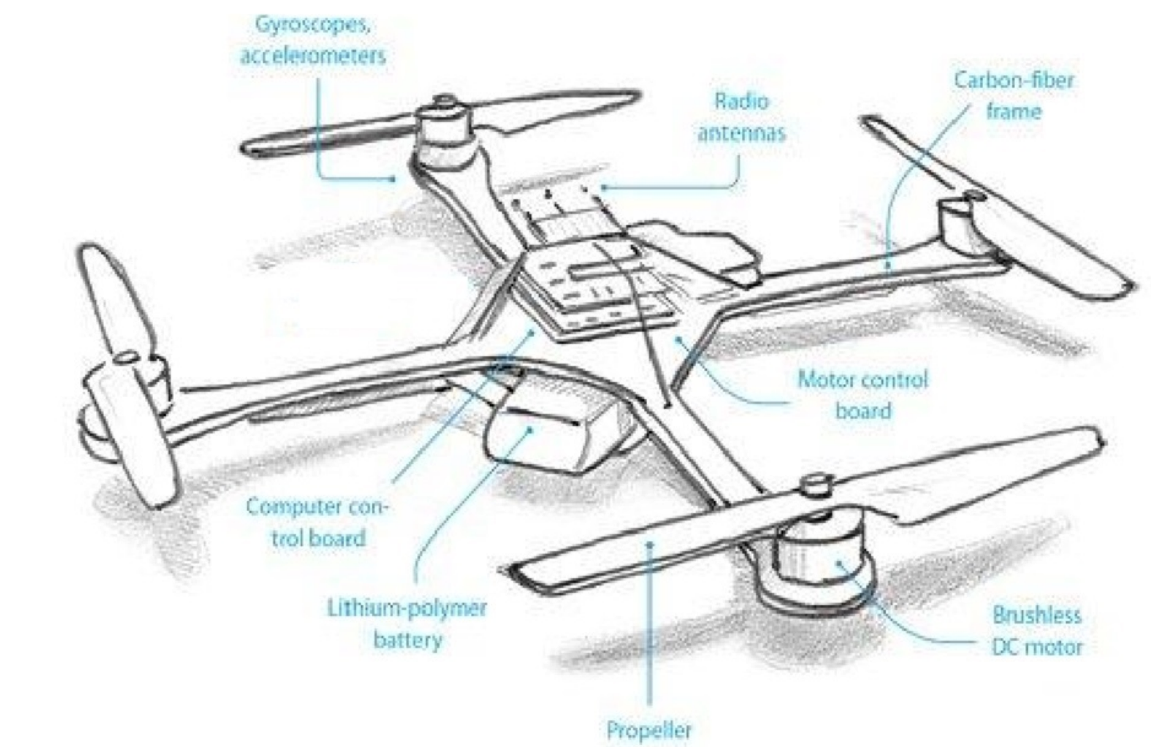

Figure 1: Diagram of a basic quadcopter. [1]

2 Background

Autonomous quadcopters are normally highly specialized and quite complex. This makes it difficult to understand how they function and what the limitations are. In order to develop an understanding of research efforts, an overview of autonomous vehicles will be established.

2.1 Autonomous Vehicles

In order for a vehicle to be autonomous or even semi-autonomous it must take inputs from its environment and make high level decisions without the involvement of a user. This has taken the form of many things in the robotics field, however one of the most important is autonomous vehicles. Autonomous (unmanned) vehicles are defined in the 2007 Department of Defense Unmanned Systems Roadmap as follows:

> "Unmanned Vehicle. A powered vehicle that does not carry a human operator, can be operated autonomously or remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload. Ballistic or semi-ballistic vehicles, cruise missiles, artillery projectiles, torpedoes, mines, satellites, and unattended sensors (with no form of propulsion) are not considered unmanned vehicles. Unmanned vehicles are the primary component of unmanned systems." [21]

During WW1 the first UAVs were being developed [22], since then, autonomous vehicles have been sent to the moon, and even to mars. Recent efforts have brought autonomous systems in reach for cheaper vehicles. In 2004, the Defense Advance Research Projects Agency (DARPA) hosted the Grand Challenge, a race for autonomous cars. This challenge was won in 2005. The 2012 DARPA Robotics Challenge is to develop autonomous humanoid robots; efforts were demonstrated in the 2013 trials with some success. All of these systems shared similar technology for autonomy. Each robot required a sensor package capable of perceiving its environment, electronics suited to process the huge amounts of data, software algorithms able to make high level decisions from the data, and hardware equipped to respond to those decisions to react to the environment. These are the requirements of a robotics system capable of autonomy.

2.2 Quad Specific Systems

A quadcopter is defined by its use of four propellers to fly through the air. All four propellers on a quadcopter work to provide thrust in the same direction. A quadcopter has four controllable degrees of freedom (DOF) yaw (1), pitch (2), roll (3), and altitude (4). In order to control these DOF the propellers are mounted in an alternating direction of rotation (see fig). When spinning the propellers a moment occurs at the center of the quadcopter. By spinning the propellers in alternating directions the moment can be cancelled out, or if spun at different angular velocities a moment occurs at the center, allowing for yaw control. To control roll or pitch, opposite propeller speeds can be increased and decreased respectively. When there is an angle relative to the ground in roll or pitch the thrust vector is no longer vertical, causing forward movement of the quadcopter. A quadcopter is an underactuated system, meaning there are more DOF than there are inputs. There are six DOF (three translational and three rotational), however only the angular velocity of each propeller is controllable. This makes the ability to control all six DOF of the quadcopter a sophisticated problem. The dynamics and kinematics are widely published topics and will not be discussed here. In order to control the quadcopter a flight controller will take sensor information regarding the quadcopters current position in space and output controls to the four motors to send the quadcopter to the desired position in space. A typical sensor package will include an inertial measurement unit (IMU), which includes an accelerometer and gyroscope for stabilization. In addition, many systems use a magnetometer for orientation (yaw) control.

In order to keep the quadcopter in the air the flight control (FC) has to update very fast, somewhere between 200 Hz and 1 kHz is typical. The flight control sends commands to the propulsion system based on the desired response of the controller. A typical propulsion

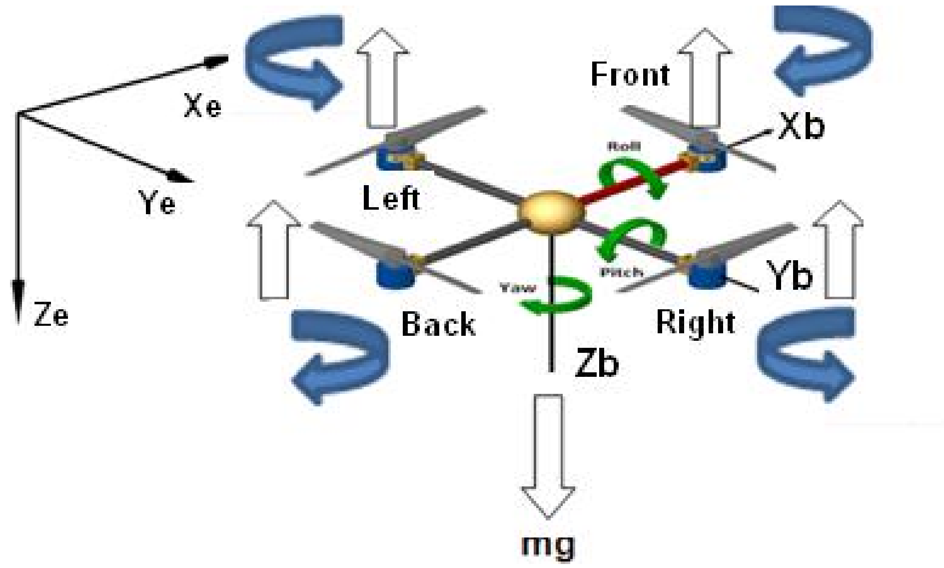

Figure 2: Descriptive diagram of yaw, pitch, roll on a quadcopter. [2]

system consists of electronic speed controllers (ESC) that take input from the FC, brushless direct current (BLDC) motors, and fixed pitch propellers. ESC current draw, motor torque, and propeller size requirements vary with application, allowing for no standard combination. This makes nearly each research platform completely unique in these areas. However one thing that all quadcopters have in common is the high power demand of four motors.

The development of cheap lithium polymer batteries (LiPo) was one of the key technological advancements that led to the development of these vehicles. LiPo batteries are extremely power dense and have high discharge rates, making them ideal for energy storage on quadcopters. LiPo batteries allow for long enough flight times to make quadcopters useful in real applications. Even with LiPo technology, battery life is a major restriction. This makes weight a major priority in design, and adds to the difficulty of complete autonomy. Powerful computer systems capable of processing the sensor data required for autonomy are heavy and demand a lot of power. This makes on-board perception extremely difficult to implement. Specialized, energy efficient platforms have been developed but off-board localization in instrumented environments are favored in research labs.

Figure 3: Ascending Technologies Pelican. [3]

3 Related Work

Many autonomous aerial systems have been developed for research with a wide range of capabilities and performance. Some have focused on acrobatics and aggressive maneuvering [23], while others have complex sensor packages for precision mapping [24]. Some researches have developed techniques for using minimal sensors [25], and others developed systems for multi-vehicle coordination [26]. While some of these systems use motion capture devices [27] and/or GPS localization, others carry all sensors used for localization, mapping, control and navigation [24].

4 Methods

This paper was written in conjunction with the development of an autonomous quadcopter. All sources were gathered during the course of the project. The research presented was determined to be the most relevant in the field at the time for direct implementation on a quadcopter. This paper aims to inform the reader of the current state of research and development for autonomous quadcopter systems. This will be done by acquanting the reader with the most prevelant solutions of each subsystem. Prevelance of solutions was determined by analyzing research trends. Additionally, the systems presented were selected for their congruence with the autonomous quadcopter under development. This paper is a not an exhaustive compilation of research in autonomous quadcopters. While there are existing compilations of research for individual subsystems, no overarching compilation of autonomous quadcopters exists. Filling this void is the intent of this paper.

5 Literary Survey

A survey of subsystems used and developed for these research platforms will give insight into technology soon to be seen in the mass market. The following sections have been divided into solutions in perception, flight control, navigation, coordination, and mapping.

5.1 Perception

5.1.1 Motion Capture

Some researchers, e.g. Vijay Kumar of the University of Pennsylvania GRASP Laboratory, have illustrated some amazing feats using quadcopters. Specifically, their demonstration of aggressive and complicated maneuvers [23] and multi-robot coordination. In order to perform these maneuvers a motion capture system was used. The motion capture system uses infrared cameras to track infrared reflectors on the quadcopters. The final result is an accurate and fast localization of the quadcopter in 3D space (225 Hz). This information gets passed to a powerful off-board computer for processing. Then commands are sent to the flight control onboard the quadcopters.

5.1.2 Optical Flow

Optical flow on a quadcopter operates the same way as your computer mouse. Key points are located with a camera for a specific frame. Accounting for rotations, those points are

Figure 4: Illustration of optical flow. [4]

again located on the next frame and the difference between the two determines the speed and direction of travel. Flow estimation can function with cheap sensors and works reliably even under indoor conditions without strong infrared lighting [28]. Researchers from the Swiss Federal Institute of Technology have developed a cheap open source flow camera (PX4FLOW) designed to provide local x/y coordinates to a flight controller in exterior and indoor environments at 250 Hz [28]. This system offers an extremely light weight low power localization solution for autonomous systems.

5.1.3 Computer Vision

Monocular Research from universities like Cornell [25] have developed vision algorithms that can use a single camera to navigate an indoor environment. Using perspective cues from a single camera mounted on a Parrot AR Drone the navigation is independent of building a 3D model. The vision algorithm identifies lines to determine the vanishing point of the 2D image [25], allowing for the quadcopter to navigate hallways and even stairs. A major development in monocular research is the OpenCV library. This is a open source library with several hundred computer vision algorithms [29]. A standardized toolbox of efficient computer vision algorithms is a huge development for autonomous systems, allowing for fast

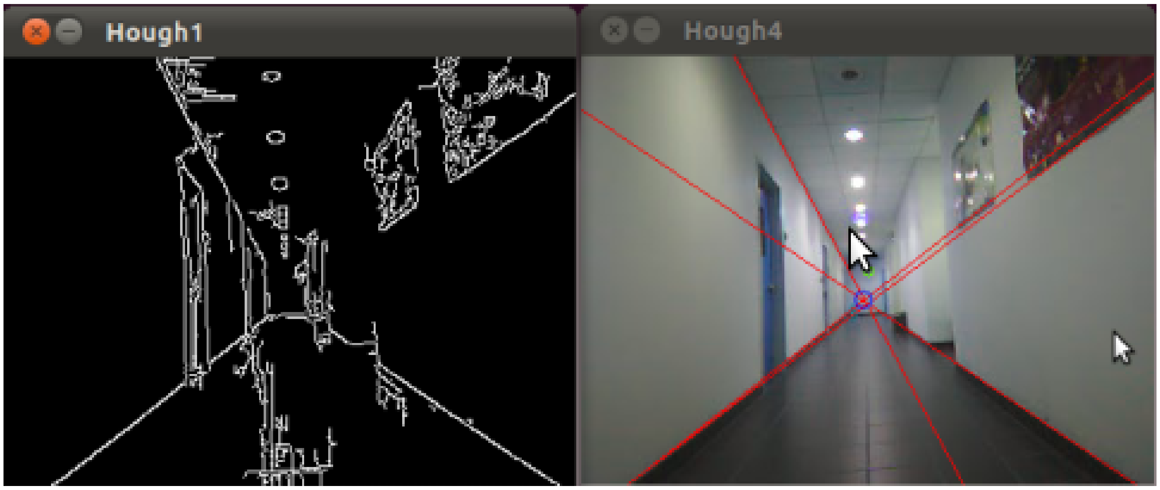

Figure 5: Hough transform filtering lines and showing vanishing point with monocular vision. [5]

implementation of previous research. Currently more than 45 thousand users are contributing to its development and the library has been downloaded over 7 million times [29].

Stereo Vision Stereo vision uses two cameras a known distance apart to compare each frame and through triangulation is able to identify objects in 3D. The horizontal distance between the same object in the composite image determines the distance the object is away from the cameras. A limitation of this technology is that it is very dependent on textured environments; regions of homogeneity will not give detectable distances [30].

5.1.4 RGB-D

The development of the Kinect introduced a cheap sensor package that could build a 3D map of an environment. The Kinect uses an infrared projector and an infrared camera for depth while another camera captures RGB (red, green, blue) video, to produce a 3D map of the environment at 30Hz [31]. The combination of RGB video and depth data is called RGB-D. An algorithm developed by researchers of the University of Freiburg Germany called rgbdslam is able to accurately (within 10 cm and 4 degrees) [32], localize and map an environment. RGB-D sensors have been used more and more frequently in indoor systems.

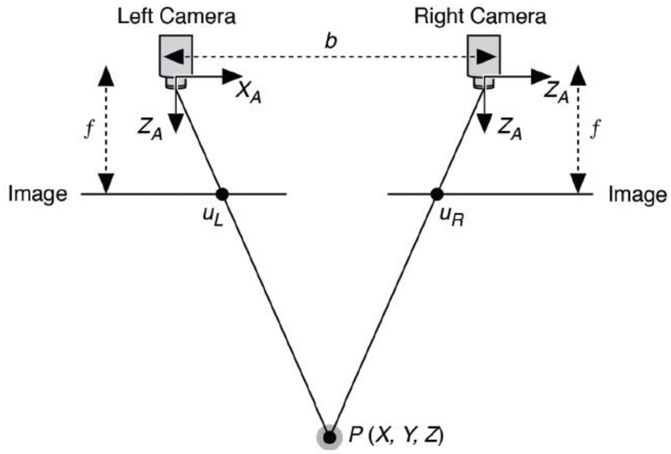

Figure 6: Diagram of two cameras (stereo vision) locating a common point, and calculating its position in 3D space. [6]

5.1.5 Lidar

Lidar sensors are currently an order of magnitude more expensive than the RGB-D sensor package. However, lidar is more accurate, and has a faster update rate than RGB-D sensors. Lidar operates by rotating an angled mirror with a laser directed at it. As the mirror rotates the light reflects back from objects to sensors. The time differential accounts for the distance to the object. Lidar is currently used in many industrial application and performs better in outdoor environments than RGB-D systems. The Hokuyo UTM-30 lidar sensor, commonly used in quadcopter autonomy, can scan up to 30 meters in 270 degrees. This platform has been demonstrated to perform autonomous indoor navigation and mapping with success [24]. The Hokuyo lidar is capable of +5 cm accuracy, ideal for precision mapping requirements.

5.2 Flight Control

5.2.1 PID

A variety of control techniques have been developed for use in quadcopters. Proportional integral derivative (PID) control is the most commonly used controller for quadcopter systems. The PID control uses tuned constants and multiplies them with the measured error (proportional), the change in error (derivative), and the cumulitive error of the system (integral). Tuning these constants gives an output from the flight controller that will ensure the quadcopter will not become unstable.

5.2.2 LQR

Linear Quadratic controllers can be used in favor of PID controllers because LQR controllers are known to be robust and produce very low steady state error [33], however PID controllers generally have a faster response. While a quadcopter is a nonlinear system, a Linear Quadratic Regulator (LQR) controller can still be applied. This controller functions by linearizing the dynamics of the quadcopter and then minimizing a cost function. The cost function is the sum of error from the measured and desired values. Weighting different measurements increases their importance allowing for an optimized controller.

5.2.3 MPC

Model Predictive Control (MPC) uses accurate understanding of the system's dynamics to optimize the output. The controller takes into account future events (i.e. prediction horizon) through prediction using a model of the system's dynamics. It follows the same control theory as LQR, however it optimizes the cost function over the entire receding horizon [34]. MPC is dependent on a comprehensive understanding of the vehicle, requiring system identification before implementation. System identification is a mathematical model representing the dynamics of a system; think input vs output.

5.2.4 Failsafe

Researchers from the Institute for Dynamic Systems and Control in Zurich, Switzerland, have developed a failsafe algorithm to allow for the loss of a propeller/motor [35]. A broken propeller induces the quadcopter into a spin, by correcting the controller to accept the spin the quadcopter is able to maintain control during an emergency landing. The algorithm

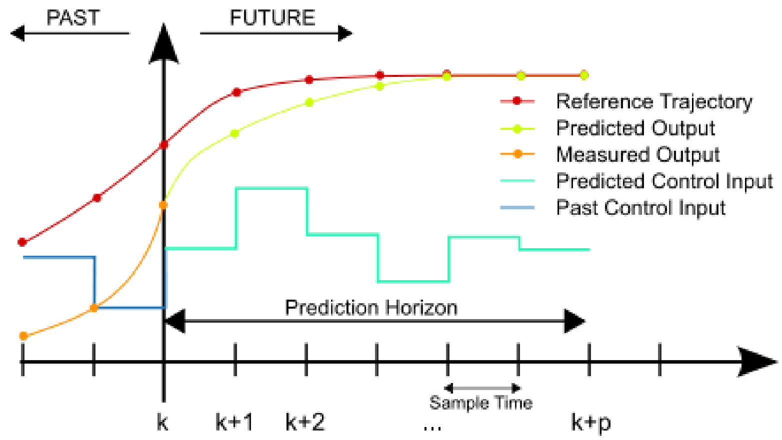

Figure 7: Descriptive plot of an MPC controller. [7]

detects the failure automatically and is able to gracefully recover its control. This algorithm is a critical research development for the necessity of safety and robustness to use autonomous quadcopter systems in industry.

5.3 Navigation

5.3.1 Path Planning

Waypoint With quadcopters using global positioning systems (GPS), a method of autonomous control using waypoints has been developed. Waypoint navigation functions by setting key points of interest to the lower level controller. The path planned between the points is a straight line but a PID controller usually is implemented to handle takeoff and approach to each waypoint. This form of path planning depends on a human user to pick a path known to be clear of obstacles and then the quadcopter navigates indepently along the route chosen. This is the simplest form of path planning and is well established on current systems.

Potential Field This form of path planning gives obstacles repulsive potential and the target attractive potential. As the robot gets nearer an object the stronger the desire becomes for the robot to move away. Similarly the closer the robot gets to its desired location the stronger the attraction becomes. This is a fairly common method of path planning because it is very simple. A limitation to this technique is that the robot can get stuck in local minimums, where the repulsion is stronger than the attraction and the robot can't move closer. A more effective implementation of this planner incorporates the orientation of the robot, allowing for the robot to travel in parallel with objects at a close proximity without repulsive forces. Additional filtering of distant objects is sometimes added as well. This is called the extended potential field method.

Cell Decomposition Just like previously discussed map storage techniques, cell decomposition divides the map into squares of a set resolution and stores them as either occupied or unoccupied. Then a connectivity map is generated. A connectivity map is a numerical representation of how every cell is connected to each other. The map is used to search for the path along cells that leads from the robot's initial position to its goal. The searching algorithms will not be explained in this paper but the techniques include A*, breadth first search, and depth first search.

5.3.2 Trajectory Optimization

Trajectory optimization if very similar to path planning, however it focuses on optimizing the path from current state to final state, usually in respect to time or energy. In other words; while path planning focuses on generating a solution, trajectory optimization focuses on finding the best solution. Researchers have been able to optimize trajectories of complex maneuvers to gain repeatability and precision [23][36]. In their research the trajectory is optimized to minimize the quadcopters snap (derivatives of position with respect to time, in order; velocity, acceleration, jerk, snap). This generated smooth trajectories capable of the impressive maneuvers through moving objects and tight spaces. Optimizations require repeated experimentation and parameter tuning in order to work, making on the fly optimization difficult.

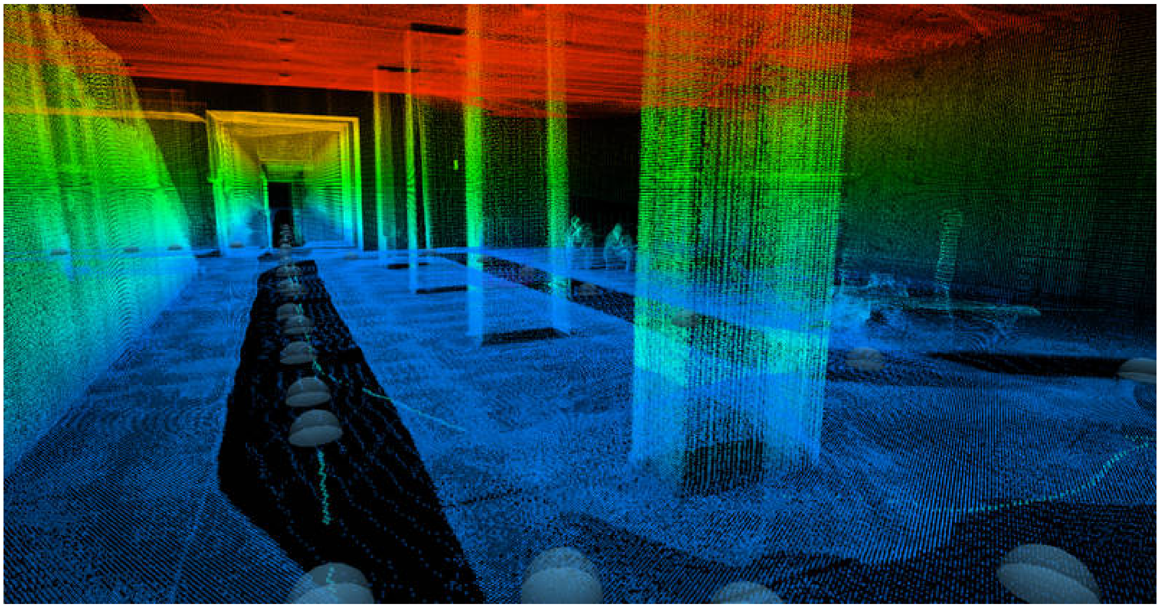

Figure 8: Point cloud map of indoor environment with color corresponding to height. [8]

5.4 Mapping

5.4.1 Point Cloud

Point clouds are a collection of data points that can be mapped to 3D space. Each point stores an associated values for localization on a 3D coordinate system, usually cartesian x, y, and z. Additional information can also be stored for each point, including color, surface orientation, and reflection intensity. Point clouds are generally used for visual inspection by the user, for anything else they are usually processed into meshes (edges and surfaces generated between points).

5.4.2 Octomap

Updating and storing a map can be a computationally expensive task, and a lot of research has focused on making this efficient. Several different approaches have been explored, including: point clouds, elevation maps, multi-level surface map, and voxel (combination of volume and pixel) representation [37]. A voxel map is a divided area of squares, that uses a point cloud to update stored values of the squares to reflect if it is 'occupied', unoccupied or

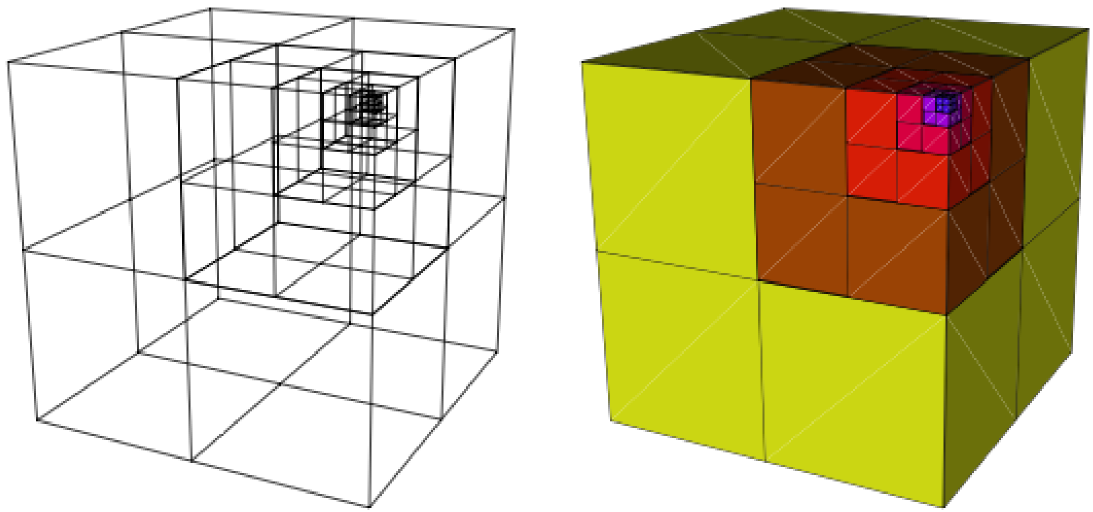

Figure 9: Illustration of an octree. [9]

even unexplored. As the voxel map is updated each frame, that point cloud frame becomes unnecessary and is deleted. Point clouds store large amounts of data comparatively and are therefore quite inefficient. Elevation and multi-level maps do not represent unmapped areas. Voxel maps are able to efficiently store large maps while representing occupied, unoccupied and unexplored areas. Octomap, a voxel map approach, uses an octree (tree based hierarchical data structure) to store data efficiently at cascading resolutions [37]. The development of this research has led to accurate modeled environments using minimum memory.

5.4.3 Projected 2D, 2.5D Maps

When building a map it is possible and often times practical to map the environment in 2D. A 2D map can be made using only a slice of the 3D map or actually projecting down multiple layers to incorporate all obstacles in the map. This can be used to simplify the navigation algorithm as all obstacles are projected down into 2D. Sometimes however, navigating extremely cluttered indoor environments can demand the need to pass above obstacles. A 2.5D map stores maximum height values for each obstacle, allowing for 3D navigation and obstacle avoidance without generating large 3D maps. However, navigation under obstacles

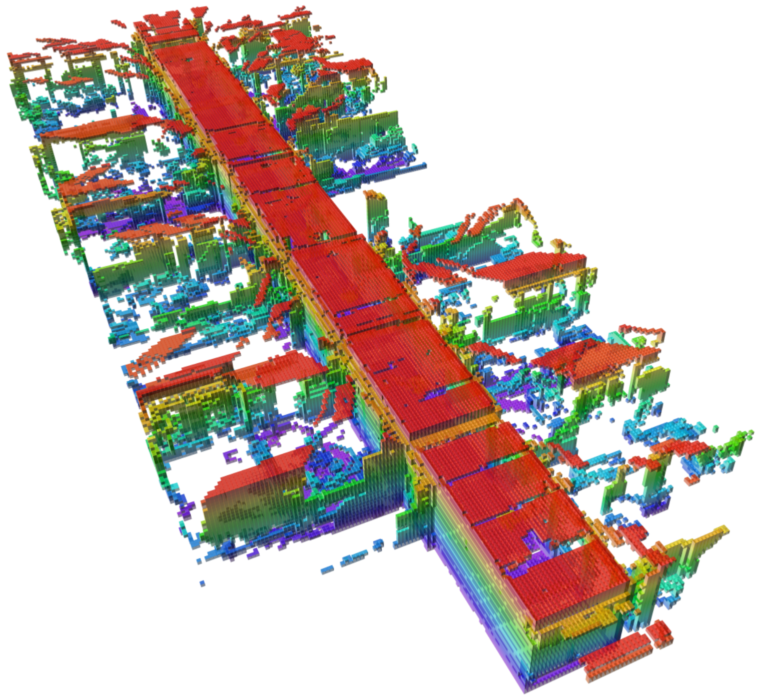

Figure 10: Large octomap of building with color corresponding to height. [10]

becomes impossible because only the maximum height is stored in each cell

5.5 Coordination

5.5.1 Cooperative Mapping

Frontier-Based Exploration Without an intelligent coordination algorithm, robots in a multi-robot system may hinder, rather than help, each other. Researchers have developed an algorithm called frontier based exploration which has performed with promising results in map exploration. The algorithm can perform multi agent exploration through building 2D map of the environment. At the boundaries between explored and unexplored areas on the map the algorithm marks frontiers. The robot is sent to the nearest frontier, therefore constantly searching the unexplored areas. [38]

Sensor-Based Random Graph A different coordinated map exploration algorithm called sensor-based random graph (SRG) develops a local safe region (LSR) and local reachable region (LRR). A node is set where it can be reached from other nodes while staying within the LSR and nodes are generated as each robot explores. Arcs between nodes allow for quick simple path planning through the known safe areas. At the boundaries of the LRRs the unexplored area determines the weighting of each node. Robots travel to the highest weightings, continuing the process. [39]

5.5.2 Motion Coordination

Researchers have developed coordination algorithms capable of performing amazing feats, such as building structures [40], playing songs [41] and even dancing to music [42]. Other efforts have flown in large formations, including path planning through obstacles [27]. Complex dynamical interactions such as passing and balancing a stick between two quadcopters was also accomplished by researchers from Swiss Federal Institute of Technology in Zurich [26]. All these have used off board processing and a motion capture system.

5.5.3 Communication

Decision making in regards to communication is often vital to the success of robot coordination. Algorithms have been developed to account for connectivity failures when exploring an environment [43][39]. Other research has developed methods of maximizing communication networks of autonomous systems [44]. Most research is based on assured connectivity for efficient coordination. coordinating with intermittent connectivity has yet to be researched in depth.

6 Analysis

In the following sections the need for autonomous quadcopters will be established in the military, business, and humanitarian markets. Current efforts to meet the need will be presented and discussed. Supporting evidence will show the future impact of the technology.

> "The unmanned systems community must wean itself from the telecommunication bandwidth. Autonomy will certainly be required in order to accomplish this goal." [21]

6.1 Military

There are over 3,000 deaths from improvised explosive devices (IED) in the Iraq/Afghanistan wars that have occurred since 2001 [45]. Reconnaissance vehicles are able to provide safe inspection of possible explosives. Quadcopter systems can even fly fast enough to be used ahead of a moving convoy, saving lives. UAVs have been used in military actions since WWII [22], and in the Iraq/Afghanistan war more than 25,000 robots were deployed [20]. Of these, half were UAVs mainly used for tactical surveillance. The majority of UAVs deployed in the field were planes, which are limited to continued motion. VTOL systems are capable of fixed angled viewing allowing for significantly improved tactical awareness.

In relation, the company AeroVironment has begun selling Shrike VTOL a semi autonomous quadcopter that streams video to ground forces for reconnaissance, IED mapping, payload delivery, and hover and stare [46]. Given trends in research and development, it will be likely to see tactical quadcopter units autonomously providing surveillance and even clearing a building of hostiles in the near future. To reinforce this notion, the 2013 IARC competition involved an autonomous quadcopter navigating a building through a window to retrieve and replace a flash drive while avoiding cameras. A team from Tsinghua University completed the mission using the AscTec Pelican and Hokuyo lidar system [47]. Government funding

Figure 11: Aerovironment's military grade quadcopter. [11]

seeks autonomous quadcopters that can collaborate when navigating an indoor environment. The objective is to save soldiers' lives by using autonomous quadcopters to return a map of potentially hostile environments. Law enforcement also desire autonomous indoor navigators to help with hostage situations, aerial tracking during pursuit, and border patrol.

6.2 Business

6.2.1 Delivery

While unmanned aerial systems have already been implemented in many military applications, a relatively new and growing commercial demand has developed. New startups all over have begun establishing themselves in this market. However, these small businesses are not the only interested parties. Recently, large companies have made known their intents to incorporate unmanned quadcopters in their business. These large companies are going to be the driving force that make these autonomous systems commonplace. The internet marketplace Amazon, wants to add thirty minute aerial delivery by autonomous drones to its list of shipping options. While the company hasn't released any set date, it has published a promotional video of the service [19]. Large delivery companies such as DHL are also interested in such solutions. DHL performed its first official test sending a package filled

Figure 12: DHL test quadcopter. [12]

with medicine from a nearby pharmacy via remote controlled (RC) quadcopter to the DHL headquarters [18]. The express delivery industry generated sales of $175 billion in 2008 [48], that is a lot of parcels. FedEx alone ships more than 10 million packages everyday [49]. The impact of implementing autonomous delivery systems is on a global scale.

It is however important to note that this is not limited to parcel services; Dominoes has shown interest in autonomous delivery of its pizzas. More than 10 million miles are travelled for delivering Dominos pizza each week [50]. Dominoes performed pizza delivery tests this summer in the UK. These tests were not performed autonomously but with remote control [51]. These companies are right on the forefront of a logistics revolution, the introduction of autonomous vehicles in this industry will be revolutionary.

6.2.2 Cinematography

Professionals in the movie industry are also no longer able to ignore the benefits of quadcopters. Several scenes in recent movies including, Oscar nominated best picture of the year The Wolf of Wall Street, were shot from quadcopters [17]. Aerial photography and cinematography has developed as a huge market for quadcopters. While most demand is currently for RC systems, precision and repeatability of autonomous systems will lead to the eventual replacement of RC operators in this field. Sports filming has been an early adopter of the technology. Sports like surfing offer a huge demand because without aerial photography it is difficult to film the surfers in action. Hobbyists have begun presenting compilations of video coverage they have done, getting films that were only available before by renting helicopters, with a lot of positive feedback [52]. Additional sports, like snowboarding and mountain biking, have the same need for aerial coverage. These users are not necessarily RC experts and require systems capable of high level decision making from user input. Autonomous systems will be implemented in athletic competitions in the future with a dramatic affect on visualization capabilities.

6.2.3 Structural Inspection

There is a huge demand for autonomous systems to perform inspection tasks. Several businesses have established themselves for this service, including German company AirRotorMedia. They offer services such as industrial flare stack inspections that normally would require the plant to shut down, costing up to millions a day. HD images, video and thermal images taken from the unmanned system provide engineers enough data to avoid costly shut downs. Similarly, natural gas pipelines are quite expensive to maintain; it costs roughly $3,000 an hour for a helicopter inspection [53]. They run for huge stretches and need constant inspection. Companies like BP are experimenting with using quadcopters, designed by Aeryon Labs, to inspect the pipeline instead of expensive pilots. With 300,000 miles of pipeline just in the United States, the potential market for autonomous quadcopters is substantial.

6.3 Humanitarian

In the last few years natural disasters show the real need for autonomous vehicles in disaster relief. For example, after Fukushima there has been a worldwide effort for autonomous systems that can navigate an environment with rough terrain and tight spaces [54]. Ad-

Figure 13: Aeryon Scout for structural inspection. It also has thermal imaging capabilities. [13]

ditionally, after Haiti suffered an earthquake aerial vehicles were used to compose hazard maps, and search for signs of life [55, 56]. In the future some companies hope to be able to autonomously deliver relief packages to these disaster ridden areas. Among these visionaries, a company called Matternet looks to develop a network of autonomous quadcopters and landing stations that could function as a shuttle system for small (2kgs) packages including medicine, blood tests, or clean water as an alternative infrastructure. “Currently 1 billion people do not have access to all season roads” [57]. Matternet recently performed their initial disaster relief tests in a camp in Haiti. If 3rd world, developing countries could leapfrog transportation forward in the same way as with cell phones then the humanitarian impact would be huge. HIV/AIDS testing would become easier, vaccinations would be delivered quicker, and disaster relief could be feasible.

Some people are trying to maximize the amount of physical aid relief that can be flown in. A gas powered quadcopter is being developed by students from San Jose State University. The vehicle, called HLQ (H-U-L-K) is designed for delivering disaster relief packages with a 50 lb payload capacity [58]). Other humanitarian efforts are putting efforts into documenting

Figure 14: Rendering of Matternet quadcopter aid delivery system. [14]

disaster areas and the relief workers. Social Drones used quadcopters to document floods and landslides from heavy rains in Uttarakhand, India [59].

While disaster relief packages are wonderful, sometimes more immediate help is needed. The Pars Aerial Rescue bot is a lifeguard quadcopter that would aid in water related emergencies [60]. The quadcopter carries and deploys rescue buoys to people in danger of drowning. Possible applications include extreme weather conditions, boat wrecks, and tsunami/flash flood situations. Every year almost 5,000 people die from drowning in the US alone. Safety vehicles such as these, that can deploy immediately to your rescue, are likely to become a standard in dangerous water areas.

7 Conclusion

This paper examined the developing technologies in autonomy, specifically for quadcopters. An overview of autonomous vehicles and quadcopter specific systems was presented. Relevant research in all fields corresponding to quadcopter autonomy were surveyed. Finally, an analysis of current developing businesses and markets were explored with discussion regarding the global impact of market realization of autonomous quadcopters. Autonomous systems just now coming into the market are GPS dependent, making them impractical for indoor or obstacle dense environments. With the implementation of the discussed research in perception, mapping, navigation and control, the autonomous systems market will expand on a global scale.

References

[1] K. Phan-Dang. (2013, August) Autopilot quadcopter-toradex. [Online]. Available: http://www.challenge.toradex.com/projects/10078-autopilot-quadcopter

[2] A. Alshbatat, A. Khamaisa, and M. Khreisat, "Adaptive control system for an autonomous quadrotor unmanned aerial vehicle," April 2013.

[3] (2014, March) Ascending technologies pelican. [Online]. Available: http://www.asctec.de/uav-applications/research/products/asctec-pelican/

[4] M. P. I. of Neurobiology. Research news. [Online]. Available: http://www.mpg.de/618968/pressRelease20100915

[5] (2012, June) Vanishing point detection for corridors and hallways. [Online]. Available: http://dasl.mem.drexel.edu/wiki/index.php/Vanishing_point_detection_for_corridors_and_hallways

[6] (2013, August) 3d imaging with ni labview. [Online]. Available: http://www.ni.com/white-paper/14103/en/

[7] (2009, October) Mpc scheme basic. [Online]. Available: http://en.wikipedia.org/wiki/File:MPC_scheme_basic.svg

[8] (2012, September) Improved positioning indoors. [Online]. Available: https://www.tum.de/en/about-tum/news/press-releases/short/article/30040/

[9] (2014, March) Douar. [Online]. Available: http://www.cedricthieulot.net/douar.html

[10] (2014, March) Octomap. [Online]. Available: http://octomap.github.io/

[11] (2014, March) Aerovironment. [Online]. Available: http://www.avinc.com/av_uas_flash/UAS1/config.xml?sid=48376

[12] (2014, January) Package copter microdrones dhl. [Online]. Available: http://commons.wikimedia.org/wiki/File:Package_copter_microdrones_dhl.jpg

[13] (2012, August) Aeryon scout gets advanced gis solution. [Online]. Available: http://www.uasvision.com/2012/08/31/aeryon-scout-gets-advanced-gis-solution/

[14] E. Macguire, "Road to nowhere: Could drones be the highways of the future?" June 2013.

[15] J. Drezner and R. Leonard, "Global hawk and darkstar," Tech. Rep., 2007. [Online]. Available: http://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR1475.pdf

[16] (2013) International aerial robotics competition. [Online]. Available: http://www.aerialroboticscompetition.org/past_missions/mission6.php

[17] (2014, March) Projects. [Online]. Available: http://www.freeflycinema.com/freeflyProjects.html

[18] (2014, March) Tv footage: Dhl parcel-copter approaching. [Online]. Available: http://www.dpdhl.com/en/media_relations/media_library/tv-footage/tv_footage_dhl_paketkopter_aerial_drone.html

[19] (2014, March) Amazon air. [Online]. Available: http://www.amazon.com/b?ref_=tsm_1_yt_s_amzn_mx3eqp&node=8037720011

[20] T. Collaborative, "From internet to robotics," 2009.

[21] J. Clapper, J. Young, J. Cartwright, and J. Grimes, "Unmanned systems roadmap 2007-2032," *Office of the Secretary of Defense*, p. 188, 2007.

[22] S. Bouabdallah, "Design and control of quadrotors with application to autonomous flying," *Lausanne Polytechnic University*, 2007.

[23] D. Mellinger, N. Michael, and V. Kumar, "Trajectory generation and control for precise aggressive maneuvers with quadrotors," *The International Journal of Robotics Research*, vol. 31, no. 5, pp. 664–674, 2012.

[24] A. Bachrach, S. Prentice, R. He, and N. Roy, "Range–robust autonomous navigation in gps-denied environments," *Journal of Field Robotics*, vol. 28, no. 5, pp. 644–666, 2011.

[25] C. Bills, J. Chen, and A. Saxena, "Autonomous mav flight in indoor environments using single image perspective cues," in *Robotics and automation (ICRA), 2011 IEEE international conference on*. IEEE, 2011, pp. 5776–5783.

[26] D. Brescianini, M. Hehn, and R. D'Andrea, "Quadrocopter pole acrobatics," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*. IEEE, 2013, pp. 3472–3479.

[27] A. Kushleyev, D. Mellinger, C. Powers, and V. Kumar, "Towards a swarm of agile micro quadrotors," *Autonomous Robots*, vol. 35, no. 4, pp. 287–300, 2013.

[28] D. Honegger, L. Meier, P. Tanskanen, and M. Pollefeys, "An open source and open hardware embedded metric optical flow cmos camera for indoor and outdoor applications," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*. IEEE, 2013, pp. 1736–1741.

[29] I. Coporation, "Opencv reference manual," 2001.

[30] S. Scherer, S. Singh, L. Chamberlain, and M. Elgersma, "Flying fast and low among obstacles: Methodology and experiments," *The International Journal of Robotics Research*, vol. 27, no. 5, pp. 549–574, 2008.

[31] (2014) Kinect for windows sensor components and specifications. [Online]. Available: http://msdn.microsoft.com/en-us/library/jj131033.aspx

[32] F. Endres, J. Hess, N. Engelhard, J. Sturm, D. Cremers, and W. Burgard, "An evaluation of the rgb-d slam system," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*. IEEE, 2012, pp. 1691–1696.

[33] L. M. Argentim, W. C. Rezende, P. E. Santos, and R. A. Aguiar, "Pid, lqr and lqr-pid on a quadcopter platform," in *Informatics, Electronics & Vision (ICIEV), 2013 International Conference on.* IEEE, 2013, pp. 1–6.

[34] A. Bemporad, "Introduction to mpc," 2009. [Online]. Available: http://www.seas.upenn.edu/~ese680/papers/IntroductionMPC.pdf

[35] M. Muller. (2014, March) Research. [Online]. Available: http://www.mwm.im/research/

[36] D. Mellinger and V. Kumar, "Minimum snap trajectory generation and control for quadrotors," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on.* IEEE, 2011, pp. 2520–2525.

[37] K. M. Wurm, A. Hornung, M. Bennewitz, C. Stachniss, and W. Burgard, "Octomap: A probabilistic, flexible, and compact 3d map representation for robotic systems," in *Proc. of the ICRA 2010 workshop on best practice in 3D perception and modeling for mobile manipulation*, vol. 2, 2010.

[38] B. Yamauchi, "A frontier-based approach for autonomous exploration," in *Computational Intelligence in Robotics and Automation, 1997. CIRA'97., Proceedings., 1997 IEEE International Symposium on.* IEEE, 1997, pp. 146–151.

[39] A. Franchi, L. Freda, G. Oriolo, and M. Vendittelli, "The sensor-based random graph method for cooperative robot exploration," *Mechatronics, IEEE/ASME Transactions on*, vol. 14, no. 2, pp. 163–175, 2009.

[40] F. Augugliaro, A. Mirjan, F. Gramazio, M. Kohler, and R. D'Andrea, "Building tensile structures with flying machines," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on.* IEEE, 2013, pp. 3487–3492.

[41] "Robots that fly and cooperate," February 2012. [Online]. Available: http://www.ted.com/talks/vijay_kumar_robots_that_fly_and_cooperate

[42] A. Schollig, F. Augugliaro, S. Lupashin, and R. D'Andrea, "Synchronizing the motion of a quadrocopter to music," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on.* IEEE, 2010, pp. 3355–3360.

[43] G. Hollinger and S. Singh, "Multi-robot coordination with periodic connectivity," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on.* IEEE, 2010, pp. 4457–4462.

[44] J. Fink, A. Ribeiro, and V. Kumar, "Robust control for mobility and wireless communication in cyber–physical systems with application to robot teams," *Proceedings of the IEEE*, vol. 100, no. 1, pp. 164–178, 2012.

[45] A. Roberts and L. Knight, "By the numbers: Memorial day and veterans." [Online]. Available: http://www.cnn.com/2012/05/25/politics/numbers-veterans-memorial-day/

[46] Aerovironment. (2014, March) Shrike vtol. [Online]. Available: http://www.avinc.com/uas/small_uas/shrike/

[47] Y. Li, Y. Wang, W. Lu, Y. Zhang, H. Zhou, and B. Yan, "Throne team entry for the 2013 auvsi international aerial robotics competition," August 2013. [Online]. Available: http://www.aerialroboticscompetition.org/2013SymposiumPapers/TsinghuaUniversity.pdf

[48] O. E. Forecasting, "The impact of the express delivery industry on the global economy," *Abbey House, St Aldates*, 2005.

[49] (2014, March) Fedex corporation. [Online]. Available: http://about.van.fedex.com/fedex_corporation

[50] (2013) About domino's pizza. [Online]. Available: http://www.dominosbiz.com/Biz-Public-EN/Site+Content/Secondary/About+Dominos/Fun+Facts/

[51] (2014, March) Domicopter. [Online]. Available: http://tandbiscuits.co.uk/project/domicopter/

[52] (2013, August) Aerial surf filming with the dji phantom quadcopter. [Online]. Available: http://www.surfertoday.com/surfing/9159-aerial-surf-filming-with-the-dji-phantom-quadcopter

[53] K. Krishnamurthy. (2013, June) Alaska uses dronesto inspect oil and gas pipelines at a fraction of the cost. [Online]. Available: http://www.rawstory.com/rs/2013/06/07/alaska-uses-drones-to-inspect-oil-and-gas-pipelines-at-a-fraction-of-the-cost/

[54] (2014, March) Darpa robotics challange. [Online]. Available: http://www.darpa.mil/Our_Work/TTO/Programs/DARPA_Robotics_Challenge.aspx

[55] (2010, February) Evergreen supports uav team mapping haitian relief. [Online]. Available: http://www.ainonline.com/aviation-news/aviation-international-news/2010-02-18/evergreen-supports-uav-team-mapping-haitian-relief

[56] S. M. Adams and C. J. Friedland, "A survey of unmanned aerial vehicle (uav) usage for imagery collection in disaster research and management," in *9th International Workshop on Remote Sensing for Disaster Response*, 2011.

[57] A. Raptopoulos, "No roads? there's a drone for that," June 2013.

[58] N. Conover, C. Fulmer, C. Guerrero, and G. Tellez. (2014, March) Incredible hlq. [Online]. Available: http://www.incrediblehlq.com/

[59] M. Sharma, "Indian startup uses drones to drop aid in flood-ravaged areas," 2013. [Online]. Available: http://techcrunch.com/2013/08/20/indian-startup-uses-drones-to-drop-aid-in-flood-ravaged-areas/

[60] (2014, March) Rts lab. [Online]. Available: http://rtslab.blog.com/research-projects/