DRONES FOR MEDICAL SUPPLIES

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1.1 Abstract

In this project, the use of current drone technologies is reviewed, optimized, and used to demonstrate the feasibility of medical supply delivery to remote areas of China via UAV (unmanned aerial vehicle). This project focuses on the design of a biocompatible payload and a modified drone to accomplish medical supply delivery to remote areas of China. The design of the payload and UAV arm mechanism must consider the safety of medical supplies, medical equipment and blood biocompatibility throughout the duration of the delivery. Multiple drone and payload design iterations were created to address the lack of medical attention in remote areas of China. Various designs were implemented in a prototype to create a demonstration of concept feasibility. Each design has its own parameters and components that collectively make up the payload and drone delivery system. This research paper describes, analyzes and reports experimental results of the final drone delivery and payload design, as well as the steps taken throughout the duration of the project.

1.2 Executive Summary

This study is aimed to provide medical assistance to people through the delivery of medical supplies by unmanned drones. The use of unmanned drones is reinforced through an application that has the potential to benefit people in distant areas around the world. This study hopes to expand drone technology and the application of drones. The timetable for this project was broken into two categories: Pre and post-departure. The pre-departure research for this project was conducted over six weeks at Worcester Polytechnic Institute (WPI) in the United States. The design, prototyping and testing of the project was conducted over seven weeks at the University of Beijing Chemical Technology (BUCT) where the project was completed alongside of three BUCT students. The nature of the project and how it was conducted will be explained in further detail throughout Chapter 3. Outcomes of this study include a proof of concept, the assembly of a working prototype and the evaluation of the prototype's performance. In order to make the project a success, adequate funding and resources were sought out for prototype assembly. Success of the project relied heavily on the consistent communication between the WPI students, the BUCT students, and the project sponsor and advisors. The budget for the project was developed ahead of time to ensure the production of the designs with respect to expense and resource constraints. Cost of the project was adjusted to assure the expected outcome of the project. A plan was in place if the cost became too large of a constraint so that the project would then be scaled back and adjusted to remove the least cost-effective expenditures.

2 BACKGROUND RESEARCH AND LITERATURE REVIEW

2.1 INTRODUCTION TO DRONES

Drones, in this paper, are referred to as any small unmanned aerial vehicle that is remotely or automatically controlled. There are many types of drones, but the two main designs consist of rotary-wing drones or fixed wing drones, both of which have advantages and disadvantages. Drones are very small and land and take off with very little need for clearance. Overall, current drone technologies can be understood by examining UAV classification, definition and applications in various fields. This includes the analysis of each respective operating system, various sensors and routing systems. According to the *National Defense University's Library*, a drone is any "land, sea, or air vehicle that is remotely or automatically controlled" [1]. Drones have various purposes and are currently used by the United States Government in the private sector for purposes including "investigation of agricultural crops, observation of weather, relay broadcasting and communication, investigation of the extent of damage during disasters, recognition of traffic flow, and unmanned security" [2]. There is a wide range of potential drone applications that may be optimized through a better understanding of the use of UAVs. Therefore, the engineering principles involving drones must be reviewed.

2.2 ENGINEERING PRINCIPLES PERTAINING TO DRONES

2.2.1 FORCES RELATED TO FLIGHT

To understand the motion of flight for a drone, it is important to understand what forces the drone is experiencing during flight. The same forces that allow a plane to fly are the same for any object in flight - for example a ball or Frisbee. The forces are thrust, drag, weight and lift. Thrust is a force that moves an object in the direction of motion, allowing air to be pulled in and then pushed out the opposite direction. Drag is the force that acts opposite of motion. Drag is caused by friction and difference in air pressure. Drag is what slows down the object in flight. Weight is the force caused by gravity and lift is the force that holds an object in the air. Consequently, these forces are what a pilot experiences while in flight. The same forces experienced by the pilot would be true for any load being carried by the drone [3]. This becomes important when analyzing the load that will be delivered.

The forces experienced by the pilot in flight, directly relate to the degrees of freedom (DOF) also experienced by the pilot. The trajectory of an airplane in flight has three degrees of freedom. There is also the altitude along the trajectory that has three degrees of freedom, totaling six DOF while in flight. Understanding the forces applied during flight and the degrees of freedom will help determine which maneuvers a drone can experience. As seen in Figure 1 below, the drone will experience rotation about axes x, y, and z simultaneously experiencing translation in positive x and y-axes [4, 5].

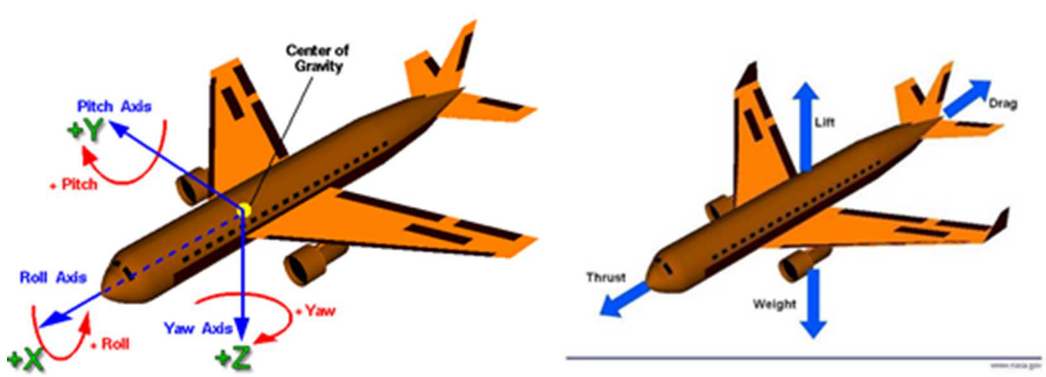

FIGURE 1: FORCES AND DOF OF AIRPLANE

During Flight, an object carried by the drone can experience three types of acceleration: linear acceleration, radial acceleration and angular acceleration. Linear acceleration reflects a change of speed in a straight line, and linear acceleration is what occurs during take-off, landing or in level flight when a throttle setting is changed. Radial acceleration is the result of a change, such as when a pilot performs a sharp turn. Angular acceleration results from a simultaneous change in both speed and direction, which happens in spins and climbing turns [6].

In addition to understanding the general theories that allow a drone to fly, understanding the mathematical equations that relate to aerodynamics will be useful for design and control of a medical drone for this project. This information can be found in Appendix A for reference [7]. For example, an aircraft's lift capabilities can be measured from Equation 1, shown below [8].

$$L = (1/2)\ d\ v^2\ s\ CL \qquad \text{Eq. (1)}$$

Where:

- **L** = Lift, which must equal the airplane's weight in pounds
- **d** = density of the air. This will change due to altitude. These values can be found in a I.C.A.O. Standard Atmosphere Table.
- **v** = velocity of an aircraft expressed in feet per second
- **s** = the wing area of an aircraft in square feet
- **CL** = Coefficient of lift, which is determined by the type of airfoil and angle of attack.

2.2.2 CONTROL ENGINEERING FOR DRONE MANEUVERING

Hierarchical control structures for unmanned aerial vehicles are frequently used for operation of Autonomous drones. Lateral position (roll), longitudinal position (pitch), heading (yaw), and altitude (throttle) are the key drone components that can be utilized to adjust and control drone position [9]. Both the Draper Small Autonomous Aerial Vehicle (DSAAV) and BErkeley AeRobot

(BEAR) utilize microcomputers and navigation sensors to develop a control system successful in controlling autonomous air vehicles [9, 10]. Analysis and comparison of the key system components for these successful drone projects will provide necessary information to base the development of a control system capable of the autonomous delivery of medical supplies.

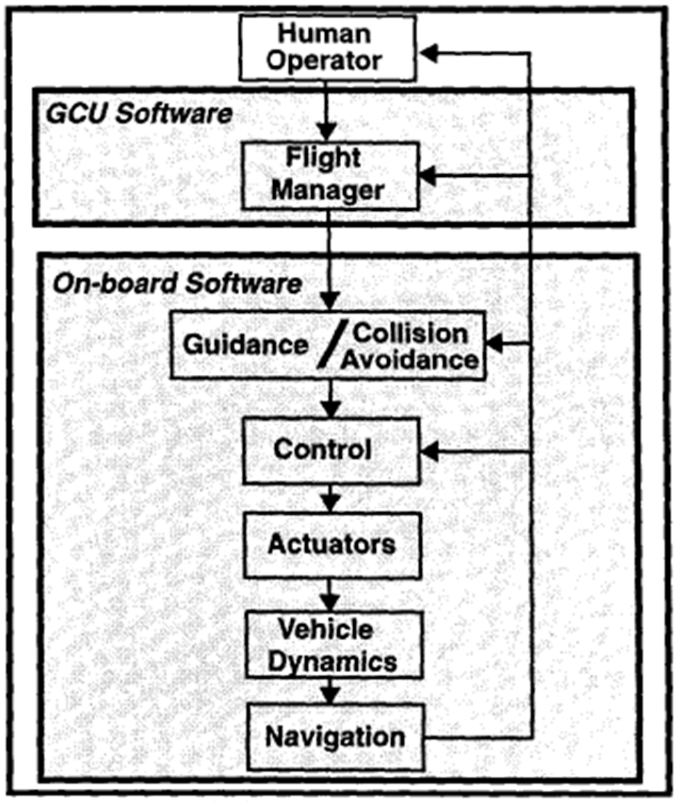

FIGURE 2: DSAAV CONTROL ARCHITECTURE

The DSAAV control system's hierarchy has an inner-loop hover control system at the lowest level that acts as an autopilot. This system is commanded by a waypoint guidance system that can be changed/controlled by a grounded flight manager. Each level of this hierarchy, illustrated in Figure 2, is reliant upon a navigation filter. To achieve this autonomous control, on-board hardware must remain as minimal as possible to maintain hovering capabilities and maneuverability. Table

1B, shown in Appendix B, summarizes the flight hardware and each component's purpose in the drone.

The navigation filter requires a continuous-discrete extended Kalman filter to merge data from the GPS system, sonal altimeter, and digital compass. Local drone position (north-east-down frame), velocities (taken at CG and aligned forward, starboard, and down), altitude, and the magnitude of gravity are the required filter inputs. A state vector using the inertial measurements of angular velocity and inertial acceleration are also propagated in the filter. Since this is a rigid body equation of motion, each time the sensor data is updated the state vector and Kalman filter equations are updated.

At the lowest level, position, heading, and velocity are controlled based upon the navigation system and can be divided into four PID control loops of roll, pitch, yaw, and throttle. The next level of control for these commands is in the outer-loop guidance which is dependent upon the current guidance mode of the drone. The nine guidance modes used in DSAAV are:

1. Ground mode: executed when drone is on the ground, guidance algorithm commands in a low throttle setting.
2. Run-up mode: throttle is ramped up to takeoff level but no lift is produced.
3. Take-off mode: run-up throttle commands continue and pitch or main rotors in increased to create lift.
4. Waypoint hover mode: drone is specified a location, altitude, and hover time and guided through the most direct trajectory.
5. Waypoint through mode: drone passes through specified waypoint (no hovering occurs).
6. Track hover mode: same as mode 4 with the additional command to follow a straight ground track.
7. Track through mode: same as mode 5 with the additional command to follow a straight ground track.

8. Waypoint land mode: composed of several sub-modes that guide the drone to a safe landing.
9. Pilot assist mode: operator controls movement with a joystick.

To prevent a faulty landing, when in land mode the drone is prompted to hover when at an altitude of 3 feet. From there it descends at a rate of 0.5 feet per second until it is 1.5 feet from the ground, at this point it prepares for the final stage of landing where the commands are decreased so that position and velocity errors are not corrected. If the control loops continued eliminating these errors the chance of a false landing increases. Additional system performance algorithms to prevent collisions are in place during drone use. A collision avoidance system, which overrides the guidance loop, is always running when the drone is operating to move the drone away from any objects posing as a potential threat.

The final control algorithm in place for DSAAV is a flight manager software that controls communication between the DSAAV, operator, and sends guidance commands to the drone. Commands such as reading operator inputs, starting a mission, and telling the drone to return home are all functions of the flight manager. So, overall this last algorithm oversees the drone and guides it to the final destination by following five steps:

1. Checking that the drone is prepared for the next guidance mode
2. Determining the next waypoint of interest
3. Transitions drone through run-up and takeoff
4. Notifies the drone of the next mode
5. Switches into the new guidance mode

From there the flight manager algorithm begins again, waiting for the mode completion. Control algorithms with a higher bandwidth would increase the maneuverability, mission planning algorithms could be developed to increase autonomy from waypoint to waypoint [9, 10].

2.2.3 Dimensional Analysis and Payload for Drones

A dimensional analysis is necessary in this project to obtain meaningful results from a cost-efficient prototype. According to Ain Sonin, former mechanical engineering professor at MIT, "at the heart of dimensional analysis is the concept of similarity" [11]. For a prototype to yield any useful results, a dimensional analysis must be performed to define any relationships between physical properties with respect to certain variable conditions. These similarities must be found through mathematical transformations of the certain variables. Variables pertaining to the aerodynamics of a drone may include lift (L), air velocity (V), density (p), wing surface (S), speed of sound (a), and viscosity (u). All units must be broken down into simplified units. A Newton can be broken down into a kilogram-meter per second squared. For mass, length and time, the dimensional analysis must use the most basic units of M, L and T respectively [11]. Using these simplified components, we can apply the Buckingham Pi-Theorem. The Buckingham Pi-Theorem rewrites an original equation, which relates important variables, in terms of a set of dimensionless parameters. Table 2B shown in Appendix B represents examples of variables represented by their most basic components. Using the Buckingham Pi-Theorem we use the known relationships between variables to determine relationships between additional dimensions that would otherwise be unknown.

2.3 Existing Technologies

2.3.1 Drone Applications in United States

Drone applications in the United States have the potential to shape the future of the economy, society and the daily lives of people. In today's society, there are many negative connotations that are associated with drones. When people think of drones they usually associate them with video surveillance or military warfare purposes. Drones are currently being used in the U.S. for surveying, inspecting, and imaging. Strict regulations and licensing requirements are enforced by U.S. federal agencies, which currently hinder the exploration of drone technologies. Some regulations include; drones under 55 pounds that are being flown for routine non-hobbyist use have to remain in visual line of sight of the pilot; operation is allowed under appropriate lighting during daylight hours only; maximum groundspeed of 100 mph; maximum altitude of 400 feet; and pilots must hold a "remote pilot airman certificate" issued by the FAA. However, the use of drones for commercial application has been an increasing topic of exploration for many companies. The top three companies that are exploring the use of commercial drone applications are Amazon Prime Air, DHL and Google [12].

Google has been exploring commercial drone and disaster relief applications. Recently, Google released information about a new project they have been developing, "Project Wing." Project Wing has been a work in progress for two years with a goal of completion coming in 2017. The goal of Google's Project Wing is to provide disaster relief by delivering aid, including water and medical supplies to affected areas. To avoid any legal conflicts Google has consulted the Federal Aviation Administration (FAA) and has been conducting their flight and performance tests in Queensland, Australia. Regulations were established after consulting the FAA, which include a maximum drone altitude of 500 feet and air traffic control system structured by existing cell network infrastructure [13]. Among these regulations established with the FAA are many more, such as the previously listed regulations, hindering the launch of Google's Project Wing.

The current status of drone use in the U.S is halted by legal constraints and according to Henry Perritt, of the *Vanderbilt Journal of Entertainment and Technology Law*, commercial drone applications must "obtain a special airworthiness certificate or a Section 333 exemption" [14]. This means that the drone must be registered with an online federal database, and will assume limited operations to specific geographical locations. Additionally, the pilot requires private level or higher certification. However, UAVs, or "drones", have slowly been making progress. In February of 2012, President Obama passed the "FAA Modernization and Reform Act into law, heralding the official introduction of unmanned aerial vehicles into domestic airspace. The Act calls on the Federal Aviation Administration to begin integrating drones into the national airspace system by 2015" [15]. Moreover, the potential applications of UAVs have caused concern amongst many people regarding the Fourth Amendment, which declares a person's right to privacy (fully defined in Appendix C) [15]. Drones pose many threats to the privacy of just about anyone considering that they undetectably fly at low altitudes in public airways. The ease of gathering intimate details about people's daily lives is frightening to many, not to mention unmanned aerial vehicles can "maneuver through every loophole of the jurisprudence for warrantless searches" [16]. The implementation of drones in the United States will continue as a stalemate until further regulations are conceived and implemented. Privacy concerns enter the discussion for potential situations that involve an attack launched on a drone that can result in the hacking of the camera and video transmission module on the drone. Hackers can potentially even take over the drone's flight control unit and fly the drone wherever they please while gathering live video surveillance data. If federal agencies can find a solution to the potential privacy implications, then medical drones will offer a tremendous amount of assistance and will benefit people around the world.

Though there are still many obstacles, multiple companies have been making progress towards medical delivery. On May 4, 2016, the smart vehicle tech company EHang announced a partnership and long term agreement with the US biotechnology company, Lung Biotechnology. The two companies have agreed to work side by side for fifteen years to develop and purchase one thousand UAVs. These UAVs will be customized specifically for rapid transit for the implantation of artificial organs. EHang will provide the UAV, while Lung Biotechnology will provide the organs to be transplanted. Additionally, EHang is awaiting a pending FAA approval for the production of the “EHang 184”, a 440lb autonomous drone that can transport a person up to 10 miles in the case of an emergency [17]. In summary, drone applications in the U.S. are in their infancy and seem to be the direction of the future.

2.3.2 Drones Applications in China

Drone applications in China have a great potential to improve the country in every aspect. The potential applications that have started emerging are as follows: Aerial Photography, express business delivery, electrical powerline inspection, environmental protection, disaster relief, aerial mapping, and agricultural protection. A brief description of each drone application follows.

Aerial photography: In this application, the UAVs are equipped with high-definition cameras and are controlled over intermediate distances via wireless remote control using video recording for guidance. Real-time high-definition images may be achieved up to a distance of 5 km, while the standard-definition transmission distance is up to 10 km. Different UAV capabilities may vary in altitude from as low as one-meter-high to forty-five kilometers. Drone maneuvering for aerial photography include vertical ascent and descent, left and right rotation, and forward thrust. Aerial photography is often used in movie making procedures. The use of UAVs can be seen behind the scenes of many productions. For example, CCTV (China Central Television) reported the tide of the Qiantang River and other important events with the help of UAVs. In addition, the development of aerial UAVs in China is becoming a more widely used technology for hobbyists.

Express Business Delivery: The implementation of UAVs for the delivery of goods and services is being developed and tested for business across China. Packages, similar to that of a shoebox, can be transported for the rapid distribution of goods. The delivery UAV is programmed with the recipients GPS location for a precise and accurate delivery. In the last few years China's express delivery industry has gained the interest of companies, such as SF Express, to aid in developing and testing drone applications for this business.

Electrical inspection: Drones equipped with high-definition digital video and still cameras can be used to autonomously target locations along the grid through the use of a GPS positioning system. Transmittance of real-time video allows for synchronization and enables the monitoring personnel to view and manipulate the UAV via computer based controller. Compared to the traditional way of performing power line patrol, UAVs can retrieve information electronically through an intelligent inspection procedure and improve work efficiency of the overall power line inspection process. In the case of natural disasters, UAV applications for electrical inspection can help avoid dangerous situations by eliminating the need to climb an electrical tower or survey an area [18].

Environmental protection: UAV applications in the field of environmental protection can be divided into three types. 1. Environmental Monitoring: observation of air, soil, vegetation and water quality condition, real-time tracking and monitoring of the development of environmental pollution emergencies. 2. Environmental Enforcement: EM department use drones equipped with collection and analysis device in a particular area. Waste gas and waste water companies monitor the plant and look for sources of pollution. 3. Environmental Governance: the use of meteorological observation and carrying a catalyst provided soft wing UAV in the air to spray with pesticides in a certain area to eliminate haze. [19]

Disaster relief: The use of a high-definition imaging apparatus equipped to a UAV for aerial photography of the affected areas to provide real-time images. UAVs act quickly, and take off to landing can take as little as only seven minutes while covering 100,000 square kilometers of aerial coverage. Time is of the essence when a disaster strikes and therefore it is a race against time for disaster relief work. In addition, unmanned aerial vehicles protect the safety of rescue teams by helping to avoid danger zones that involve the collapse of a building. Furthermore, the UAV real-time monitoring of the situation in the affected areas, and in all directions, will help to prevent secondary disasters triggered. [20]

Aerial Mapping: use of remote sensing technology and a GPS system, the UAV can retrieve the necessary data for mapping purposes.

Agricultural Protection: plant protection for agriculture and forestry jobs. The unmanned aircraft by the flight platform (fixed-wing, single rotor, multi-rotor) composition, GPS flight control, spray bodies of three parts, by remote control or GPS ground flight control to achieve spraying operation, the agent can be sprayed, seeds, powders, etc. China's sales of plant protection drones consist of two types, oil dropping plant protection agents and plant protection spraying drones. [21]

2.3.3 Drones Applications in Other Countries

Among EHang and Lung Biotechnology are many other companies located in the US moving in a similar direction. Zipline, a company based out of California, has recently partnered with the government of Rwanda to deliver blood and emergency medicine via a “small fixed-wing drone” [22]. These drones are deployed through an air catapulting system and can reach a destination 90 miles in radius away within 30 minutes. The fleet of drones can deliver between 50 and 150 deliveries per day, and can fly up to 180 mph (miles per hour) [23]. With this contract, Rwanda has become the first country to implement a medical drone network system and is leading the evolution of technology and society around the world.

In addition to Rwanda, drones have been used in Haiti after an earthquake to deliver small care packages, and in Papua New Guinea to transport mock tuberculosis test samples from a remote area to a large city. These few examples illustrate the usefulness of drone applications in other countries and should provide the U.S. and China with enough evidence to move towards this technology.

2.3.4 Existing Hardware and Software for Prototyping Drones

This project utilized a vast range of hardware components and software platforms that were integrated into the overall design of the medical drone. It is not in the scope of the project, nor in this paper, to delve into the details and logistics of the electrical and computer engineering relationships involved in the overall design. However, in this section the use and function of the various hardware and software platforms used in the project will be explained briefly.

There is an abundance of existing software platforms (Paparazzi, APM, MultiWii Copter, KK, Dji naza, pixhawk) and hardware components used for drone prototyping [24]. The most common hardware components involved in prototyping include GPS and compass, flight control unit, data transmission module, data receiving module, remote controller, electronic speed control, motor(s), battery, motor powerhub, servo(s), voltage sensor, current sensor, remote controller, camera, video transmission module, on screen display, powerboard, battery, and a voltage converter. Using these components, the UAV’s body design was developed to allow for an appropriate implementation of each component while carefully considering the weight, the balance, and the drone’s overall center of mass.

The most important electrical component used for drone prototyping is called a flight controller, or flight control unit. The flight controller is essentially the brains of the UAV. This component is what allows the drone to maintain balance, and it does this by gathering data through sensors and computing the necessary changes for the motors. The flight control unit dynamically controls each motor to keep the drone from becoming unbalanced based on the sensory information it is processing. The fight control unit must be configured to the number of motors being used. If the drone is a quadcopter, the flight control unit must be configured to control four motor units, thus controlling four degrees of freedom, yaw, roll, pitch and lift or altitude.

There are various types of flight controllers on the market so it is important to determine which flight control unit will fit the needs of a particular project or UAV design. When considering flight control units for UAV implementation it is important to consider its capabilities. Capabilities that are important include gyro stabilization, mobile self-leveling, care free capabilities, hovering capabilities (altitude and planar position hold), and return home and waypoint navigation. These features should be considered so that the needs of the UAV can be met to satisfy the UAV’s purpose. Additionally, the price of the flight control unit is worth considering, especially depending on the particular budget for the creation of the UAV. Moreover, the flight control unit is the most important component integrated on the body of the drone. Therefore, a briefer description of the remaining components will be provided below.

Flight Controller: ArdupilotMega (APM) is an open source flight controller. We use it to maintain the balance of the UAV by PID algorithm.

Camera and Video Transmission Module (VTM): Camera can capture image data and VTM can send the image data to the user, providing the user with information around the UAV.

Data Transmission Module (DTM): Use the DTM for UAV and terminal connection. The terminal includes smart phones and computers. Can send commands from mobile phones or computers to control the UAV.

Electronic Speed Controller (ESC): ESC uses the information and signals gathered by the sensors of the flight controller to control the current provided to the motors.

Global Positioning System (GPS): GPS module can receive signals from the GPS satellite to find the position of the UAV during flight navigation.

Motor: Motor converts electrical energy into mechanical energy to rotate the propellers which provide the aircraft with lift.

Motor Power Hub: The power from the battery is divided into four parts for the motors and is made by PCB (printed circuit board) board.

On-Screen Display: Displays the current flight information to the user. Provide information about the performance of the UAV as well as video.

Power Hub: This module converts the battery voltage (22.4V in our case) to the standard voltage (5V) and controls part of the power supply.

Remote Control: Converts the physical change of the joysticks and buttons on the remote control to information that is converted to electrical signals and sent to the wireless signal receiver.

Receiver: Converts the wireless signal from the remote-control and sends information to the flight control unit.

Servo: Provides control of a desired operation through the use of feedback. It can be rotated to the angle needed for control of the UAV arm.

2.4 Engineering Standards

Throughout this project, important documents known as engineering standards, which specify characteristics and technical details of what the product must meet and abide by, were followed closely [25]. The American National Standards Institute (ANSI), the Society for Standards Professionals (SES), and the International Standards Organization (ISO) are three important sources for ensuring that the project was abiding by engineering standards. In this project the ISO was used to help with the standardization of the unmanned aircraft systems, with regard to the "design and development, manufacturing, delivery, maintenance; classification and characteristics" of the unmanned aircraft system [26]. In addition to these standards, this project also utilized standard software, and would not have been possible without the assistance of SolidWorks, which was used to create a three-dimensional model which was then saved as a stereo-lithography (STL) file, which is the standard format for production in the rapid-prototyping industry.

Since the product must comply with medical device standards and quality standards, the team closely researched ISO standards. ISO standards are widely recognized and closely regulated. If this project was entered into the market, there would have to be many quality regulatory documents created to comply with ISO standards. The most widely known standards for this are the ISO 13485:2012 standards. These set the requirements for regulatory processes. In addition to quality and regulatory procedures, there are biocompatibility standards that the device should be in compliance with. These include ISO-10993-1:2009, BS-EN-ISO 10993-4:2009, and ISO-10993-5:2009. Each of these standards discusses the biological evaluation of medical devices, which applies to the payload in this project. The ISO-10993-1:2009 standard involves evaluation and testing within a risk management process, the BS-EN-ISO 10993-4:2009 involves the selection of tests for interactions with blood, and ISO-10993-5:2009 involves tests for cytotoxicity specifically [27, 28].

Moreover, engineering standards for drones in China and in the United States were closely considered before prototyping and testing. To be sure the team was in the clear, the engineering standards for drone use in China were researched and are as follows:

> "*Provisions on Light and Small Unmanned Aircraft Operations (UAS Operation Provisions) issued by China's civil flight regulatory agency regulate the operation of unmanned aircraft systems (UAS) with a maximum empty weight of 116 kilograms or less, or a maximum take-off gross weight of 150 kilograms or less, and a calibrated air speed of no greater than 100 kilometers per hour. UAS weighing 1.5 kilograms or less are generally not required to follow the Provisions*" [29].

In addition to the provisions above, the UAV must not be flown in restricted airspace and must give way to manned aerial vehicles at all times. Furthermore, to relate the project to regulations in the United States, the standards for drone flight were again researched and are as follows:

> "*Unmanned aircraft must weigh less than 55 lbs. Visual line-of-sight only; the unmanned aircraft must remain within VLOS, may not operate over any persons, under any covered structure, or inside a covered stationary vehicle Daylight-only operations. Must yield right of way to other aircraft. Maximum groundspeed of 100 mph, maximum altitude of 400 feet above ground level or 400 feet above a structure.*" [30].

Based on the standards for both countries, the drones were carefully constructed and operated within all limitations, restrictions and regulations.

2.5 Biomedical Applications of Drones

2.5.1 Medical Relief

Drones have proven to be effective in many commercial applications when abiding by the regulations set by respective governments. But, aside from commercial applications, UAVs can also be used to transport blood and small emergency medicine and medical supplies, such as a portable heart defibrillator or first-aid kit. In the express delivery industry, the development of package delivery systems through the use of UAVs is far from maturity, but has reached the stage of broadening its applicability. Using unmanned aerial vehicles for applications in the field and study of biomedical engineering seems to be the next immediate step in the broadening of drone applicability.

First and foremost, in the event of an emergency situation drones can be a form of immediate relief. Hospitals located in remote areas have a limited amount of supplies, and during a state of emergency the supplies run out extremely fast. Drones can aid in the restocking of supplies in remote hospitals as well as the delivery of needed supplies to area in need. The time that a truck delivery would take is too late for the majority of people in need. This raises the biomedical application of drones to cut down the time of an emergency delivery from what could take up to 4 hours to just 20 minutes. For example, if a mother is giving birth and is suffering from postpartum hemorrhaging, her life is dependent on receiving a blood transfusion. The blood is needed immediately and depending on the geographical location, there may be many forms of physical boundaries and obstacles that would impede ground vehicles. With blood being readily available at nearby hospitals, drones could be safely loaded with blood bags and the necessary equipment for transfusion upon delivery, ultimately saving the mother's life. Transportation in remote and underdeveloped rural areas is a prominent issue in many countries, and UAV transport undoubtedly provides a quick pass through closed roads and rugged terrain while carrying small and light transportable medicine and other medical supply solutions.

In the case of a natural disaster, such as a major flood or earthquake, affected areas often experience traffic grid lock-up, which inhibits first responders from acting promptly and effectively. The use of unmanned aerial vehicles can be implemented to increase rescue efforts by defining key areas of relief, identifying rescue routes and providing care packages. In addition, real-time UAV monitoring of the situation in all directions of the affected areas can prevent the triggering of a secondary disaster. This biomedical application will undoubtedly provide a reliable and efficient solution for disaster relief while working in a time sensitive manner.

Furthermore, in densely populated metropolitan areas where high traffic congestion is a serious problem, UAVs can be used to transport light and small time sensitive emergency medical supplies. UAVs offer dynamic transportation methods for biomedical applications such as transporting vaccines and first-aid kits.

Additionally, in terms of pharmaceutical delivery, UAVs can provide biomedical applications to benefit patients by increasing treatment times through rapid drug delivery. Moreover, when delivering sensitive materials, it is imperative that the materials are kept safe. To keep the containing materials safe, the components must be fully understood.

2.5.2 Understanding Biology and Physiology

Identifying relevant biological and physiological systems for review is essential in understanding the choices made throughout this project. More importantly, understanding the appropriate biological components will allow for a meaningful analysis of the biocompatible materials and designs. The biological and physiological components to be transported include blood, medicine, and first-aid supplies. All chemical, biological and physiological elements must be treated in different respects and therefore must be briefly introduced to understand why. But first, it is necessary to recall what the differences and similarities are between biology and physiology.

Biology is defined as the study of living organisms. An organism is considered to be an entity consisting of one or more living and functional cells. Physiology is a branch of biology that is dedicated to the study of the functions and activities of organs, tissues, or cells, as well as the physical and chemical phenomena involved [31]. Blood is a physiological phenomenon which means that there are living cells in blood that contribute to its overall function as a biological system. Blood holds critical responsibilities of transporting oxygen and nutrients to cells around the body while simultaneously taking away waste products like carbon dioxide and ammonia. Therefore, if a person is in need of blood, it is imperative that the transfusion be done as soon as possible because the longer the person waits, the more their life is put in jeopardy. Additionally, blood plays an important part in the body's immune system, as well as aids in homeostasis by maintaining the body's internal temperature [32]. According to the *National Center for Biotechnology Information*, "red blood cells are the most commonly transfused blood component" [33]. Taking this into consideration, it is important to understand the characteristics of red blood cells, among the other components, so they can be preserved during transport. The main biological components that make up blood are erythrocytes (red blood cells, RBCs), leukocytes (white blood cells, WBCs), platelets, and plasma [32]. Figure 3 below indicates the components of the blood suspended in the plasma [34].

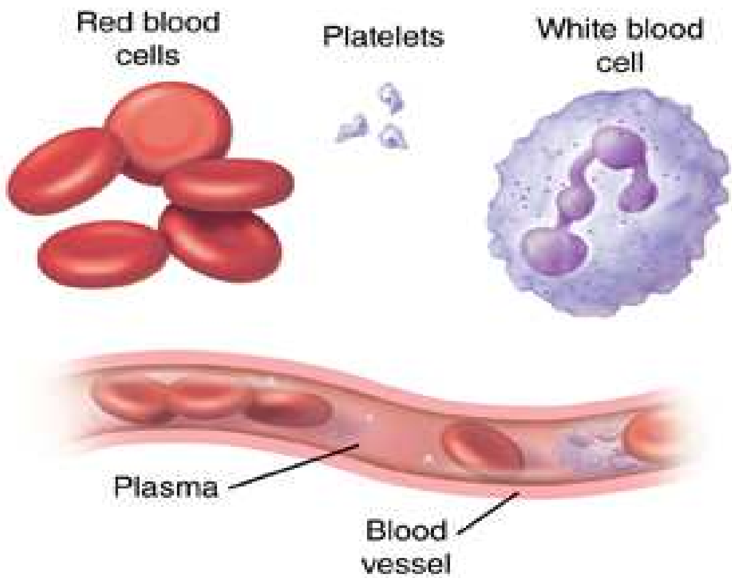

FIGURE 3: COMPONENTS OF BLOOD

Blood, being as vital as it is, must be well understood so that it does not lose its viability during transport. It is imperative to recognize that blood expires, meaning the blood is unusable after a period of time, or if it is not maintained in ideal conditions. In addition to maintaining blood in ideal conditions during transport, it is also vital that any drugs being transported are kept in a safe environment.

2.5.3 BIOCOMPATIBILITY FOR SUPPLIES BEING TRANSPORTED

The transportation of medicine and biological components requires that the storage container and all other materials be biocompatible. To understand the interactions between the materials and the biological system in transit, it is important to understand the fundamentals of biocompatibility, the relationship between medicine, the biological components, and the payload materials. Additionally, the environmental requirements for both blood and various types of medicine must also be understood. The medical supplies must be protected by properly storing and transporting them. Proper care of the supplies will prevent contamination or damage to the supplies, and thus will aid the patients in need. Table 1, below, shows a list of elements that may be transported and the proper storage requirements to ensure that the payload remains biocompatible for all possible components.

Table 1: Component Biocompatibility Chart

Payload Components	Function/Purpose	Storage
Medicine		
Nitroglycerin Tablets	Relieves acute attack of angina	T ≤ 77°F, protect from heat, moisture and light
Refrigerated Vaccines	Prevents disease	36°F ≤ T ≤ 46°F
Frozen Vaccines	Prevents disease	−58°F ≤ T ≤ 5°F
Aminophylline Tablets	Treats Asthma attacks	Store away from UV light
Nifedipine, Nimodipine (Antihypertensive Drugs)	Treats stroke or myocardial infarction	Store in cool/dry place
Insulin Regular	Treats diabetes	Store in refrigerator, away from light
Blood		
Whole/Red Blood Cells	Transfusion to treat anemia/blood loss	Preservatives solutions, blood bag, and temp. control
Platelets	Ensures blood clots	20°C-24°C for 5 days and must be agitated continuously
Plasma	Transfusion to treat deficiencies of clotting factors	4°C or 22°C for 24 hours with preservative solutions
Other Medical Supplies		
Small Defibrillator	Treats cardiac fibrillations with electric current	Protect from the elements and potential damaging vibrations
First-aid kit	Provides aid for minor injuries	Keep dry and protected
Syringes/Other equipment	Provided equipment for transfusion	Keep in bubble wrap or other fragility-focused packaging

Following is a more detailed description of biocompatibility requirements for each of the elements in the above table. In addition, the function, purpose and the means of storage/transportation is described for each element.

<u>Blood</u>

Whole Blood/Red Blood Cells – Any change in specified temperature ranges or conditions during the storage and transportation of blood can negatively affect the viability of the blood and lead to reduced efficacy or loss of blood transferability. Blood is collected and used for transfusion to treat people with blood loss or other symptoms. Collection occurs at a collection site and separation of the blood takes place in the hospital before UAV transport. This process is not within the scope of this paper. Please see Appendix D for more information regarding separation techniques. Upon transportation, the blood must be stored and preserved with anticoagulants to prevent anemia when transfused to a person who has suffered blood loss. If the blood is not stored with anticoagulants and preservatives the blood viability will be decreased. A composition of different preservative and anticoagulant solutions can be found in Table 4C of Appendix C [35].

By using preservative solutions, the red blood cells can remain viable and functional for the patients in need of a blood transfusion. The blood is to be stored between 2 and 6 degrees Celsius to preserve ideal blood viability. If the blood viability is compromised that means it is due to the “lesion of storage” [35]. This refers to the decrease in pH, buildup of lactic acid, decrease in glucose consumption, decrease in ATP level, and low levels of 2,3-DPG [36]. A description of the importance of these factors can be found in Appendix D.

In addition to preservative/anticoagulant solutions, the low temperature is also very important during storage and transport. The low temperature is ideal for minimizing the rate of glycolysis. Glycolysis causes the production of lactate and a consequent decrease in pH. Additionally, the lower temperature also keeps the proliferation of any bacteria that may have entered the blood. In general, blood needs to be stored and transported in low temperatures and contained in blood bags with a preservative/anticoagulant solution.

<u>Medicine</u>

Nitroglycerin tablets – mainly used to relieve acute attack of angina. While its main pharmacological effect consists of relaxation of vascular smooth muscle by dilating blood vessels, it must be noted that nitroglycerin is volatile and unstable if it is not stored at or below 77 degrees Fahrenheit and protected from heat, moisture, and light.

Vaccines – proper vaccine storage and handling practices are vital when dealing with vaccine-preventable diseases. Vaccine quality is a must to ensure individual and community protection. Storage practices will vary with refrigerated vaccines and frozen vaccines. Refrigerated vaccines must stay between 36 and 46 degrees Fahrenheit while frozen vaccines must be stored between –58 and 5 degrees Fahrenheit. To read in detail, CDC-developed vaccine fact sheets are provided in Appendix C.

Aminophylline tablets – Used to treat an asthma attack or patients with wheezing, shortness of breath or chest tightness. Taking aminophylline tablets can relieve these symptoms. However, the sun's ultraviolet radiation can accelerate the deterioration of theophylline, therefore colored tablets should be kept in the bottle, and placed out of the sunlight.

Nifedipine, nimodipine antihypertensive – easy to break down when exposed to light, reduced efficacy. Most of these drugs themselves are in capsules covered in a thick colored coat to reduce the impact of light. When storing these drugs, it is best to maintain in the container.

3 Objectives

3.1 Detailed Plan to Achieve Objectives

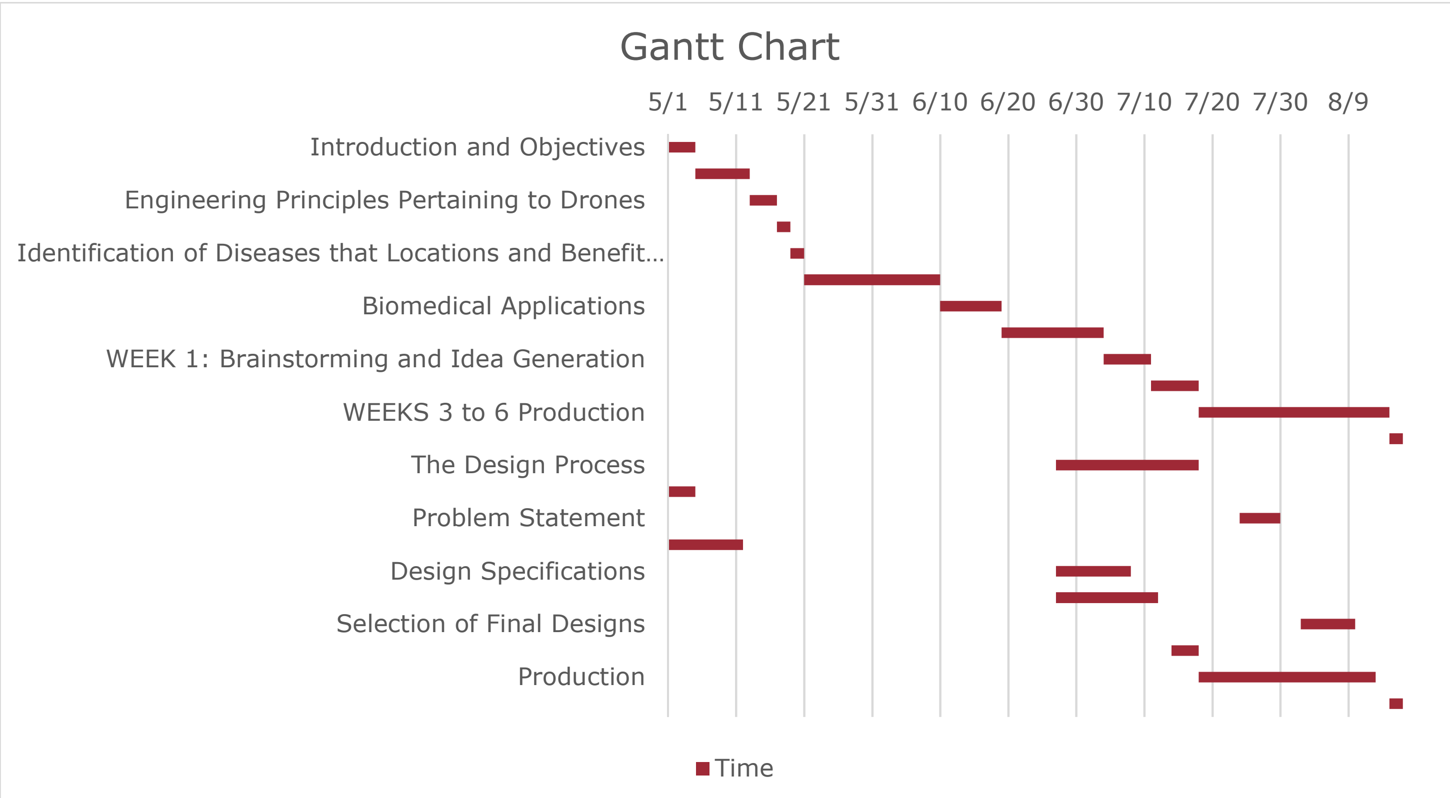

Figure 4: Gantt Chart

3.1.1 Week 1: Brainstorming and Idea Generation

- The first week is dedicated to culminating the ideas of the WPI students and the Beijing Students
  - Developing the foundation (two days)
    - Prior to the Start of E-16, the WPI students should have developed the following
      - Identification of Need
      - Problem Statement
      - Project Goal
      - Design Specifications
    - Prior to the Start of E-16, the BUCT students should have developed the following
      - Identification of Need
      - Problem Statement
      - Project Goal

        - Design Specifications
            - The first two days is then spent with BUCT & WPI students exchanging ideas to create a final version of the identification of need, problem statement, project goal and design specifications
            - One student has a responsibility of creating the design matrix and pairwise chart
    - Developing Ideas takes two days
        - The next two days is spent creating preliminary designs
        - The BUCT team and the WPI team can work separately or together in the phase
    - Selecting the Final Design takes One Day
        - Students present their favorite designs to the team
        - A decision matrix and a pairwise chart are created to pick the best design

3.1.2 WEEK 2: ANALYSIS

- The second week is dedicated towards analyzing the final design.
- The final design analysis can be placed into the following categories
    - SolidWorks Model
    - Weight Analysis
    - Force analysis
    - Stress & Strain Analysis
    - Material & Cost Analysis
    - Kinematics Analysis
    - Power & Force Analysis
    - Material Safety for Biomaterials in Transport
- The work can be split between the WPI students and the BUCT students

3.1.3 WEEK 3 TO WEEK 6: PRODUCTION

- The most amount of time Is dedicated towards the production of the device, because manufacturing a prototype can usually lead to unforeseen problems
- The manufacturing of the device can be broken into three components
    - Mechanical Production
    - Electrical Production
    - Software Production
- We need to decide on which platforms to use the build the drone. [explain here]

3.1.4 WEEK 7: CONCLUDE RESULTS

- The last week is dedicated to putting the final results into the paper

4 METHODOLOGY

4.1 THE DESIGN PROCESS

4.1.1 IDENTIFICATION OF NEED

Healthcare services is among the most common concern of citizens in remote areas of China. Low income families located in remote areas of China suffer from treatable illnesses due to the absence of medical assistance and lack of disposable income to seek out medical attention many miles away. Addressing these medical needs is extremely important for the evolution of China's healthcare delivery system and the well-being of citizens located in these areas. Currently, the supply and demand of medical care services is out of balance and is largely due to the "rapid [population] growth . . . and the unreasonable structure of China's health delivery system" [37]. In addition to the people in need of medical attention, the medical industry and healthcare system in China is in need of modernization. By addressing the needs of the Chinese citizens, the healthcare system can be improved simultaneously. To address the needs of the people, the problem must first be well understood.

4.1.2 PROBLEM STATEMENT

The process of seeking medical attention in remote regions of China should be improved to increase healthcare accessibility. The healthcare system should aim to provide the best and fastest possible medical attention to all people throughout the country while optimizing for cost and time-efficiency. However, China's current healthcare system is inefficient and lacks the accessibility of medical services in various regions of the country. By being inefficient, outdated and slow to provide services, the current healthcare system causes distress and unfavorable scenarios in remote communities where people are in need of immediate medical attention.

The inefficiency of the current medical services represents a significant problem for the healthcare system and introduces an unnecessary burden on many families. Based on a multitude of studies and surveys, approximately "24.4% of China's population declared that because of their poor economic status and the high cost of medical services, they did not seek medical care when they needed it" [37]. To put the magnitude of assistance needed into perspective, according to the United States Census Bureau, the population of the United States is approximately 324 million people. Comparing this to 24.4% of China's total population, which is approximately 332 million people, it can be seen that more than the total population of the U.S. is in need of medical attention.

Using a modified drone to implement a medical supply delivery system which carries blood, first-aid equipment, medicine and other medical supplies, China's healthcare system can eliminate the unnecessary burdens that families face and simultaneously enhance the technology of their medical services. The significance of the UAV application in this project lies with the potential benefit on communities located in remote areas of China. UAVs for medical supply delivery will save time, money, and lives. In the case of a natural disaster, a fleet of drones could be deployed to deliver medical supplies needed to save lives and minimize collateral damage. The use of UAVs for medical supply delivery alleviates suffering and provides many Chinese citizens with the chance to recover from illnesses. The use of UAVs will reduce the cost of medical assistance and benefit many people with low income.

4.1.3 Design Objectives

Setting the design objectives is among the most important steps during the early stages of the project. The main design objectives that were ascertained from the team's revised problem statement were that the design of the arm and payload should be reliable, durable, cost effective, small and compact, electrically powered, safe, easy to sterilize, and serviceable. The design should be reliable because if any part of the device fails it jeopardizes the viability of the blood and medicine in transport. This makes reliability an important objective because it ensures the constraint of safety as well. Jeopardizing the viability of the materials in the payload also directly jeopardizes the health of the person it is being delivered to, and therefore defeats the purpose of the medical UAV application. The UAV arm and payload should be durable so it lasts through multiple deliveries and fulfills the objective of being reusable.

Additionally, this device should be reusable because the resources and money available in remote areas of China are too little to be constantly replacing the payload and/or servicing the UAV on demand. Moreover, a device that is reusable is much more cost effective and efficient than a disposable payload because it is produced and purchased once and used for multiple deliveries over the UAV’s lifetime. Along with reusability comes the ease of sanitization. If the device is used and reused for deliveries with different blood types, medicine, and medical supplies, it is vital that the payload is easy to clean and sanitize to ensure the health and safety of the blood transport recipients. Since the payload will be coming into contact with people who have illnesses, it is vital that the payload be clean before reaching the next person in need. The slightest contamination of the payload can cause harmful, adverse situations for the recipients of the payload materials.

Furthermore, the design should have a relatively low cost because it should be affordable for hospitals to implement and for citizens in need of medical attention to call upon when needed. The families in China that are in need will not be able to afford medical attention if the UAV is too expensive to implement. After determining the design objectives, it is necessary to analyze the relative importance of each objective through a ranking system.

In order to determine the relative importance of each objective, they must be ranked throughout the progression of the design process. To do this, an objective tree was created to aid in breakdown of the objectives into smaller sub-objectives. The reason for using an objectives tree is to allow for a better representation of the overarching objective. The objectives tree for the UAV arm and payload can be seen in Figure 3 below.

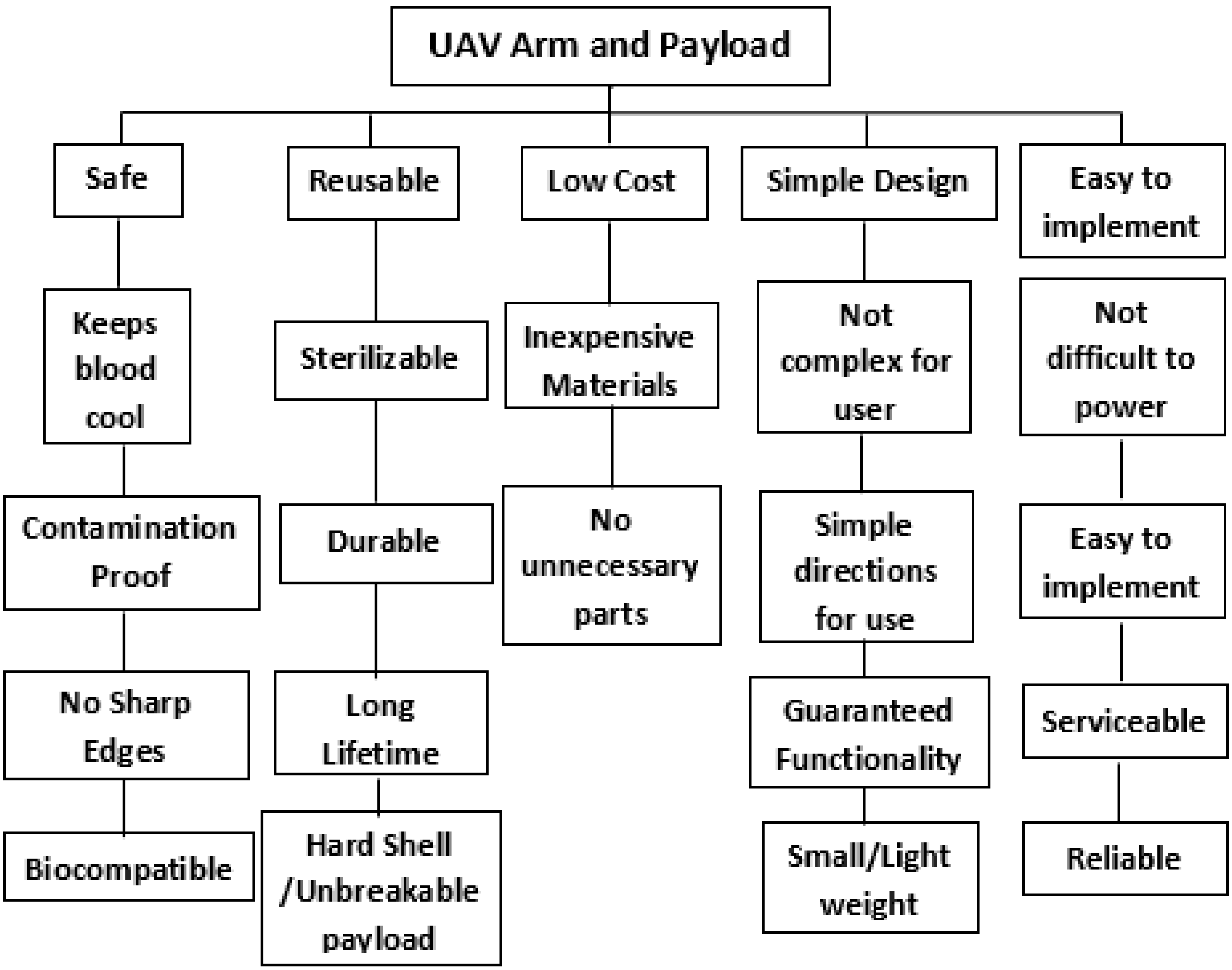

FIGURE 5: UAV ARM AND PAYLOAD OBJECTIVES TREE

After understanding the objectives tree, it is easier to determine which objectives are overall more important. Some objectives must be sacrificed or focused on less in order to ensure that the most important objectives are fully satisfied by the design. To identify the objectives that should be considered to be the top priority, compared to the remaining objectives, the team formed a pairwise comparison chart (PCC). A PCC is used to judge a group of objectives to determine which entity is preferred. The PCC is depicted below in Table 1.

Table 2: Pairwise Comparison Chart

Goals	Easy to use	Safe	Low cost	Reliable	Simple Design	Score
Easy to use	-	0	1	1	1	**3**
Safe	1	-	1	1	1	**4**
Low cost	0	0	-	1	1	**2**
Reliable	0	1	1/2	-	1/2	**2**
Simple Design	0	0	1/2	1/2	-	**1**

It has become clear through the use of an objectives tree and pairwise comparison chart that the most important design objective is safety of the user, recipient and the safety of the blood and medical supplies being delivered. The payload should safely store and preserve the blood, medicine and medical supplies during transport so that the viability of the contained materials does not jeopardize the health of the recipient. The design is not a success if it cannot achieve this objective and perform this function. If the design is not safe and the blood viability is jeopardized, it endangers the health of the individuals in need, which is the original problem being addressed. Moreover, if the individual who is in need of medical attention cannot use the medical supplies or blood that has been delivered, his or her current medical issue will remain untreated. The design objective “safe” refers to the overall design that aims to keep the user, recipients, and the materials being transported safe. The blood cannot be contaminated by the external environment; nor can it be allowed to coagulate because this will result in a loss of blood viability. The device is not a success if it does not perform this function because it indicates that it does not meet the objective of being safe, and this is the reason for being ranked the highest priority of the objectives.

Furthermore, from the PCC, the objective that received the lowest ranking was "simple design." This objective indicates that the device should be simple, streamlined and basic. Any user should be able to determine how to use the device with little to no instruction or explanation. Although this is an important objective, additional complexity will not jeopardize the main functions of the device, and therefore is ranked lowest because it is the least important in comparison to other objectives. The team decided that this is the easiest objective to sacrifice and accommodate for because if the design is complex, then an instruction manual will be included with the design if needed.

4.1.4 DESIGN FUNCTIONS

When considering the design of a technology that is up and coming, it is important to determine the necessary functions of the design. In this case, drones have a huge potential to be a means of medical supply delivery, and therefore need to be strategically analyzed in a systematic approach before implementing any sort of design. Thus, the overall objectives must be thought of closely for proper production of a working prototype.

The team determined multiple design functions that the UAV arm and payload must perform to fulfill the revised problem statement. These functions include: contain the blood, medicine and other medical supplies, open easily for the recipients ease of access to the payload materials, seal the container, cool the blood, and insulate the blood and medicine. One purpose of the payload is to hold a specified amount of blood and medicine for a period of time. The blood and medicine must be contained safely in an enclosed environment that insulates and protects all containing materials. The device should use insulating materials to maintain a viable internal temperature for safe storage of the blood so that it can be safely preserved during delivery. The opening of the payload should seal tight enough to prevent any rain or foreign elements from entering the payload and potentially contaminating the needed medical supplies. The opening should seal tightly while still allowing the user to easily gain access to the medical supplies. The opening to the payload should also prevent medical supplies from escaping the container. Overall, the design specifications are more easily identified by previously determining the design functions.

4.1.5 DESIGN SPECIFICATIONS

Various types of drones and UAVs exist today, including fixed-wing and helicopter style drones. Ideally, the main design specifications needed for medical supply delivery include safe and high speed transit, while avoiding the use of excess battery power during transport. The main objectives and constraints in this project propose using a copter-style UAV for concept feasibility, rather than a fixed-wing drone. To effectively continue with the design process, the design functions and constraints must be laid out.

The team determined which design specifications were the most important in influencing the guidance of the brainstorming process in order to create a number of alternative designs to choose from. The first specification that the team determined was that the design must be able to carry at least five kilograms of weight. If the UAV cannot lift at least five kilograms of blood/medical supplies, then it was determined that each delivery would not have a sufficient amount of medical supplies for the recipient. After consulting the team, it was also noted that the payload needs to be biocompatible with the containing blood and medicine. This means that the materials used in the payload cannot jeopardize the viability of the medical supplies.

Additionally, the design needs to be cost effective to ensure the affordability of medical care for people in remote areas of China. According to Edward Wong of *The New York* Times, families in rural areas of China have an average annual income of $1,600 [38]. Due to this, the cost of each UAV delivery should allow for a family to afford at least five deliveries per year to appropriately meet medical needs. Aside from affordability, the UAV must fly for at least ten minutes under maximum loading, and reach a radial distance of at least five kilometers to allow for the implementation of a medical drone network. Furthermore, the payload must be able to maintain an internal environmental temperature of 10 degrees Celsius to 30 degrees Celsius for at least 1 hour to ensure blood viability during transport. The material of the payload must not cause contamination, should be well insulated, and should be impact resistant.

Overall, these are the determined specifications because the team agreed on conditions that the design must meet to be considered safe. In general, the design specifications are geared towards influencing the creation of multiple design alternatives to choose from.

4.2 Design Alternatives

4.2.1 Preliminary Design No. 1

The first UAV arm design, the basic pincer, was initially designed based on using the least amount of materials possible to pick up the payload. The basic pincer design seemed ideal because of the simple design that it achieved. The design was determined to be effective and inexpensive because it achieves the objective of ease of manufacturability and assembly, while maintaining an overall cost effective design.

The basic pincer design is meant to attach underneath the UAV and centered on the bottom board where it can carry a payload designed to be carried like a grocery basket. This is because the distance between the pincer arms is small and does not allow for a large grasp. The attachment is designed for the attachment of a small servo to allow for controlling the movement of the arm. Once the UAV is ready for takeoff, the arm is moved by the servo to clamp onto the payload handles. The servo is directly attached to the left gear of the pincer, which, when turned, engages the teeth of the pincer arm gears to initiate the pincer arm movement. The pincer arm can be completely closed and opened with a displacement of about 2 inches. Because of the small displacement of the pincer arms there must be a higher accuracy of placement in terms of engaging and securing the payload. The design of the basic pincer can be seen in Figure 4 and 5 below.

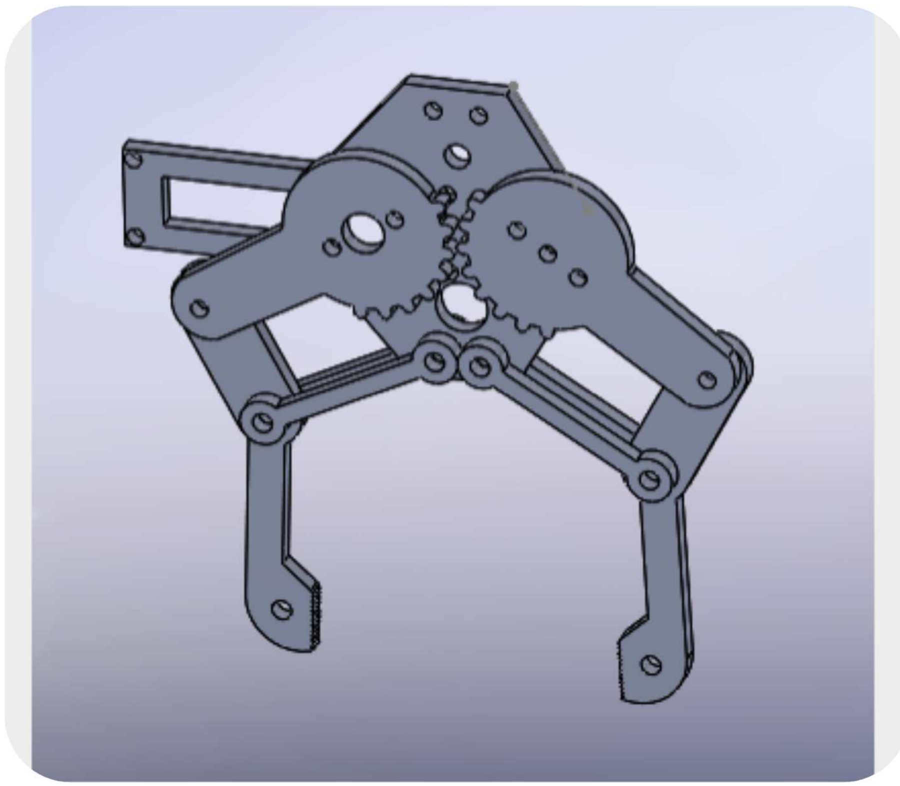

FIGURE 6: BASIC PINCER DESIGN SOLIDWORKS DRAWING

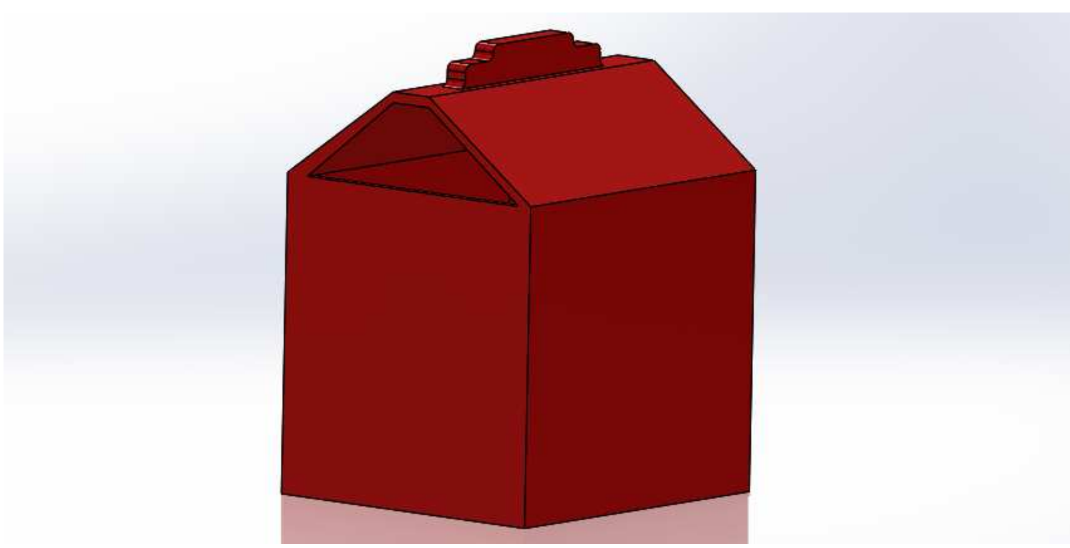

FIGURE 7: PAYLOAD DESIGN 1 FOR PINCER

Based on the basic pincer design, the first design of the payload must be similar to that of a basket where two handles meet in the middle above the payload. The basic pincer will grip the handle upon takeoff of the delivery and upon delivery it will land the payload securely on the ground and then release the payload handles. The handles can then be swung to either sides of the payload to expose the lid of the payload for user accessibility to the medical supplies contained in the payload. The lid can then be pulled upward so that the compartment where the medicine is held is exposed. Once the top is pulled upward so that it slides to expose the storage compartment, the user can then lift the removable storage compartment out of the payload to expose the compartment where the blood for transfusion is stored. Once the user removes the needed medical supplies that was requested, the removable compartments are then placed back into the payload in the order they were removed and the lid is placed back on top. The UAV then gets ready for return to home with the empty payload.

This design conceptually achieves the necessary requirements to store and transport the blood and medical supplies, and does so with minimal materials. The design had been conceptually formulated to achieve the ease of use and it demonstrated this by the fact that the user would just remove the top of the payload to gain access to the medical supplies. The design has proven to function conceptually and has also proven to meet specific objectives, but not all. This design fails to meet the objective of being safe because the basic pincer design relies only on the strength of the servo to pinch the payload handles and uphold the weight of the payload. The design does not effectively secure the payload and therefore exposes the payload to unwanted risk and jeopardizing overall safety.

4.2.2 Preliminary Design No. 2

The next design, the flat-arm variation, is a design that consists of similar materials and parts to the first design, but with different arms. This design was meant to allow for a safer grip around a larger payload rather than gripping onto small handles. By choosing to grip the payload on the sides, the arm attachment is squeezing the load in a safer way. This allows for the elimination of the small handles, which reduces weight, and adds a more aesthetically pleasing look.

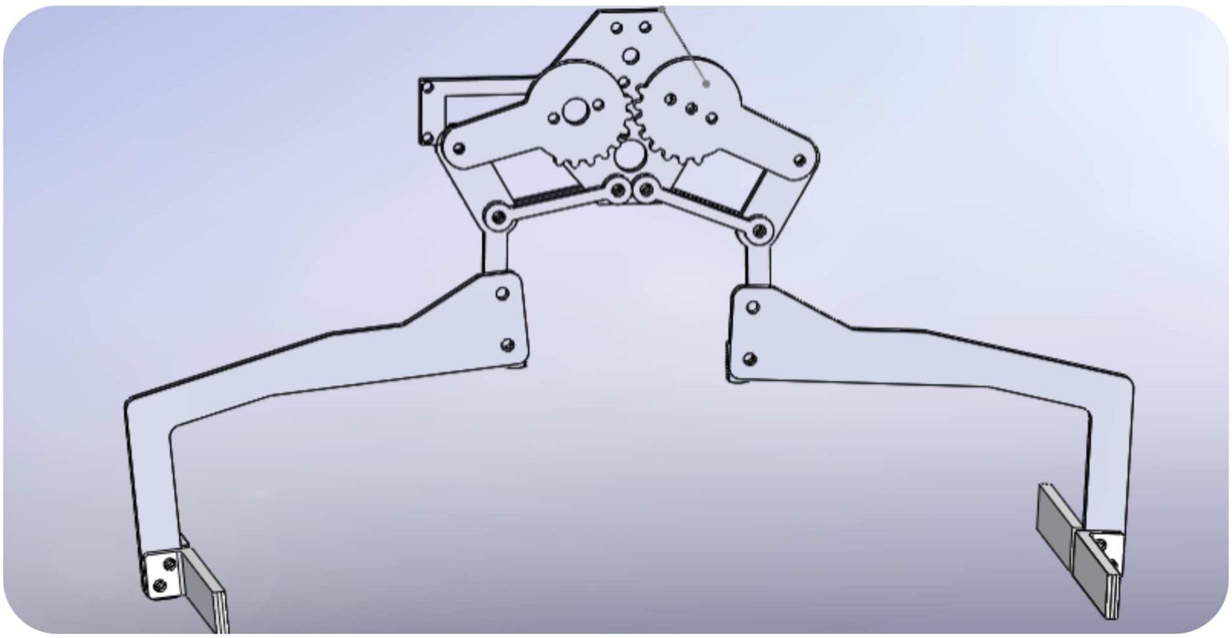

FIGURE 8: FLAT-ARM DESIGN VARIATION

FIGURE 9: FLAT-ARM COMPATIBLE PAYLOAD

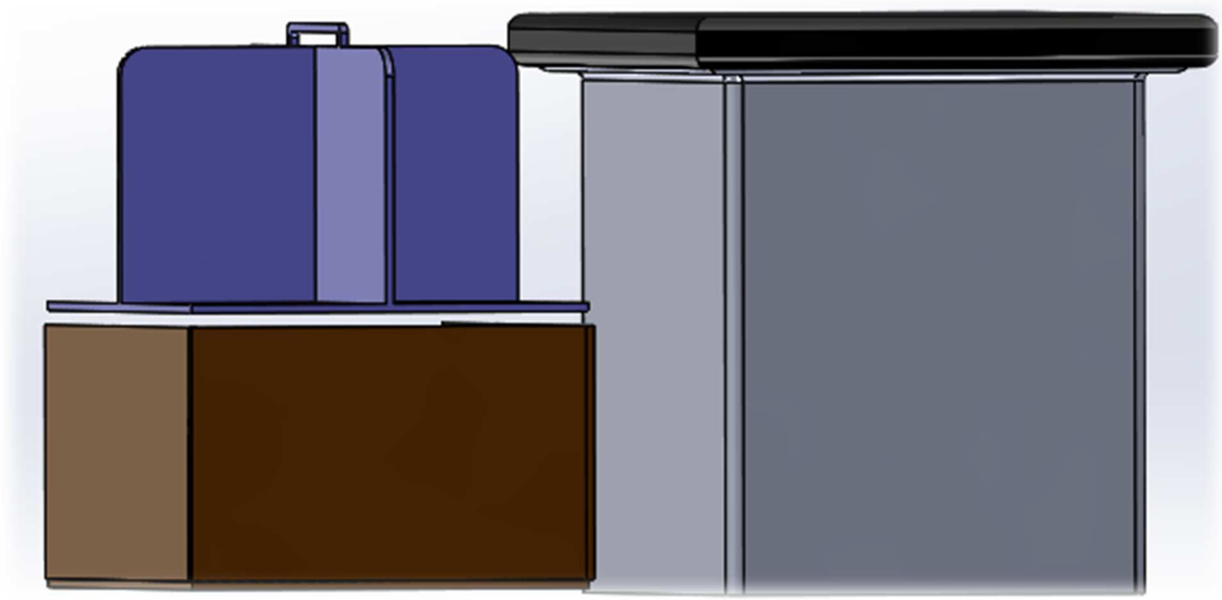

FIGURE 10: FLAT-ARM COMPATIBLE PAYLOAD AND INTERNAL COMPARTMENTS (LEFT)

The flat-arm variation was designed and meant to be safer, more reliable, and more aesthetic. This design would pick up a simple payload, shown in Figure 7 above. Unfortunately, after the conceptual design, the team determined the flat arm design would fail to protect the payload on all four sides of the payload. As you can see, the flat arms would contact the payload and squeeze from only two sides, thus leaving two of the four sides vulnerable.

4.2.3 Preliminary Design No. 3

The third design was designed based off of making the strongest and safest arm design while still achieving cost efficiency. This design was successful in terms of strength because the branch of the arm was reinforced with cylindrical extrusions designed in a grid pattern on the sides of the connecting arm. This allowed for the design to withstand a much higher stress and strain. A higher stress-strain tolerance meant more reliability of the UAV arm. This design works very well in terms of guaranteed reliability while under maximum load. Due to the cylindrical grid pattern, when the arm is under high stress and strain the arm will not bend as much. Ultimately, the grid relieves the main branch by providing reinforcement under heavy loads. This design achieved cost effectiveness, strength expectations, and reliability.

FIGURE 11: CYLINDRICAL GRID REINFORCED ARM DESIGN

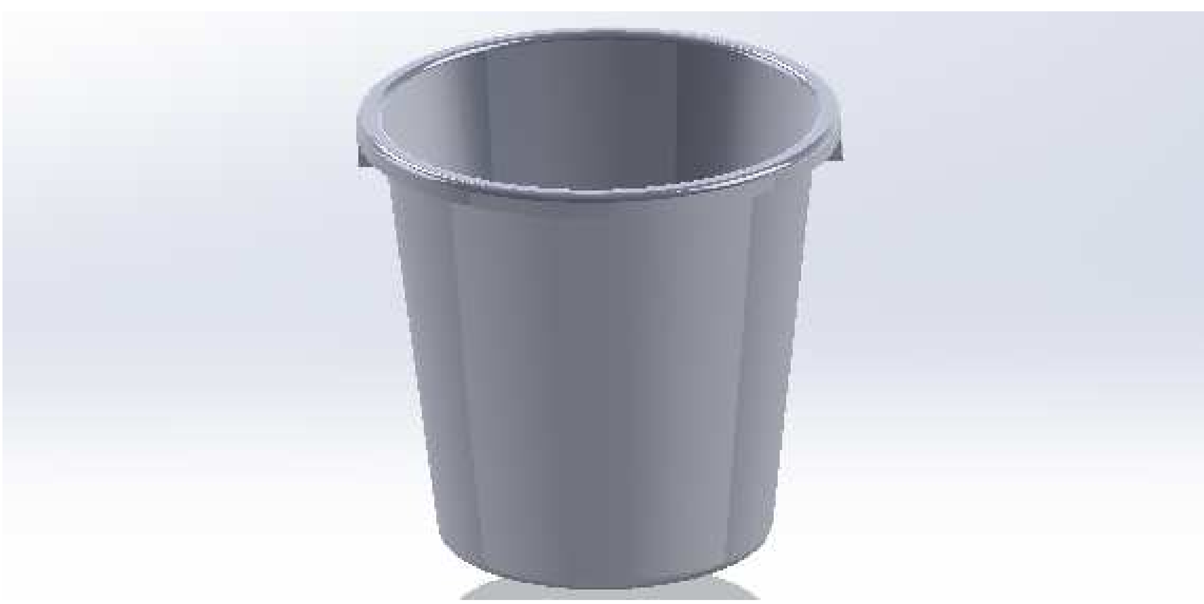

FIGURE 12: ROUND-ARM COMPATIBLE PAYLOAD DESIGN

The reason for continuing with other design variations and not settling with this design is because the team wanted to design grippers that have more compatibility for payloads. These rounded grippers are compatible with a payload that is rounded and shaped like a bucket. The team wanted to design something more compatible to allow for the potential need for transportation and delivery of various payloads. Thus, preliminary design no. 4 was produced.

4.2.4 PRELIMINARY DESIGN NO. 4

The next design was a variation of preliminary design no. 2 and 3, where the grippers are changed from being rounded to a more conventional flat gripper (as in design no. 2) with extensions added at a 120-degree angle. This design was geared towards payload compatibility and ease of use. This arm design is compatible with a flat-sided payload design. The flat-sided type payload design was considered rather than the rounded bucket-like payload due to ease of use and storage. A box-shaped payload will enable easier organization of the containing materials and will better fit the blood bags, thus having better storage. Compared to the other designs, this one has conceptually accomplished more objectives than any other design. This design is meant for reliability, strength, compatibility or ease of use, and storage effectiveness. Additionally, this user-friendly design allows the recipient to open the payload with easy access to the nicely organized deliverables.

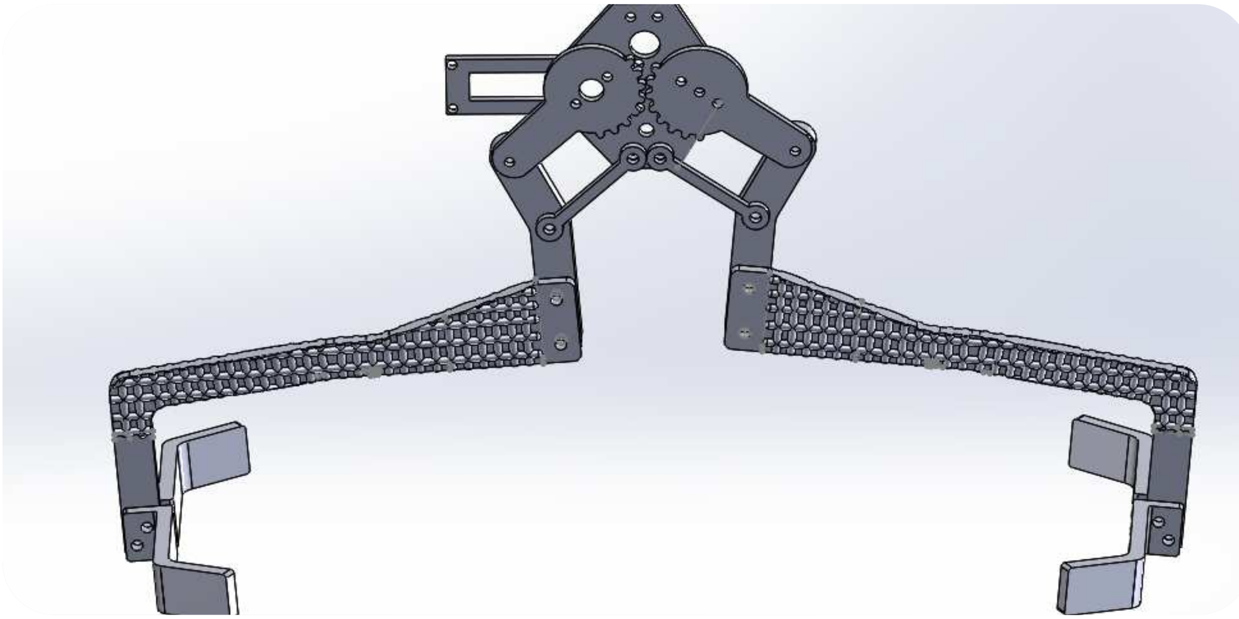

FIGURE 13: CLYIINDRICAL GRID REINFORCED ANGULAR ARM DESIGN

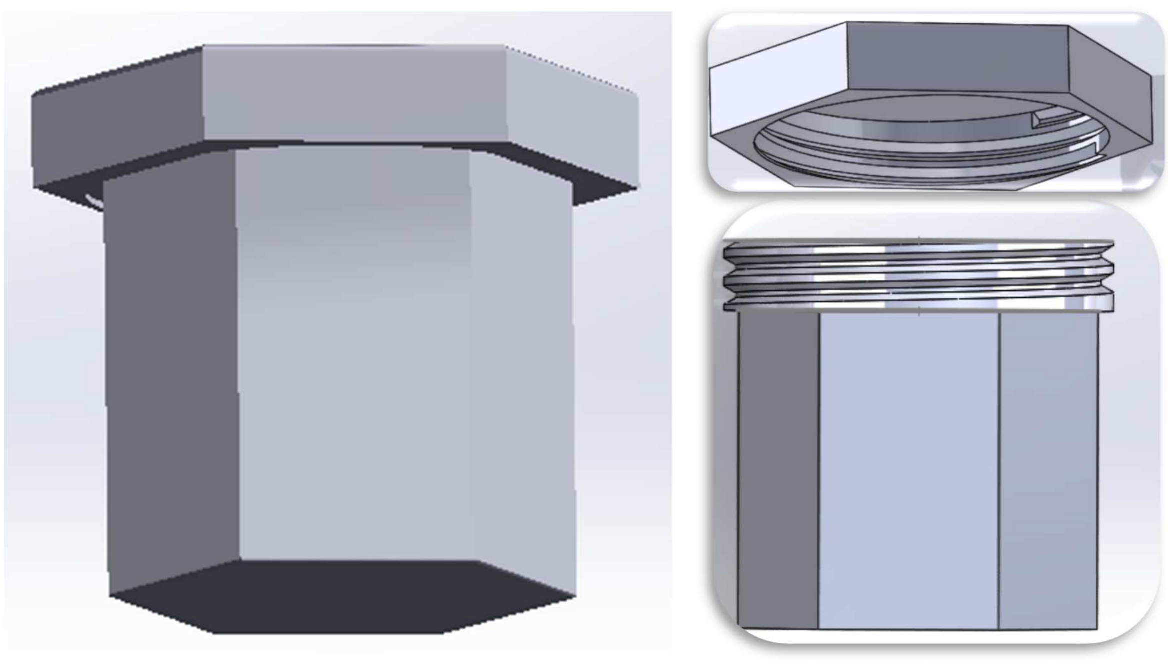

FIGURE 14: ANGULE-ARM COMPATIBLE PAYLOAD DESIGN

The reason the design team steered away from this design is because there were immediate problems with the design in terms of manufacturing and producibility. The design was not 3-D printer friendly with the available printers, thus resulting in poor-quality parts which would lead to a poor-quality prototype. The reason this design was not 3-D printer friendly with the available printers is because of the extruded grid pattern. Problems arose when printing the pattern and forced the team to steer away from this design. Additionally, another design constraint that presented itself was the low amount of strength at the connection of the branch and the grippers. Although the branch could withstand a higher load, the connection between the branch and the grippers must be addressed. To address these issues preliminary design no. 5 was created.

4.2.5 PRELIMINARY DESIGN NO. 5

Ultimately, preliminary design no. 5 was created to address manufacturing issues, and to confirm the UAV arm reliability. To ensure the arm's strength and reliability, this design incorporated a triangular gap in each arm to create a stronger, more reinforced arm when under loading. Below, in Figure 13, is the final UAV arm design for prototyping.

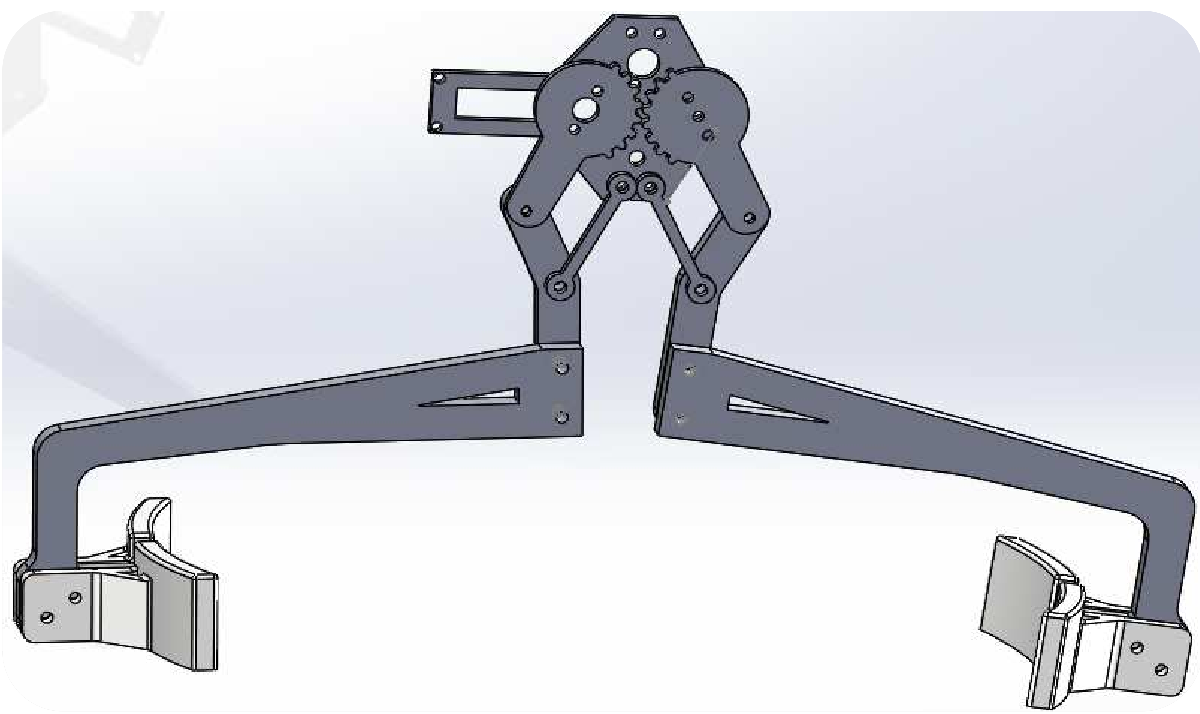

FIGURE 15: FINAL ARM DESIGN

FIGURE 16: FINAL PAYLOAD DESIGN

The final design for the payload was halted, hindered, delayed, and ultimately prevented from proper prototyping and development due to budget constraints. Thus, the above payload design, shown in Figure 14, is the design that the team used for prototype testing. Among budget constraints were also time constraints. This bucket design was found in a local retail store which allowed the team to save time and money by buying it instead of manufacturing it. Overall, time was saved for the prototype testing of the UAV by purchasing a bucket similar to this one.

However, before prototyping the designs, a very important step of the design process was carried out. This step involved analyzing and comparing the existing design alternatives to ensure the design choices were being made with educated decisions backed by standard engineering design procedures. This step is crucial in determining the best design in terms of design objectives, functions and constraints. This very important step will be delved into in the next section.

4.3 Analysis of Design Alternatives

4.3.1 Trade-off Analysis

To appropriately select the final design of the prototype arm there were a series of steps taken to evaluate the functionality and overall pros and cons of each prototype so that each preliminary design could be ranked accordingly. One of the first methods used to analyze the different designs was the Initial Design Alternatives Matrix shown below in Table 3. The purpose of this method is to get an idea of how effective each design is overall in terms of design constraints and design objectives.

Table 3: Initial Design Alternatives

	Design Alternative				
Design Constraints (C) & Objectives (O)	Design 1	Design 2	Design 3	Design 4	Design 5
C: Safe	x	✓	✓	✓	✓
C: Biocompatible	–	✓	x	✓	✓
O: User friendly	–	70	–	60	60
O: Cost Efficient	–	20	–	30	80
O: Reusable Payload	–	70	–	80	80
O: Reliable	–	50	–	60	40
O: Durable	–	60	–	60	50
O: Prototype-ability	–	30	–	20	80

This table depicts the design alternatives rated based on a numerical evaluation matrix. The numerical rankings were determined by the team and were based on specific team constraints and requirements. The first design alternative was a good start, but it does not meet the constraint of safety. The arm is too small for safely securing the payload so it is ruled out as an alternative design. The second design alternative had fairly low ratings in terms of cost, meaning it would have been too expensive to produce a prototype of the alternative under the constraints of the budget. The payload associated with this design was far too costly to manufacture in China and would have taken a substantial amount of time. This forced the group to focus more heavily on the design of the arm. The third design alternative was very simple, easy, and cost effective, but due to an issue with 3-D printing the arms, this design was incapable of being printed. Additionally, the poorly 3-D printed arm for this design would cause safety issues and would jeopardize the payload. The fourth design was user-friendly and reliable, but this design was far not cost or time efficient in terms of producing a payload prototype in China. The last design met both constraints, and due to other constraints, the cheapest payload was chosen to prototype and test due to convenience and cost efficiency. Also, the team was focused more on the design of the arm, so the fifth design alternative is the design the team proceeded with. Once the team decided on the arm design, the team used a rank-order matrix to determine the overall UAV design objectives, shown below in Table 4.

Table 4: Rank-Order Matrix

	Design Objectives				
Team Member	Battery Life	Biocompatibility	Weight	Cost	Size
Joseph	5.5	6	4.5	3	1.5
Liu You Zhi	2.5	4	3.5	4.5	2.5
Zhao Ming Huang	4	4.5	3.5	5.5	0
Chen Xiao Kui	6	5.5	4	4	0.5
Total	18	20	15.5	17	4.5
Rank	2	1	4	3	5

The final design for the UAV was determined after the trade-off analysis was performed. To perform this analysis the numerical evaluation matrix and rank-order matrix was used to ensure the most important objectives were being considered. After using these methods, the final design alternative that best accomplished the design objectives was design no. 5. After choosing the final design the team then began analyzing the design and prototyping.

4.3.2 CONCLUSIONS FOR FINAL DESIGN

In summary, the goals for the final arm and payload design were achieved by designing a drone-attachable arm to allow a package to be carried. The chosen UAV arm design successfully demonstrates the ability to carry and deliver medical supplies contained in the designated payload. This final design allowed for achieving a working prototype to demonstrate the concept feasibility. Concluding with this design, the team worked toward ordering materials and fabricating the prototype. Figure 17 below illustrates the fabricated final prototype.

FIGURE 17: FINAL PROTOTYPE FABRICATED

4.4 ANALYSIS OF FINAL PROTOTYPE

4.4.1 SOLIDWORKS MODEL

By using SolidWorks, a three-dimensional, multipart design could be produced. Because the basis of this project was to create a dynamic UAV arm and payload, the design of the UAV's structure was required to ensure design-design compatibility. SolidWorks models of the final UAV arm, payload design and models of the drone's structure are shown below.

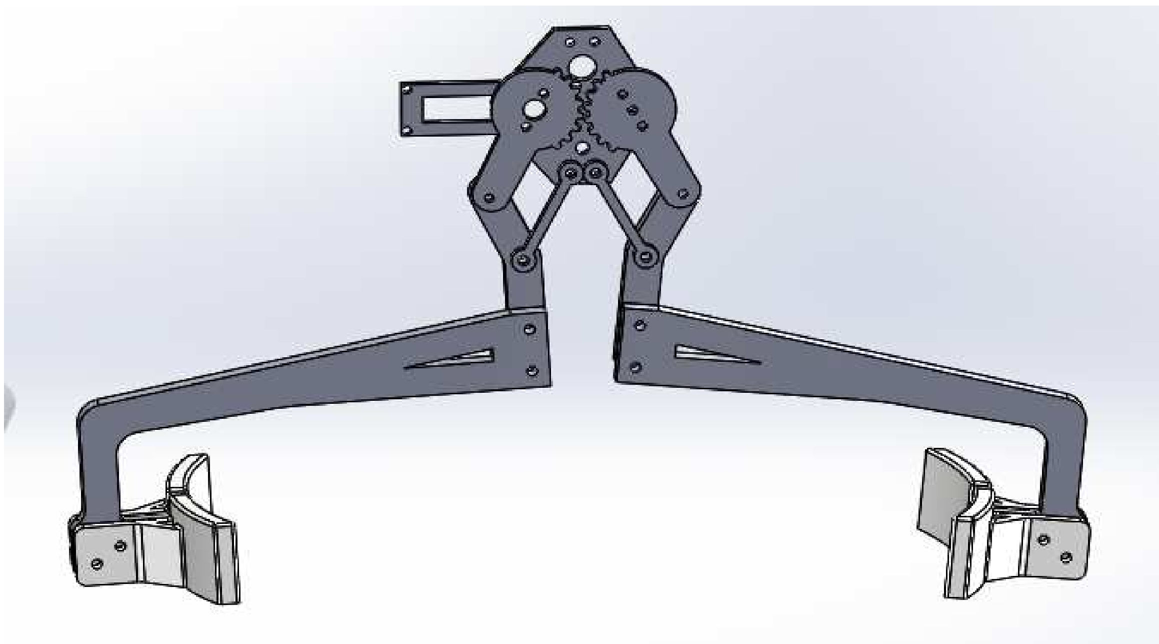

FIGURE 18: FINAL DESIGN

4.4.2 FINITE ELEMENT ANALYSIS

Finite element analysis was necessary because it allowed the team to analyze the design under experimental conditions before actually producing the prototype. First, there was a basic content analysis performed. To do this the team used SolidWorks to design three-dimensional map of parts, and then the three-dimensional map was imported into ANSYS finite element analysis software to allow for the stress, displacement distribution and variation of parts analysis to be performed.

Moreover, the methods of this analysis are important to reproduce the results. The application of the ANSYS software was used to model parts of the finite element analysis, the distribution and variation of stress and displacement. Finite Element Method today, has become a very complex practical engineering techniques. ANSYS features a financial structure, thermal, fluid, electromagnetic and acoustics all in one large finite element analysis software. It can be widely used in aerospace, machinery, automobile transportation, electronics.

The technical route taken describes the use of SolidWorks to design parts of a three-dimensional map to import into ANSYS software, finite element analysis and its parts to optimize the structure, and summarizing conclusions. The main problem to be solved was establish a grid model parts using ANSYS software for finite element analysis mesh model. Below is the part being analyzed and a brief part description.

The material used for the part is PLA (polyactic acid), a material commonly used to 3D print CAD drawings. Shown in Figure 13, there are four small hole on the right side of the two circles bear a fixed load, the right half of the left side of the two circles to the right to bear uniform load q = 0.5MPa. Material properties of the modulus of elasticity E = 2.7GPa, Poisson's ratio of 0.3, a thickness t = 7mm.

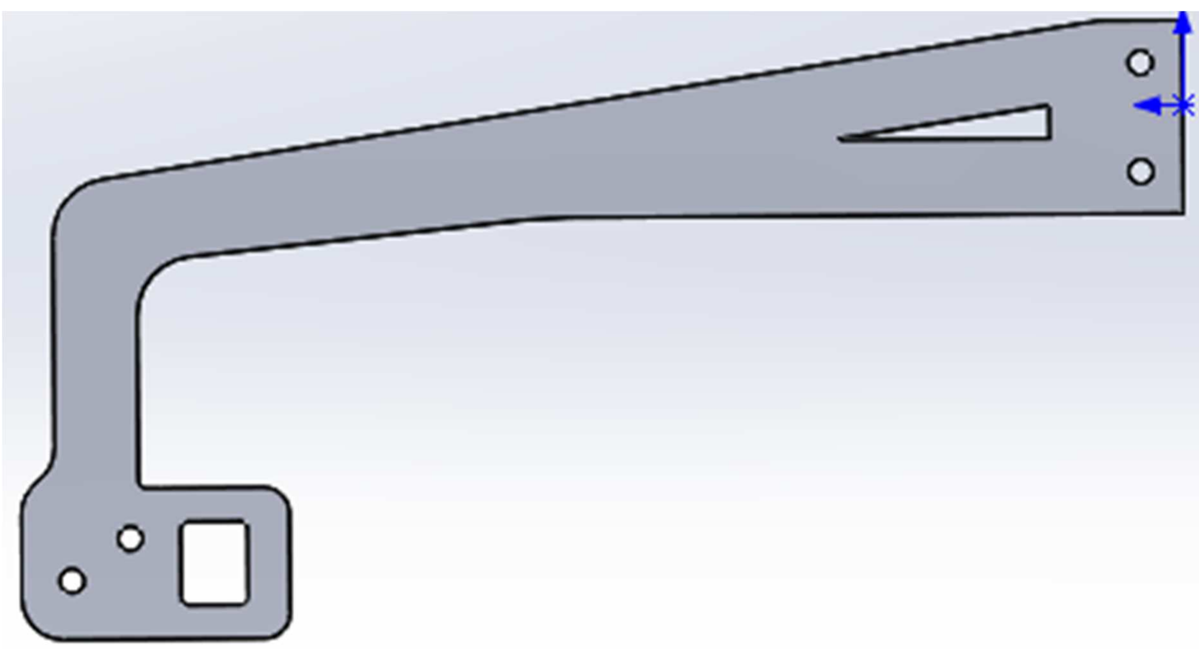

FIGURE 19: ARM CONNECTING MEMBER

4.4.3 Stress & Strain Analysis

Below are two images produced from running FEA on the part described in the previous section. The figures below show the stress and strain analysis done in ANSYS. They depict a finite element analysis of how the part would act under loading. This analysis is very helpful in determining if the design will fail. Shown in Figure 17, below, is the Von Mises Stress analysis. This figure depicts if the part is designed well or not. As you can see, the part does not have any red or orange colored areas on it and, thus, demonstrating a well-designed part. The stress diagram shown below shows a range of stress, where dark blue is the least amount of stress and red is the highest stress. The warmer the color appears the more susceptible that specific area is to failure and alternatively, dark blue represents the least vulnerable areas.

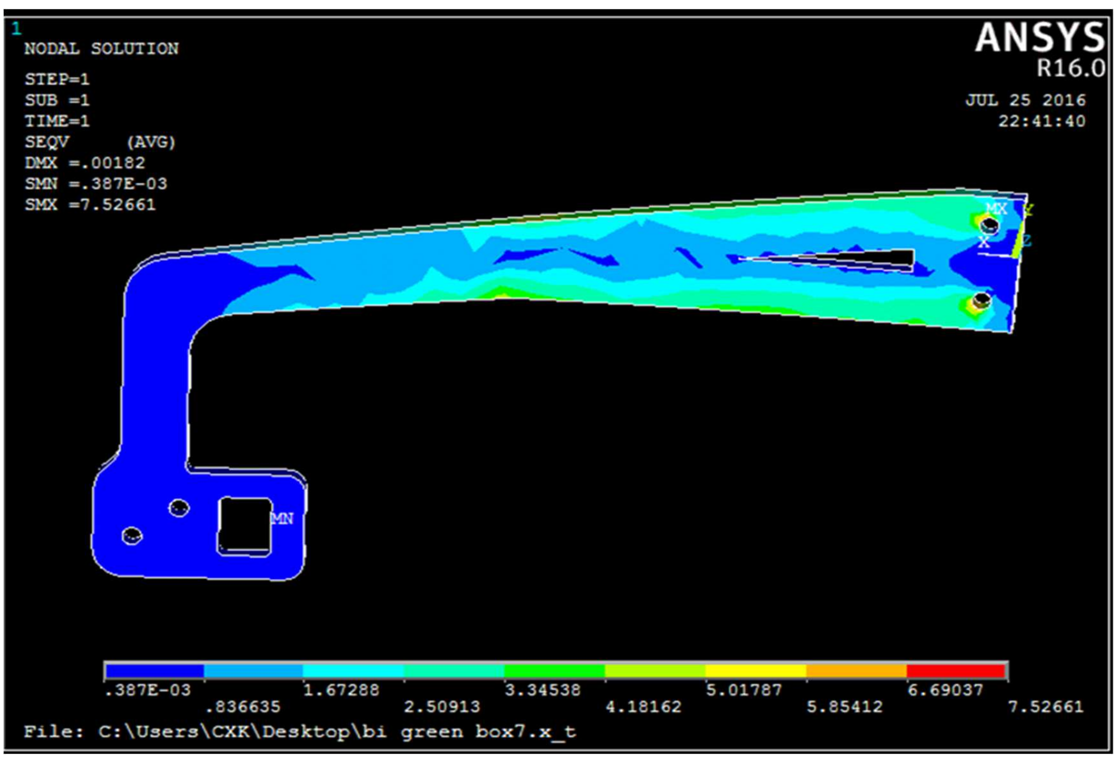

FIGURE 20: FEA ANALYSIS

By using the software known as ANSYS to perform a finite element analysis of the main load baring component, the team was able to foresee potential failures. The material being used is PLA, which has a maximum allowable stress of 107MPa, a modulus of elasticity of 2.7GPa and a Poisson's ratio of 0.3. The actual stress for the design was found to be 7.5MPa, comparing this to the maximum allowable stress we can say that our connection arm has sufficient strength. The figure below illustrates what the part will look like during maximum displacement before failing.

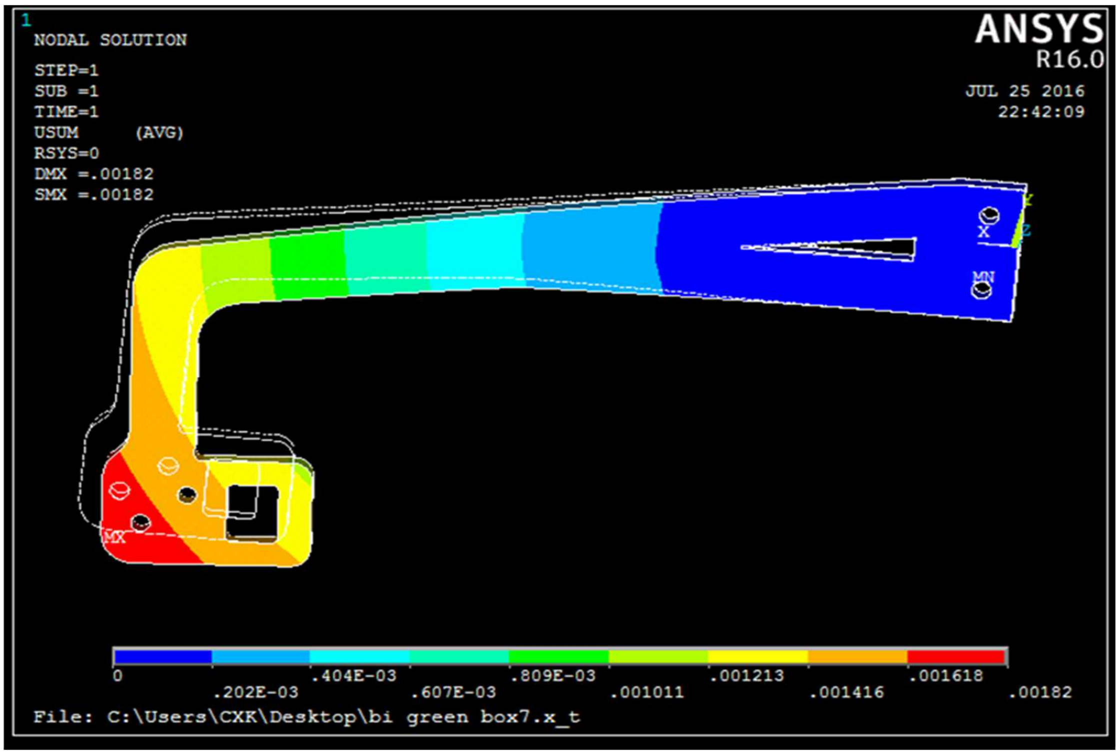

FIGURE 21: FEA ARM DISPLACEMENT

Since the main weight baring component of the arm attachment can withstand a sufficient amount of displacement with respect to the total load, the FEA analysis confirms that the design is sound. Only under excessive loads will the part fail, causing overall system failure. If the design was to be implemented into the market, the limitations would be clearly stated so that the consequences of exceeding the maximum load would be understood.

5 RESULTS & DISCUSSION

Before conducting tests, the team made necessary assumptions to obtain feasible results. Some assumptions made include: ideal weather conditions during flight, ignore force endured due to take-off acceleration, ignore drag, assume that battery charges/discharges at constant rate. Knowing the device requirements, the team set up for prototypes testing. After testing, the team reviewed the performance to see if any specifications were not met. The device specifications and goals are below in Table 10.

Table 5: Device Specifications Results Summary

Specification	Required Performance	Drone Prototype 1 Met?	Final Drone Prototype Met?
Airspeed	10 – 40 m/s	Y	Y
Loading	5 kg ≥	N	Y
Flight time	≥ 30 minutes	N	Y
Distance	5 – 10 km	Y	Y

The design team first validated the individual components of the device before assembling the device so that a better understanding of the outcome would be hypothesized. The design team tested the functionality and strength performance of the arm attachment by picking up a 5L bucket of water (shown in Figure 21 below).

FIGURE 22: ARM ATTACHMENT STRENGTH VALIDATION

After completing flight tests for the two prototypes, the group collected experimental results shown below in Table 11. The two prototypes produced expected results. The first-generation prototype was only able to carry 3.2-kg of weight, which was not satisfactory and did not meet the design specifications. After redesigning for the second prototype, the final UAV was able to carry 5.1-kg which satisfied the specification of a 5-kg maximum load. Table 11, below, illustrates the experimental data collected by the team.

Table 6: UAV Prototype results

Experimental Results		
	First Generation	**Second Generation**
Max Load	3.2 kg	5.1 kg
Duration No load	10-12 minutes	30-35 minutes
Duration Max Load	3-5 minutes	10-14 minutes
Airspeed	5-20 m/s	5-20 m/s
Distance max load	6 Kilometers	16.8 kilometers
Distance no load	14.4 Kilometers	42 Kilometers

The results produced from testing the two prototypes suggest that both prototypes are successful in providing a concept feasibility, but the first-generation prototype just needed a larger battery and larger motors. The maximum load was tested by filling up a bucket with water and attempting to take off from the ground. Prototype 1 and 2 failed to lift off the ground after 3.2-kg and 5.1-kg respectively. To test the duration with and without a load, the group flew each prototype until its battery died. For airspeed, the software being used reported the airspeed on the user interface, and the group recorded the respective airspeeds. For maximum distance traveled with and without a load, the group used the time in flight and the average airspeed to calculate the distance it will fly. The prototypes used Bluetooth, therefore calculating the max distance was the alternative to attaining these results since Bluetooth would not allow the prototypes to fly to their maximum allowable distance. Additionally, the cost of both prototypes was closely analyzed and is illustrated below in Table 7.

Table 7: UAV Prototype Cost Comparison

First generation				**Second generation**			
Component	Cost	Qt.	Total	Component	Cost	Qt.	Total
Remote control /Receiver	745	1	745	Remote control /Receiver	745	1	745
Video Transmission	479	1	479	Video Transmission	479	1	479
APM&GPS	310	1	310	APM&GPS	310	1	310
Charger	155	1	155	Charger	155	1	155
ESC	58	6	348	ESC	58	4	232
Motors (kv750 U2810)	133	6	798	Motors kv340 U4110	268	4	1072
Prop	4	6	24	Prop (Carbon fiber)	50	2	100
Battery 4s 5200mAh	245	1	245	Battery 6s 12000mAh	820	1	820
Stand	170	1	170	Stand (Carbon fiber)	600	1	600
	Total Cost		**¥3274**		**Total Cost**		**¥4513**

Overall, the results were as expected and produced promising numbers. The team was happy about the performance results in correlation to the cost of production because the final prototype was only ¥1239 more expensive than the original prototype, and it produced far greater results in correlation to the cost of production. According to the results, it is clear that the second-generation prototype satisfies the specifications and thus successfully demonstrates concept feasibility.

5.1 REGULATORY ISSUES

The UAV prototype uses a combination of many different existing UAV designs and parts that have been designed already. For example, the quadcopter design is very common, and the software and hardware used are all things that have been designed and patented. This means that by benchmarking other designs, it ensures the prototypes being produced comply with regulations and engineering standards. Also, these benchmarked designs may be patented so this means that the project team cannot legally own these parts, but as a whole design together can be patented since this exact design and creation is unique to this project. Other legal associations for the medical drones concern the U.S. government regulations. Concerns for the device would include whether it is reliable to use and whether it was safe to use. It is in the project team's best interest to meet as many constraints as possible with the design. With future projects, more field and lab experiments can be performed to ensure the design meets all constraints.

5.2 ETHICAL ISSUES/ENVIRONMENTAL IMPACT

There were many ethical considerations to take into account for this device. The design of the device is not necessarily invasive, life-threatening, or morally questionable, but there are a few ethical issues that must be considered. The most important objective for this device was that it has to be safe, and the team argued that this was even a constraint of the device. If the device is not safe, it is not a successful device. Therefore, if the device does not preserve the blood and medicine by preventing contamination, and physical or chemical damage, it is not a safe device. If the contaminated/damaged blood was accidentally transfused to a patient, it could have potentially harmful effects on the person. This device had to be safe enough to store the blood for up to 1-hour in the climate of China. Thus, the insulated payload was used to maintain internal payload temperature. Theoretically, a Styrofoam-like material is used to perform this function.

Moreover, an important consideration for the prototype would be if the device failed while in use. To avoid this, the design should predict potential modes of failure for the device. Some types of failure may be generated form low battery, failure due to inadequate material strength and fatigue, loss of Bluetooth connection, or any other electrical failure. An external temperature gauge could be added to the outside of the payload to indicate internal temperature. This function would help the user to protect themselves against potentially harmful blood even if the device failed in its foremost function of keeping the blood cool and safe. The team worked to prevent failure but if the device does fail during tests, precautions, such as implementing safety protocols, can be considered to ensure patient's wellbeing. Furthermore, the addition of safety protocols helps the team avoid any potential ethical conflicts in respect to the device.

6 RECOMMENDATIONS AND FUTURE WORK

The following recommendations are influenced by the nature of moving towards increased manufacturability and sustainability for future prototypes. The process in which the Medical UAV is manufactured is not optimal. In this respect, future designs of the device should consider ease of manufacturability. Fortunately, the components such as the battery, brushless-motors, Arduino-Uno, and GPS module are all items that are easy and cheap to acquire. Despite this, these parts do not all come from the same source, and they create a lot of components that must be fit together to create the final working prototype. In order to make this device easier to manufacture, it could be designed and sold as a kit that comes in parts in a box. This kit would include all parts for assembly. Connecting wires would be soldered to ensure circuit connection and can be contained within the body of the UAV in a protective unit – perhaps waterproof.

Additionally, the consideration of alternative power supplies and charging modules would be of benefit since the current battery is very large and bulky. The potential for solar power implementation should be considered to give the prototype charging capabilities. The payload, when delivered should come with a concise, simple instruction manual with visuals to show how the patient is to use the containing elements. The payload should be further investigated for reusability. Perhaps the medical UAV delivery system involves dropping a biodegradable payload. This would not only be environmentally friendly, but will also reduce the amount of time it takes the drone to drop the package and continue to its next delivery.

Other improvements and future work include improving the mechanical and biomedical designs implemented in the current UAV. Additionally, the future team should consider a fixed-wing design to increase the distance that can be traveled. Furthermore, adding a GPRS to use instead of using a Bluetooth module will enable long distances to be traveled. The material of the drone arm should also be improved upon since the material used was PLA to allow for the 3D printing and rapid prototyping of the design. The arm might also be improved if carbon fiber or a light weight, durable metal alloy is used. Moreover, the next group should consider changing the flight control unit from APM to PixHawk. Pixhawk will improve data transmission by increasing the speed of transmission and it is also functionally more compatible with a fixed-wing drone design.

Moreover, the team should also consider using a flight control unit that is closed source rather than open source because the respective company will offer tech support and the unit will be overall more stable and less sensitive than an open source unit. The future group should improve upon the battery life of the UAV to allow for further distances to be traveled. The team should also consider designing a payload that is specific for organ delivery, rather than general medical supplies. Dimensional analysis for multiple component sizes. The team should also keep in mind when designing the drone that the efficiency increases when the motor to motor distance increase, therefore, if a rotocopter is used then explore various motor to motor distances.

7 CONCLUSION

Overall, the basis of this project was to apply engineering principles and design concepts to drones, medicine and biology to improve healthcare accessibility in China. Through the design of a UAV, arm and payload, the transportation of medical and biological components is feasible. The use of UAVs for medical supply delivery will alleviate suffering and provide many Chinese citizens with the chance to recover from illnesses. In fact, research shows that “70.3% of people who need hospitalization [in China] had failed to be hospitalized because of the economic difficulty that doing so incurs” [38]. Medical supply delivery will significantly reduce the number of people who need to be hospitalized and, therefore, reduce the overall percentage and cost of medical services that comes with hospitalization.

In summary, there are many different medical needs across the remote areas of china, therefore, to adequately address the various needs there must be a medical drone network implemented to provide various supplies to people in remote areas. These supplies include blood, medicine, and portable medical equipment. Implementing a medical delivery system via UAVs would be helpful to an enormous magnitude of people.

In conclusion, this project provided insight on the feasibility of the goals set out to be accomplished. The team successfully designed and built a drone with an arm attachment to enable the transportation of medical supplies. Thus, the design and testing of the semi-automatic UAV successfully demonstrated the concept feasibility of implementing medical supply delivery drones in the healthcare system of China.

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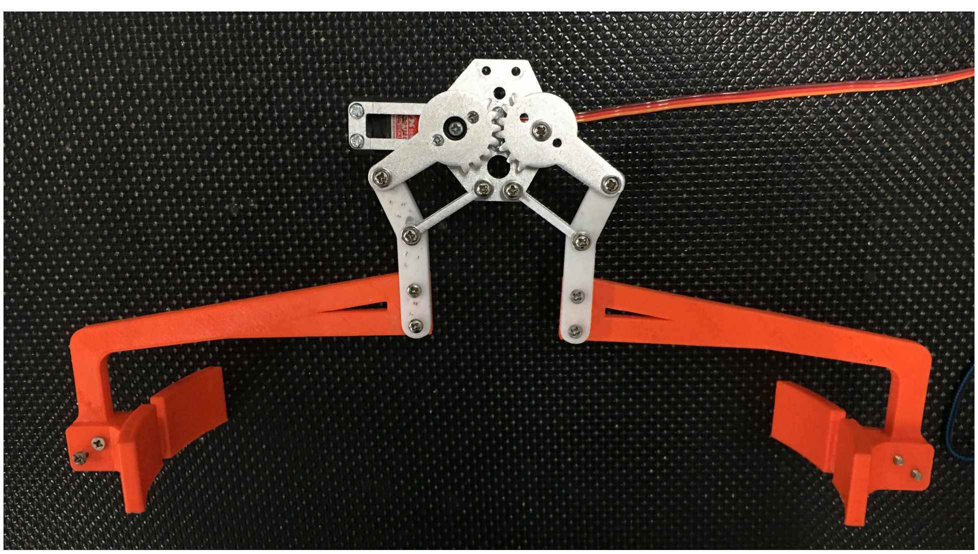
9 APPENDIX A

Prototype pictures and specs

This appendix shows various images of the UAV parts and UAV specs.

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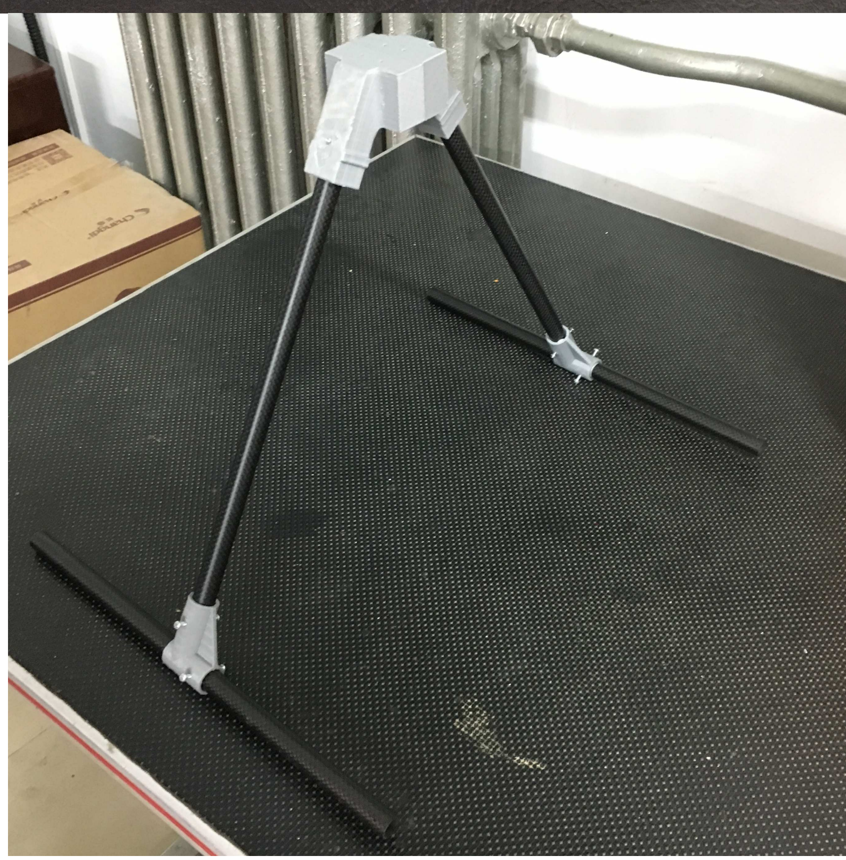

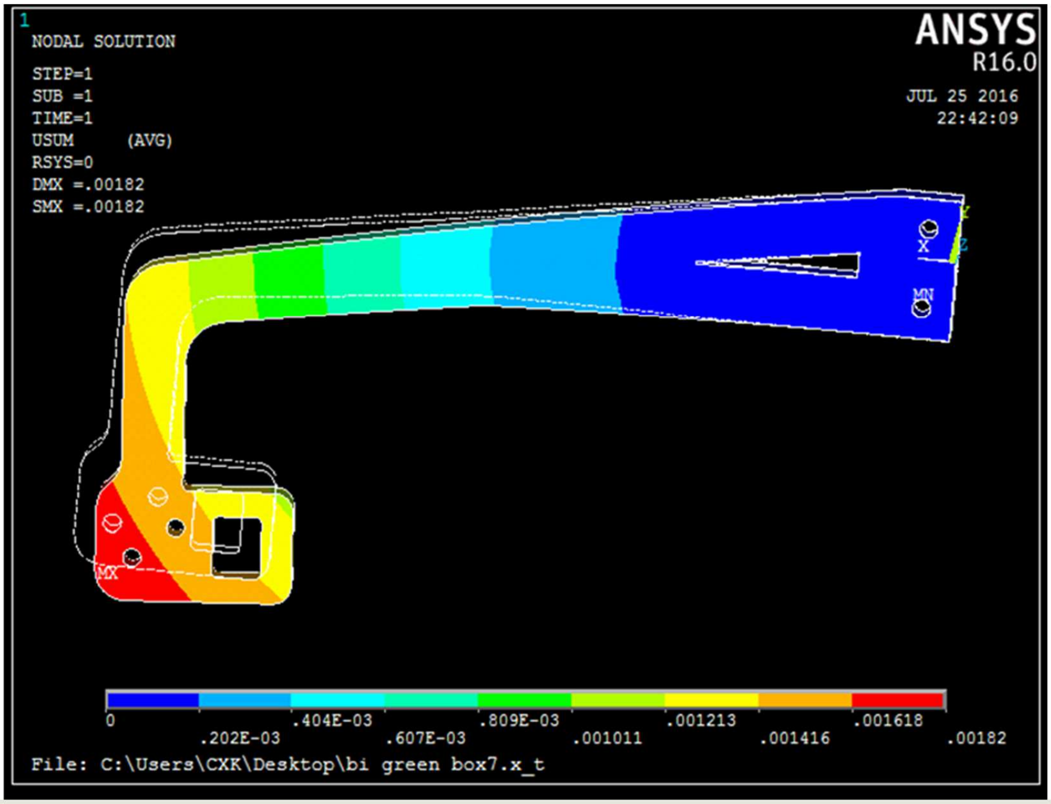
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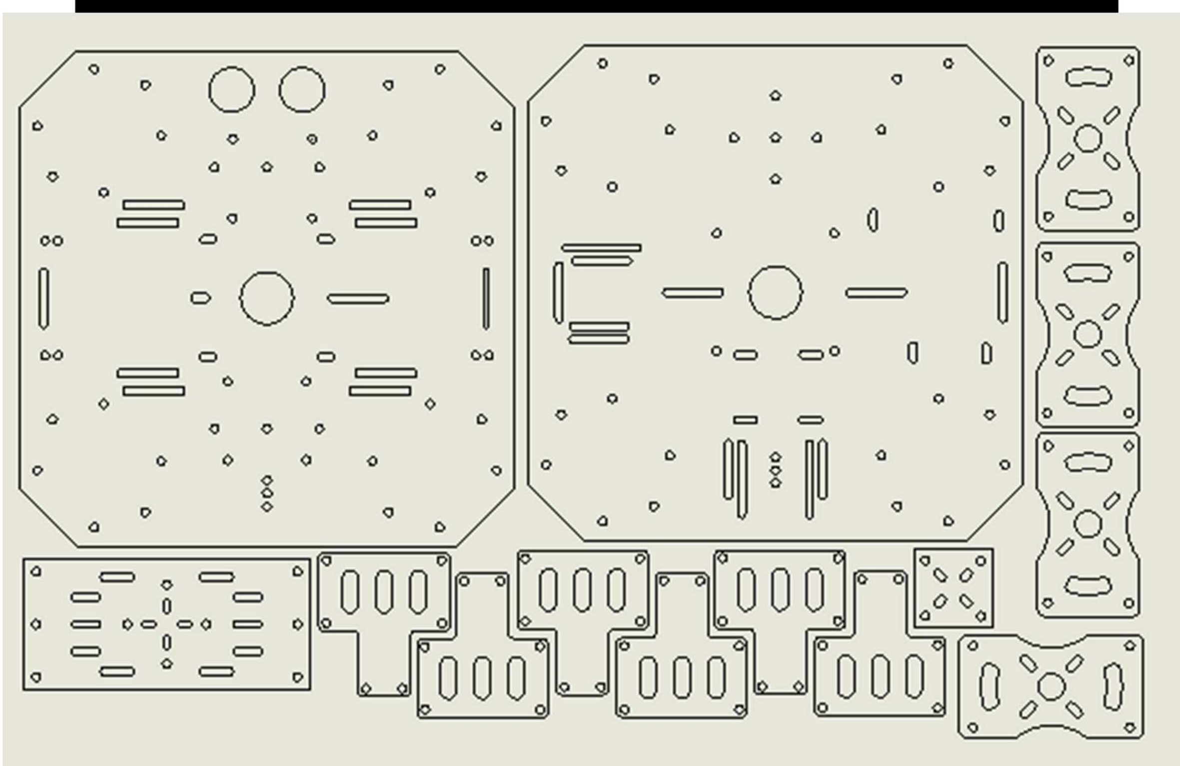
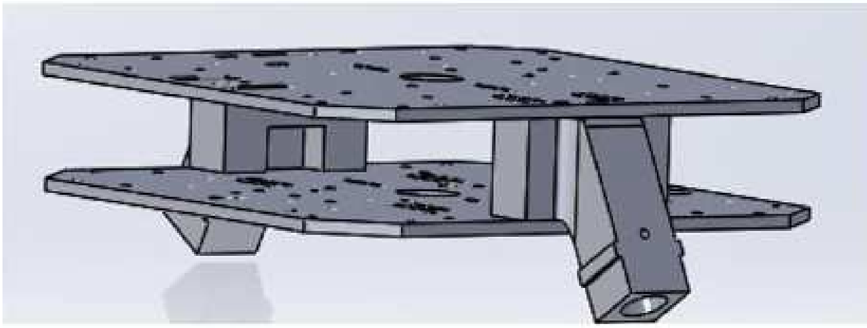
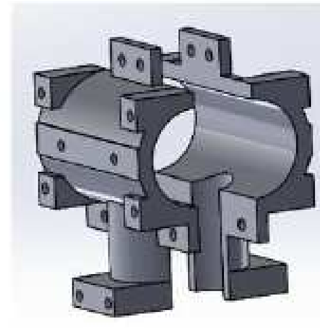
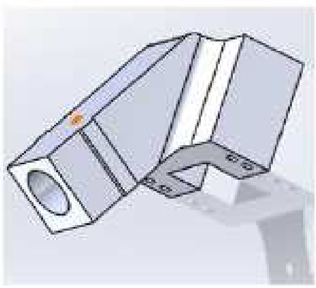
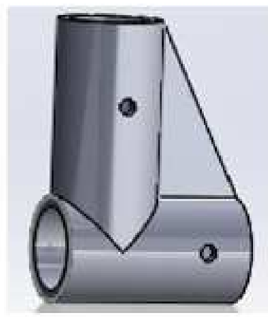
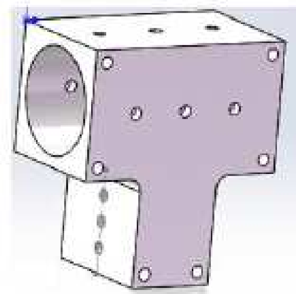


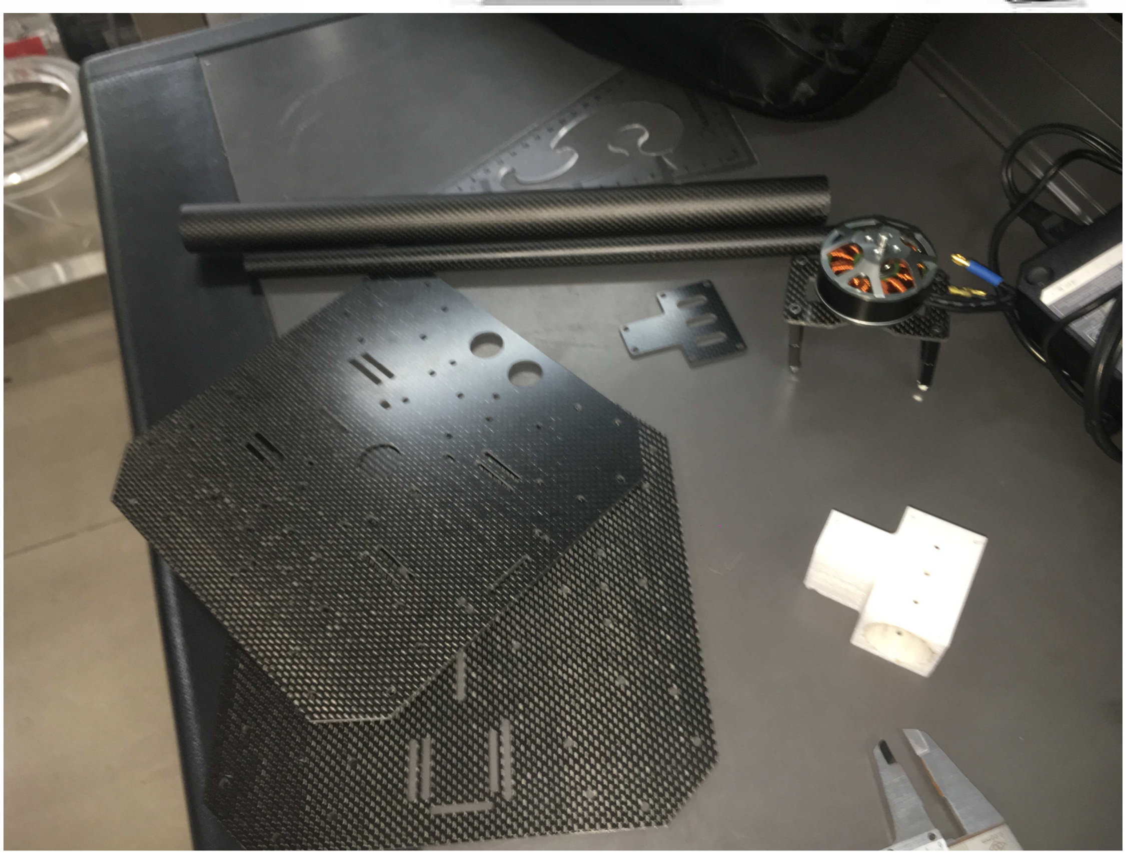












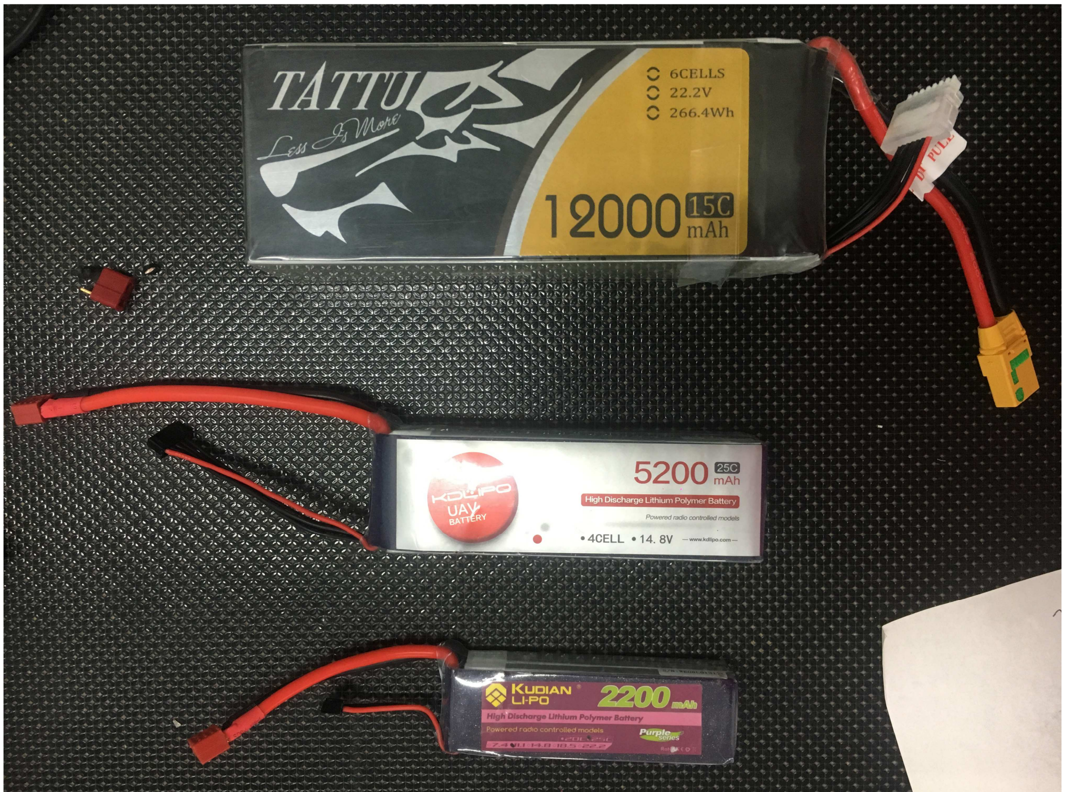

TATTU
Less Is More
6CELLS
22.2V
266.4Wh
12000 15C mAh
5200 25C mAh
UAV BATTERY
High Discharge Lithium Polymer Battery
Powered radio controlled models
4CELL 14.8V
KUDIAN LI-PO
2200 mAh
High Discharge Lithium Polymer Battery
Powered radio controlled models

Table 1A: Prototype Performance Specifications

Prototype Performance Specifications	
Weight (without payload)	3.15 kg
Payload Weight	5.1 kg
Battery life per charge	> 30 minutes
Circuitry	14.8V DC
Number of rotary motor units	4

10 APPENDIX B

Mathematical Equations Relating to Aerodynamics:

Lift:

$$L = C_L \text{ x } \left(\frac{1}{2} pV^2\right) \text{x } S$$

where, $S = wing\ area$

Drag:

$$D = Cd\ \frac{r\ V^2}{2}\ A$$

where, $Drag = coefficient \text{ x } density \text{ x } \frac{velocity\ squared}{2} \text{ x } reference\ area$

Vertical Ascent:

$$F_{net} = -W - D$$

$$a = -g - \frac{Cd\ \ A\ \ pV^2}{2}$$

$$V = V_t \frac{V_0 - V_t \tan\left(t\ \frac{g}{V_t}\right)}{V_t + V_0 \tan\left(t\ \frac{g}{V_t}\right)}$$

$$y = \frac{V_t^2}{2g} \ln\left(\frac{(V_0^2 + V_t^2)}{V^2 + V_t^2}\right)$$

Vertical Descent:

$$F_{net} = -W + D = 0$$

$$a = 0$$

$$V = V_t$$

Linear Acceleration:

$$a = \frac{v - v_0}{t}$$

Radial Acceleration:

$$a_r = \frac{v^2}{r}$$

Angular Acceleration:

$$\alpha = \frac{1}{r}\frac{dv}{dt}$$

11 APPENDIX C

Charts, Tables, and Other Graphically Relevant Information:

Table 1C: Description of hardware, controls and limitations of DSAAV UAV

	DSAAV
Hardware components	- GPS system – INS/GPS system to improve accuracy and stability of navigation (IMU and DGPS units) - Sonal altimeter – detects ground location during autonomous landing - Digital compass – compensates for IMU heading drift - 6 servos – controls actuation - Receiver interface – translates commands from control system to servos - On-board computer – processes guidance, navigation, control, and communication data - NiMH battery pack – powers equipment - Vision system – transmits live video to operator
Control Algorithms	- Navigation filter - Inner-loop control - Outer-loop guidance - Flight manager
Drone Capabilities	- Autonomous landing - Collision avoidance - In autonomous flight within 10 minutes of set up - Forward speeds of 20 ft/sec
Drone Limitations	- Powered for 60 minutes at a time

Table 2C: Variables in simplified components for dimensional analysis

Variable Units	*F [N]*	*p [Pa]*	*U[kg/(m)(s)]*	*p[kg/m^3]*	*V [m/s]*
Components	MLT^{-2}	$ML^{-1}T^{-2}$	$ML^{-1}T^{-1}$	ML^{-3}	LT^{-1}

Figure 1C: Refrigerated Vaccines
Retrieved from: http://www.cdc.gov/vaccines/hcp/admin/storage/downloads/temp-fridge.pdf

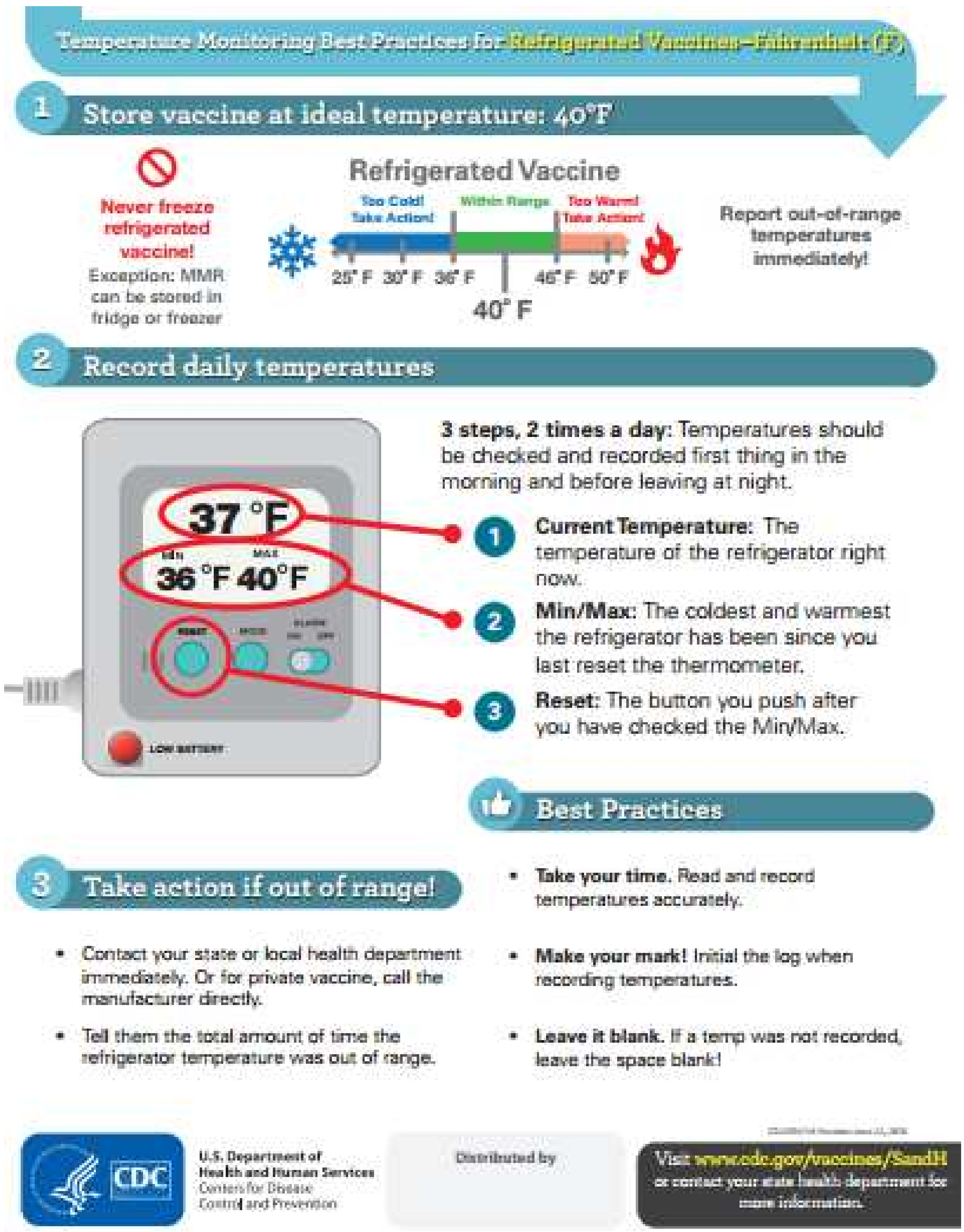


Figure 2C: Frozen Vaccines
Retrieved from http://www.cdc.gov/vaccines/hcp/admin/storage/downloads/temp-frozen.pdf

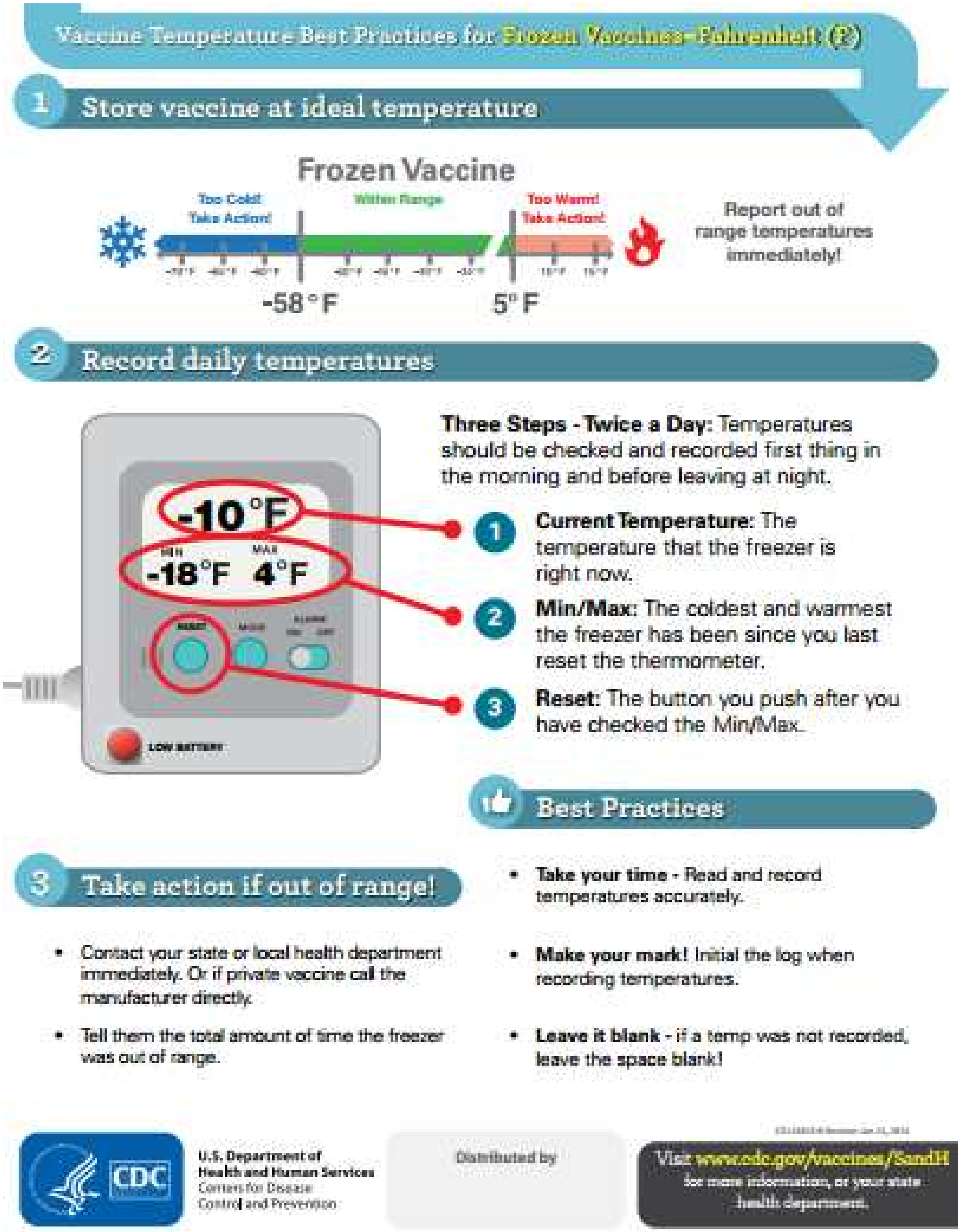


Table 3C: Blood Transfusion Blood Type Preferences

ABO phenotype of the recipient	ABO phenotype of units to transfuse (in order of preference)
O	O, A, B, AB
A	A, AB
B	B, AB
AB	AB

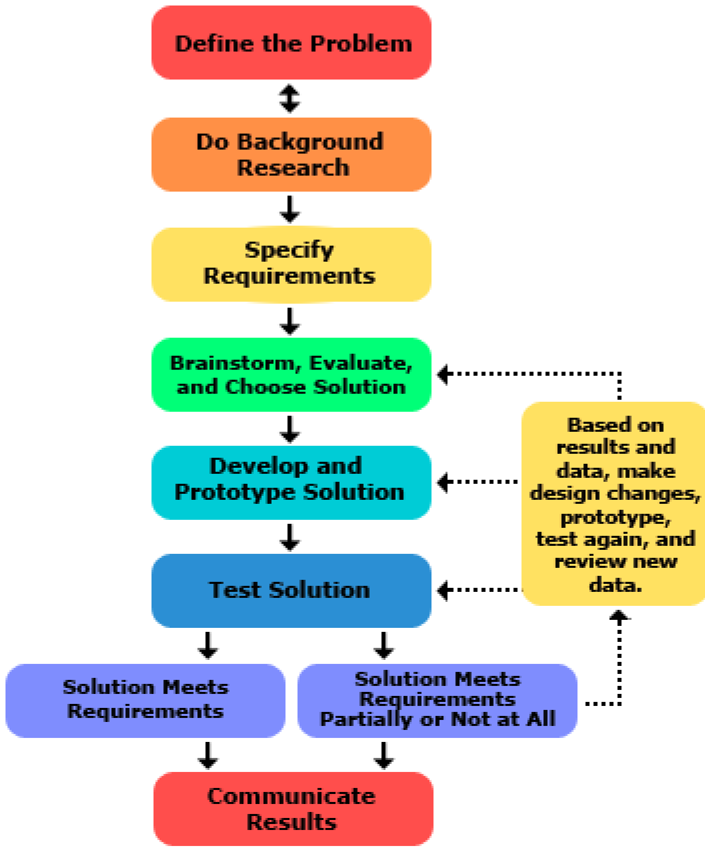
(Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2689068/)

Table 4C: Compositions of Preservatives/Anticoagulants for blood storage

	ACD (acidifieditrate dextrose)	**CPD** (citrate-phosphate-dextrose)	**CP2D** (citrate-phosphate-2-dextrose)	**CPDA-1** (citrate-phosphate-dextrose with adenine)
Trisodium citrate (g)	22.0	26.30	26.35	26.35
Citric acid (g)	8.0	3.27	3.27	3.27
Dextrose (g)	24.5	25.50	51.10	31.90
Monobasic sodium phosphate (g)	-	2.22	2.22	2.22
Adenine (g)	-	-	-	0.27
Distilled water (ml)	1000	1000	1000	1000
Preservative (ml) / 100ml blood	15	14	14	14
Preservative (ml) / 450 ml blood	67.5	63	63	63
Initial pH of preservative	5.0	5.6	5.6	5.6
On first day pH of blood in bag	7.0	7.2	7.4	7.3
Storage time (days) at 2-6 °C	21	21	21	3

(Retrieved from http://www.mahasbtc.com/preservation-and-storage-blood)

Table 5C: The Engineering Design Process



12 Appendix D

Definitions, Explanations and Additional Literature:

This appendix references the full definitions for various processes and regulations.

The Fourth Amendment provides

The right of the people to be secure in their persons, houses, papers, and effects, against unreasonable searches and seizures, shall not be violated, and no warrants shall issue, but upon probable cause, supported by oath or affirmation, and particularly describing the place to be searched, and the persons or things to be seized.

Whole Blood Separation Process

Blood collected as whole blood into bags with anticoagulant and nutrient phosphate. The whole blood is centrifuged to separate the components based on size. The heavy red cells become concentrated together and can be seen at the bottom. To separate, two methods may be used: The buffy coat method or the platelet-rich method. The platelet-rich method loses some platelets while the buffy coat method loses some red cells. Another method may be used, which is much more expensive, called the apheresis method.

Lesion of Storage: Importance of Factors that Influence Blood Viability

Decrease in pH

When blood is stored at 2-6 °C, glycosis is reduced but does not stop. Glycosis results in the production of lactate, with subsequent decrease in pH. Whole blood collected in CPD has a pH7.20 on day 0 and 6.84 on day 21. Preservative solutions provide buffering capability to minimize pH changes and optimize the storage period.

Loss of Adenosine Triphosphate (ATP)

ATP is associated with the red cells viability. Loss of ATP causes increase in cellular rigidity and decrease in red cell membrane integrity and deformability. A decrease in ATP allows the leak of Na^+ and K^+ through red cell membrane at levels exceeding those normally seen in vivo. The ATP level in CPDA-1 red cells at day 35 is 45 % (±12) of the initial level.

Decline of *2,* **3-Dipnosphoglycerate (2,3-DPG)**

A fall in pH in the stored blood results in a decrease in red cell 2,3-DPG level, which results in increase in hemoglobin-oxygen affinity. DPG-depleted red cells have impaired capacity to deliver oxygen to the tissues. The degree of reduction of 2,3-DPG levels depends upon the preservative solution used. ACD solution has lower pH than that of CPD solution. Thus 2,3-DPG falls within the first few days in ACD whereas blood stored in CPD/CPDA-1 maintains adequate levels of2,3-DPG for 10-14 days.

The pathological effects of the transfusion of red cells with low 2,3-DPG levels and increased affinity with oxygen include increase in cardiac output and a decrease in mixed venous PO_2 tension. 2,3-DPG levels in transfused blood are important in certain clinical conditions. Myocardial functions improve following transfusion of blood with high 2,3-DPG levels during cardiovascular surgery. In patients with shock the transfusion of DPG-depleted red cells makes a significant difference in recovery.

After transfusion, the red cells continue to synthesize 2,3-DPG and levels return to expected normal values within 24 hours. The acid-base status of the recipient, phosphorous metabolism and degree of metabolism influence the rate of restoration of 2,3-DPG.

Adenine

Simon (1962) showed that in CPD solution supplemented with 17 mg (0.25 mm) adenine per

63 of anticoagulant and 25% more dextrose, the survival of red cells 24 hours after transfusion of blood stored for 35 days was 80 ± 6.5 %. Adenine synthesizes ATP and its level is 56.4 ± 15.9%of the initial level in the stored blood for five weeks. Adenine nephrotoxicity due to its unmetabolized product, 2,8-dioxyadenine, is negligible at a level of 15mg/kg body weight. This amount is present in 30 units of fresh CPD adenine (0.5mM/unit) blood or in 60 units each having 0.25 mM adenine. The quantity of adenine is less if red cells are used.

Changes in$Na^+$and K^+ levels

During refrigerated storage, Na^+ and K^+ leak through the red cell membrane rapidly. The cells lose and gain Na^+, however, the K^+ loss is greater than the Na^+ gain during storage. (Retrieved from http://www.mahasbtc.com/preservation-and-storage-blood).

<u>Other Blood Components for transfusion</u>

Platelets – “It is possible to keep platelets for as long as 8–13 days, but blood banks in the U.S. are only allowed to keep them for only 5 days because of bacterial contamination. This means that 4–16% of collected platelets are lost because they do not find a recipient within their limited shelf-life” [Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2897192/]. [Retrieved http://www.transfusion.com.au/blood_products/storage/storage_temperature_range].

Plasma – The main purpose to transfuse plasma is to correct deficiencies of clotting factors. Plasma must be stored at 4 ± 2 °C and must be thawed to $30°C < T < 37°C$ in a water bath under continuous agitation. The plasma must then be transfused within 24 hours. Transfusion can be done by the recipient by carefully following provided instructions.

[Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2689068/].