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PASSIVE CONTROL: HELICOPTER SLING-LOAD STABILITY

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ABSTRACT

Helicopter Sling Load, where a payload is tethered beneath a helicopter, is the most accurate form of aerial delivery used by the military. The inherent payload instability limits the airspeed and maneuverability of the helicopters and increases delivery time and exposure to enemy fire in hostile areas. This project focuses on reducing sling load instability using passive methods to control the payload motion. The team conceived and constructed two stabilization concepts, which used elevated, angled fins and a finned fabric design. These concepts were tested on a scaled cargo container and a scaled Humvee in wind tunnel tests. A T-Rex 700E scale model helicopter was also adapted to test the two concepts by adding landing strut and video camera systems.

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Introduction

There are many methods of transporting cargo in a military, and often hostile, environment. Transporting cargo by air has become the most used method, because it has little to no dependence on the surface environment that the cargo is being transported across. Aerial cargo delivery is commonly carried out in one of two fashions. The first requires "*airdropping*" cargo from a plane. The cargo is attached to a parachute and dropped off an aircraft to float to a desired landing zone. The second is delivery via helicopter sling loading, where cargo and components are slung beneath a helicopter by one, two, or three cargo hooks, and quickly dropped off at the desired location. The interest in Helicopter Sling Load (HSL) cargo transportation has pushed the field to improve stability of payloads, but there is still much room for improvement when it comes to stabilizing payloads.

There are inherent advantages and disadvantages of using each of these transportation methods. When using the "*airdrop*" method, loading and delivery of the cargo is relatively easy, as long as proper procedure is followed. However, the most pertinent disadvantage is that once the cargo is dropped and the parachute is deployed, the cargo cannot be controlled in any way; the landing zone of the cargo is dependent on altitude and airspeed of the cargo plane as well as wind and weather. Weather and terrain issues can cause the cargo to land in an undesirable or unreachable location such as hostile territory or a body of water. Another shortcoming of airdropping cargo is the failure of parachute deployment, which can cause damage to, or destruction of the cargo. The disadvantages of airdropping cargo leads to the heavy use of helicopter sling loads for payload transportation.

Although HSL transportation has several benefits over these other aforementioned modes of cargo transport, HSL also has its disadvantages. While cargo can be more safely and accurately delivered, cargo slung beneath a helicopter greatly decreases the helicopter's maximum safe operating airspeed and maneuvering capabilities. Load yawing, spinning, swaying, and oscillating further reduce the helicopter's overall stability and maneuverability, and therefore, airspeed. To prevent or dampen these effects, the helicopter pilot must maintain strict control of the aircraft at all times. The pilot must react quickly to the motion of the sling load beneath the helicopter in order to keep the entire helicopter sling-load system stable.

Research on helicopter sling loading stability has been conducted, and many “passive control” options have been explored. The words “passive control” mean that there is no active, or dynamic, actuated control of the load; it is stabilized by aerodynamic forces and effects only. Most, if not all, of these aerodynamic effects are from the shape of the load itself. Passive control of helicopter sling loads relies solely on changing the “bluff” load into a more stable, self-managing aerodynamic shape.

Past research projects done at the Higgins Laboratory at WPI by Daniel Nyren and Zaki Akhtar investigated the aerodynamic effects on the most unstable form of military cargo: a six by six by eight foot shipping container referred to as a *Conex* container[1, 2]. These studies involved the design and testing of a few original designs for passive stabilization of the Conex container.

One of the designs extensively tested in the wind tunnel at the Higgins Laboratory was Nyren’s “flexible fin” design. The design consisted of a simple, v-shaped, fin mounted to the top of a scale-model Conex container. The second design tested was the “boat tail,” which consisted of adding a triangular tail (45° or 60°) to the rear of the scaled Conex container. This design simulated the shape of a boat, which is generally flown stern-first when slung beneath a helicopter.

1 Background

1.1 First Helicopters

The transportation of cargo via sling load has been pivotal in both military and commercial helicopter operations for many decades. During the 1960's, sling load operations were picking up in the Vietnam War and there was also increasing interest in heavy-lift helicopter programs [3]. As number of applications of sling loads increased, the demand for more advanced systems stimulated further development in the field of sling loads. There have been several theoretical studies into the dynamics of single-point sling load systems. Of these studies, most are concerned with box-shaped payloads because they represent one of the most unstable conditions [4].

1.1.1 Korean War-Marines

The U.S. Marine Corps was the first U.S. military branch to investigate the use of helicopters in combat operations. In 1950, Marine Helicopter Squadrons were some of the first helicopters used in wartime. These helicopters were predominantly used as cargo and troop transportation from boat to shore, medevac and observation. The following year, helicopters from the Marine Squadron 161 (HMR-161) become the first transport helicopter squadron devoted to combat operations. Using the Sikorsky HRS-1 (Figure 1), marines tested different operational techniques in hostile combat situations. The HRS-1 had room for 2 crewmen, 8 passengers, 1,050 pounds of payload, and cruised at 80 mph.[1]

FIGURE 1: SIKORSKY HRS-1 HELICOPTER [1] ©2013 US ARMY

1.1.2 FIRST HELICOPTER SLING LOAD MISSION

Not long after its arrival in Korea, HMR-161 orchestrated Operation Windmill I; the first combat operation for the squadron took its name from the nickname of the HRS-1: the "Flying Windmill" [1]. On September 13th, helicopter support teams were readied as 800 pound payloads were being prepared to sling. Seven helicopters were used to transport supplies and evacuate casualties from combat. Overall, this Helicopter Sling Load initiation went well, lasting two hours and forty minutes; Operation Windmill I was responsible for the transportation of over 18,000 pounds of cargo and supplies and the evacuation of seventy-four injured soldiers. The mission proved the validity of using helicopters to perform operations that would take ground troops significantly longer.

1.2 NATICK SOLDIER RESEARCH, DEVELOPMENT AND ENGINEERING CENTER (NSRDEC)

The Natick Soldier Research, Development and Engineering Center (NSRDEC) is an Army base located in Natick Massachusetts, that focuses primarily on development of war fighter systems. "The primary focus of the ATT [Airdrop Technology Team] is to provide increased mobility and logistic capabilities to the soldier by identifying and maturing technologies that show promise towards advancing the state-of-the-art in aerial delivery of equipment, supplies and personnel"[5]. The primary mission of ADEST [Aerial Delivery Engineering Support Team] is to "provide technical and engineering services for the development, acquisition, sustainment or use of products and processes that afford aerial delivery of personnel and equipment by parachute, aircraft and helicopter" [5].

NSRDEC is currently responsible for most, if not all, of the Army's testing and certification processes involved with helicopter sling sets, cargo nets and certified and un-certified cargo as determined by the US Army and the US Department of Defense.

1.2.1 Helicopter Sling Load Certification Process

When a customer requests the Sling Load Certification of a specific load, or piece of cargo, it is the responsibility of the ADEST at NSRDEC to develop a fitting rigging procedure for it. After this procedure is developed, static lifting, proof-loading, and flight evaluations are carried out before the load may be certified. These tests also ensure that the load has the desired -3 to -5 degree, nose-down configuration, and that the load does not detract from the safe operation of the aircraft being loaded. [1]

1.2.2 Helicopter Sling Load of Joint Precision Aerial Delivery System

The Helicopter Sling Load of Joint Precision Aerial Delivery System (HSL JPADS) is a system concept of the ADEST at NSRDEC. This system allows loads slung beneath helicopters to be airdropped such that they can reach the ground via parachute after detaching from the helicopter. Below is a concept image of what this system would look like placed on a dual-point sling load configured helicopter.

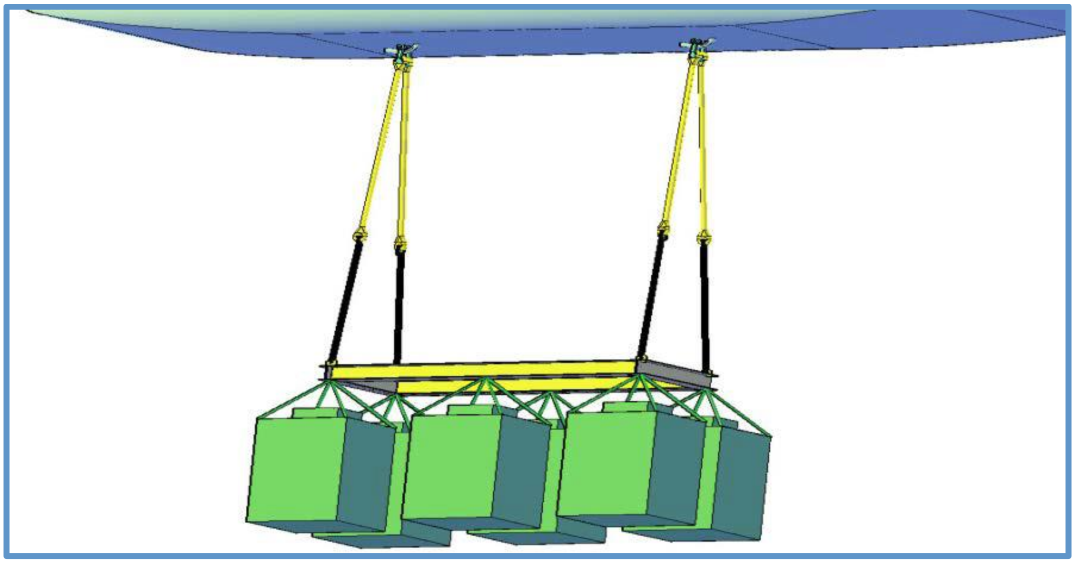


FIGURE 2: HSL JPADS CONCEPT IN A DUAL POINT CONFIGURATION [6] ©2012 US ARMY

The ADEST is still testing this system on single-point loading configurations, but is still encountering the problem of the single-point's inherent swaying and yawing instabilities [6]. The ADEST is currently pursuing passive stabilization methods to minimize these effects to ensure accurate airdrops from helicopters.

1.3 CURRENT UNITED STATES CARGO HELICOPTERS

The United States Army uses a variety of helicopters to transport cargo and mission ordinance. The main sling-load capable helicopters in use today are the UH-60 Black Hawk, the CH-47 Chinook, the UH-72 Lakota, and the CH-53 Super Stallion.

FIGURE 3: UH-60 BLACKHAWK [1] ©2013 US ARMY

The Black Hawk is the most popular of the four because it is very maneuverable, while still capable of lifting heavy loads. It was designed with many types of missions in mind, ranging from transportation of supplies to medical evacuation of Army personnel. The Black Hawk has a single point sling load configuration, which means that a load's sling legs will all hang from one point and the load will be free to spin to a certain degree.

FIGURE 4: CH-47 CHINOOK [1] ©2013 US ARMY

The Chinook is the heaviest lifting helicopter available to the United States Army at this point in time. Its counter-rotating dual rotor design does not require a tail rotor to counteract any torque from the lifting rotors. The Chinook has a dual-point sling load configuration, meaning that the load's sling legs will attach at two points, one toward the nose of the helicopter, and one toward the tail of the helicopter.

Figure 5: UH-72 Lakota [1] ©2013 EADS North America

The Lakota is much smaller than the Black Hawk and Chinook, allowing it to be much more maneuverable, but it cannot carry as much cargo. Its primary mission specifics are for personnel transport and light cargo. It is similar to the Black Hawk as it also has a single point sling load configuration.

Figure 6: CH-53 Super Stallion [1] ©2013 US Marine Corps

Finally, the Super Stallion has the highest lifting capability of any military helicopter. It is not in use by the United States army, but it is worth mentioning because of this. It can produce enough lift to hoist another Super Stallion, and it is equipped with a very stable three-point sling load configuration. Each of the three sling leg attachment points can swivel, unlike those used for single and double sling load attachment points.

1.4 Materiel

The critical part of a helicopter necessary to sling a load beneath it is the cargo hook. Without a cargo hook, there would not be any simple means of attaching a cargo load to a helicopter. The materiel used to sling loads from the cargo hook varies slightly for each style of load, but every load uses the same main components. These main sling-loading components are sling sets, reach pendants, and long lines.

1.4.1 Sling Sets, Reach Pendants, and Long Lines

The sling set is defined as all the components necessary to connect the load to the helicopter's cargo hook. A sling set contains the four sling legs, the four "grabhook" assemblies, and an apex fitting. The sling legs are the lengths of nylon rope that separate the load from the helicopter, they are typically 12ft in length and about an inch in diameter. The grabhook assemblies are the connectors between the sling legs and the chain lengths that are used to secure the load, and attach the load to the sling legs. The grabhook assemblies allow for fine adjustment of individual sling leg lengths so that the load may have the desired angle of attack.

A reach pendant is a synthetic rope with a hard tube around it that allows the helicopter to hover at a higher altitude while a slung load is being hooked up. The reach pendant is also necessary to keep the hookup team safe from accidental static discharge from the helicopter while they are working.

A long line is similar to a reach pendant, but it does not have a stiffened tube around its rope. The long line increases the distance between the helicopter's fuselage and the slung load itself. Long lines are necessary during missions where visibility is an issue. Increasing the distance between the helicopter and its load allows the helicopter to fly higher above the ground, increasing the area that the pilot can see, while simultaneously keeping the load at the same cruising altitude.

1.5 Helicopter Sling Load Missions

Helicopter sling load missions are made up of three important steps: Clearing the landing site(s), rigging the load, and hooking up the payload.

1.5.1 Landing Site

The first step of a helicopter sling load mission is to find and clear a landing site. Though the helicopter does not land during the hookup process, its internal cargo bay can also be used at the same time. In order to load the helicopter's internal cargo bay, the helicopter must have a minimum diameter landing site for these operations. In addition to the model of helicopter being used, the landing site selection also depends on the current atmospheric conditions, time of day, location relative to base, and any other local safety concerns.

1.5.2 Rigging Loads

Most helicopter sling loads are all rigged in the same fashion. All of the sling legs are attached to the apex fitting in a specific order, and the chain links on the grab hook are counted to provide a -3 to -5 degree angle of attack to passively stabilize the load.

1.5.3 Hook Up

Hooking up a sling load to the cargo hook of a helicopter is very dangerous work. However, the hookup crew only needs three soldiers to manage it. These three jobs are signal, hookup, and static probe. The signalman communicates with the pilot through hand signals to convey the proper hovering location and height above the payload during hookup. The hookup and static probe men are nearby or on top of the load during the entire hookup process. The static probe man's job is to discharge the helicopter of and static electricity that may have built up when travelling to the landing zone. After the helicopter has discharged its static electrical buildup, the hookup man can attach the load to the helicopter's cargo hook and vacate from the top of the load before the helicopter climbs for its delivery.

1.6 Bluff Body Aerodynamics Research

The fundamental principle behind helicopter sling loads involves bluff bodies; therefore it is necessary to understand the dynamics of these types of aerodynamic bodies. From Tricon and Conex containers to army Humvees and Howitzers, the majority of military helicopter sling loads are bluff bodies; that is, the shape of the object does not allow streamlined flow, including large regions of turbulent separated conditions.

The inherent challenge of this type of research is the existence of unsteady aerodynamics, which produces instabilities in cargo. The ninety-degree corners of a Tricon container lead to the creation of large pockets of separated turbulent flow. These bubbles of flow do not form predictably as in the static case. The yawing, pitching, and swaying of the container are only exacerbated by the equally random vortex shedding, which add energy to oscillations [4]. Cicolani and Ehlers studied the modeling and simulation of a sling load systems and referenced wind tunnel data from a study at Israel Institute of Technology. The study concluded that drag varied little with the container orientation (the container was close to cube-shaped) and that maximum values of lift and side-force amounted to only 25% of the drag [4].

Despite being a subject of experimentation for many decades, surprisingly few of these studies used full-scale flight testing to determine aerodynamic behavior of sling loads [7]. Full-scale testing is not only difficult, but also expensive and dangerous. It is for these reasons that many research studies draw parallels to other bluff bodies in order to further understand HSL aerodynamic behavior; examples include tractor-trailers and tether balloons.

NASA studied three similar shipping containers, each a different scaling, in the wind tunnel[8]. Two of the containers were rectangular and one was a cube. Due to scaling concerns, corrugations along the surfaces of the containers were maintained in scale models. In this study, lift, drag, and side force coefficients were chronicled along with pitching moment, yawing moment, and rolling moment coefficients. These variables were investigated with varying pitch and yaw angles. Corrugated containers were compared with non-corrugated containers of the same scaling and found to be equivalent; which proved the lack of influence corrugations play in the dynamics of these types of containers.

Buresti et al. further studied techniques to reduce drag on bluff bodies with a particular interest in commercial vehicles[9]. This research began broadly with simple bluff-body drag reduction study but narrowed to focus of standard tractor-trailer structures. Initially, the Buresti et al. explored "boat-tailing"; a commercially available means of drag reduction. Consideration of streamlines that bounded the wake turbulence behind the rear of the container showed a tendency of the mean streamlines to curve towards the axis of symmetry of the bluff-body. The boat-tail, shown in the figure below, helped this flow bend towards this axis and increased flow speeds aft of the container.

FIGURE 7: INFLATABLE BOAT-TAILING DEVICE [1]

A simple alteration in geometry, gradually reducing the cross-sectional area of the rear of the container, increased velocity and therefore decreased pressure behind the body and allowed for higher speeds. The figure below shows the drag asymptotically approaching a minimum value as the length of the length of the boat tail approaches the width of the bluff body

Buresti et al. also hypothesized other forms of drag reduction that were more sophisticated and involved active control schemes. Base bleed was one of these active systems that worked by blowing the flow out through the base (or backside) of the container. “The main mechanism causing this reduction is the alteration of the amount and distribution of the vorticity being introduced into the wake. In particular, if the blowing is through a hole in the center of the base, the consequence is the introduction of vorticity of opposite sign than that introduced into the wake from the boundary layers separating from the body surface and bounding the wake” [9]. Despite how effective base bleed was, it is limited by power consumption. It was hard for the study to justify the drag reduction when confronted with the power use blowing the air.

A step up in complexity from the last method, Buresti et at. considered the use of moving control surfaces that could stabilize instabilities. The moving surfaces in the design were rotating cylinders located at different places on the surface of the container; these surfaces were designed to inhibit or delay flow separation of the boundary layer from the surface of the body.

The use of rotating cylinders in this manner has been shown to diminish vortices behind bluff bodies in two ways. First, it hinders the boundary layer development by decreasing the relative velocity of the freestream air and the surface of the body. Second, the moving surface adds momentum to the existing boundary layer. Furthermore, power needs of this type of system would be much less than a base-bleed system. Despite its advantages, there are few, if any, realistic applications for the rotating-cylinder system and determining positions for the mobile surfaces is difficult task (with drag reduction in mind).

1.7 Helicopter Sling Load Dynamics Research

In 1977, Sheldon sought to improve the field of Helicopter Sling Load [10]. His findings detail the problems with single-point sling loads and suggest a dual-point configuration could remedy many of them. There was a strong tendency for most payloads to fly in an orientation of highest drag, and Sheldon concluded that few sling loads could be carried stably over 60kt [1]. Most bluff-body payloads either become unmanageably unstable or produce significant drag that limits the helicopter's power.

After studying the sling load bodies, Sheldon experimented with the state of the art stabilizing designs, specifically addition of fins or a drogue chute. With the addition of fins, loads tended to still fly in the orientation of highest drag. Nevertheless, fins could be used to position the container in an orientation of minimum drag and allow for faster flight speeds overall. "Subject to the fins' not being over-size and producing a pitch divergence of the bridges, a very significant reduction can be achieved on helicopter hook loads and aerodynamic drag" [10]. Sheldon found that drogue chutes, or small parachutes affixed to the rear of the container, had similar effects as the fins with some drawbacks. These chutes were very sporadic due to trailing vortices behind the load. In addition, drogue chutes posed a danger of entangling in the rotor blades or other helicopter control surfaces. HSL experience in Vietnam also showed that these types of designs are cumbersome and dangerous to attach in combat scenarios.

Cicolani et al. found that, in cases of sling loads with a swivel, the container "spun up to a steady-state yaw rate that increased with airspeed over the speed range of tests"[11]. Then in 2009, Cicolani et al. studied full-scale testing with a fully instrumented UH- 60 Blackhawk and Conex container[11]. This allowed testing to be compared to simulations. The study was designed to predict the airspeed envelope based on payload and proved that it was possible to understand sling load aerodynamics using the instrumented Blackhawk sling load setup.

In 2011, Greenwell designed a model that relied less on experimental data and instead took into account turbulence, Reynolds Number, wind tunnel effects, and geometry [12]. Initially, Greenwell categorized instabilities in three main groups: aerodynamic instability of the load, helicopter load vertical oscillations, and sling cable flapping. "For aerodynamic instabilities, the initial load motion is typically a periodic yaw oscillation which then couples into the sling and helicopter response, leading to a range of rather complex lateral and longitudinal pendulum modes" [12].

"Containers are rectangular bluff bodies, with the aerodynamic loads dominated by normal pressure forces. The loads therefore need to be considered in body axes, and not the universally used wind axes (which result in apparently highly complex variation in forces and moments with incidence)" [12]. Greenwell showed that, using empirical parameters derived from existing data, it is possible to predict aerodynamic properties of any rectangular container sling load.

1.8 HELICOPTER SLING LOAD PAYLOAD STABILITY RESEARCH

Gera and Farmer used a linear model to study how geometric and aerodynamic characteristics were related to the yawing and pendulum motion in underslung payloads[13]. The model took into account the geometric and aerodynamic characteristics of the payload, and the velocity of the helicopter to predict the variations in yaw motion and pendulum motion. In addition, Gera and Farmer looked to stabilize sling loads using fins. These fins (Figure 8 below) were used with linear control theory across a range of airspeeds to attempt to stabilize the container. The study was one of the first active control investigations of helicopter sling loads and concluded that the use of fins in this way "was sufficient to stabilize a load such as an empty shipping container" [13].

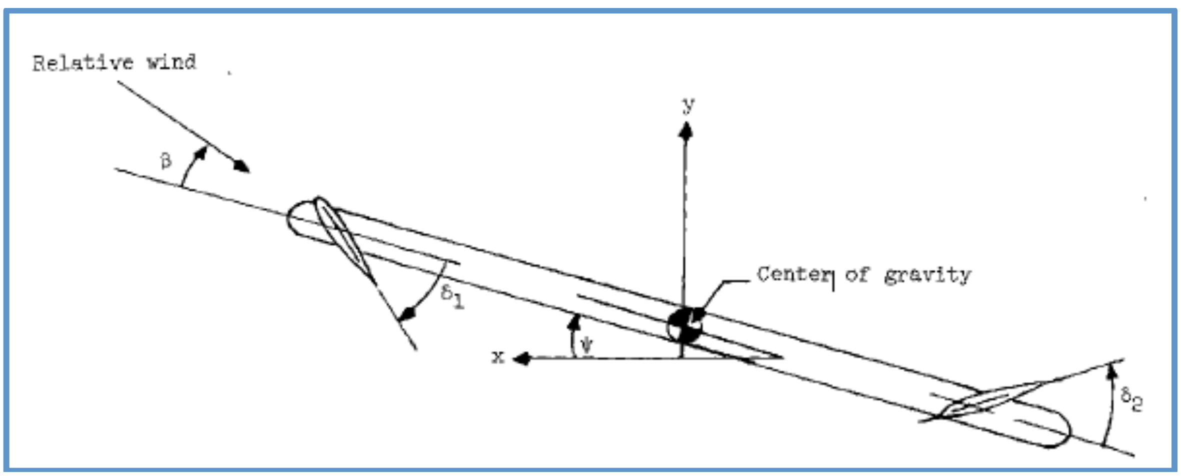


FIGURE 8: CONTROL FINS FOR AUTOMATIC PAYLOAD STABILIZATION [13]

Using Cicolani et al.'s work as a springboard, Raz et al. studied vertical fins affixed to Conex containers. Ten different vertical fin designs and orientations were tested on a scaled version of the 6’x6’x8’ Conex. Equal-height fins mounted on the rear of the container was determined to be the most stable configuration. Shown in Figure 9 below, the setup featured fins that were the same height as the container and elevated half the height of the container in the freestream flow.

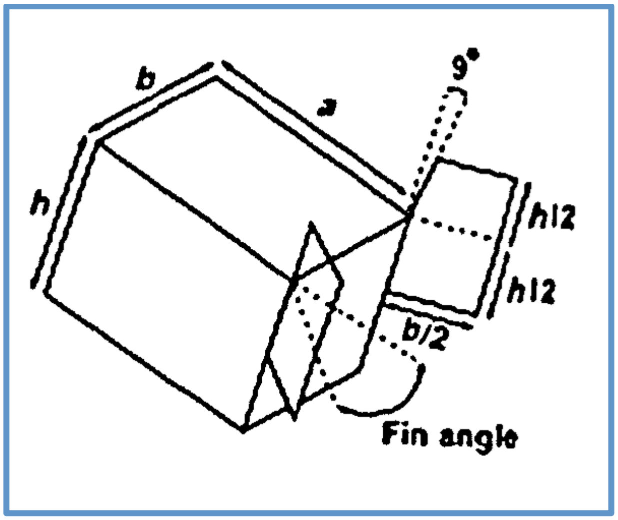


FIGURE 9: ELEVATED FINS ON THE NARROW SIDE [14] ©RAZ ET AL.

Other fin setups are shown in Appendix C. Changing the side and instead fixing the fins to the broad side of the container (Figure 10) was discovered to be more stable. This is a result of the container’s propensity to fly in the orientation of highest drag.

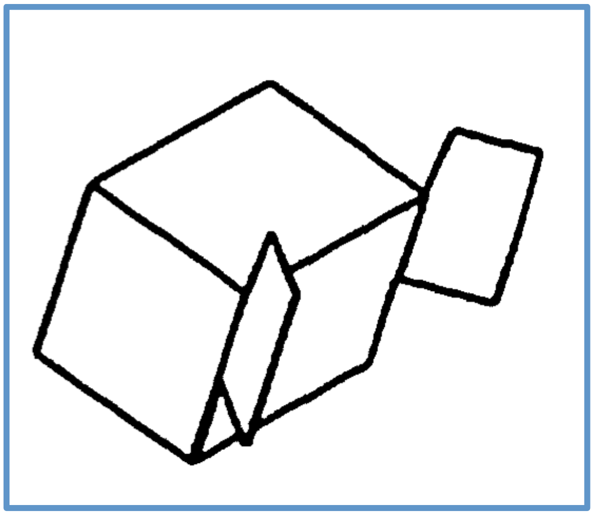


FIGURE 10: ELEVATED FINS OF THE BROAD SIDE [14]©RAZ ET AL.

After full scale testing the vertical fin design on a Conex, Raz et al. concluded that the yaw and lateral oscillations were barely corrected up to medium flight speeds. Furthermore, the instabilities exhibited in experiments were harder to control using traditional recovery procedures such as turns or pull-ups. “Fixing the controls” was the most successful recovery option. A concern with the testing was the change in payload dynamics with the presence of an actual helicopter on the cargo hook. Regardless, they noted good correlation between wind tunnel and flight test stability qualities and modes of oscillation.

As another basis of comparison, Raz et al. experimented with different sling leg configurations. Several different sling leg materials were tested and the study concluded that “Nylon thick twisted wire-white” would best simulate the legs and electrical terminals replicated the sling eyes well. The sling setup above was tested on a Conex container, a Trio Container, and a Ribbon Bridge. The Trio container is essentially a Conex split into three sections so that each can be deployed to a different location.

In their research, Raz et al. established several key points with regards to dynamics of sling loads. First, Froude number matching was a good method to scale payloads. Full-scale tests corroborated wind tunnel results well, which is due to bluff body aerodynamics that varies little with airspeed or Reynolds number. Second, the addition of the helicopter into the sling load system essentially adds a dampening term to the coupled system. Therefore, this new dampening term causes a reduction in oscillations. A decrease in pendulum motion (due to the presence of a helicopter) in full-scale tests meant that wind tunnel results were conservative estimates.

Conversely, Raz et al. determined that the introduction of a helicopter and pilot into the loop could destabilize the system through Pilot Induced Oscillations or PIO. The fact that the helicopter and pilot could act as a stabilizing influence in some cases and a destabilizing influence in others meant that pilot techniques (“stick fixed” versus “pilot in the loop) must be included as a variable in the experiment.

Another consideration was the use of a swivel hook, which would allow a free range of yaw motion. The results showed that offsetting the center of gravity from the geometric center of the container did not allow full range of motion and caused oscillations in yaw. Conversely, allowing the load to spin up increased overall stability. In cases where the sling legs are not on a swivel, winding and unwinding of the legs is another concern. This behavior is particularly dangerous because it is non-linear and dependent on sling leg material, geometry, and sling leg attachment strategy. For this reason, Raz et al. developed a cautious procedure to find the sling leg material that best modeled the arrangements without a swivel. Thus, the study developed a methodology for testing that could be used to test other bluff bodies used in HSL operations.

2 Goals and Objectives

The objective of this project was to diminish instabilities in military payloads slung underneath helicopters. This MQP investigated the modes of instabilities and sought to affix a passive control scheme to dampen perturbations in lateral pendulum motion, longitudinal pendulum motion, and yaw motion. Dampening these motions will increase stability, increase helicopter maneuverability, increase maximum safe operating airspeeds, and will make sling-load transportation safer and more effective.

Goals for this project are listed below in order of priority:

1. Develop new passive control methods to stabilize helicopter sling loads.
    a. Finned Fabric
    b. Elevated Fin
2. Test and refine scaled designs with the help of:
    a. A wind tunnel
    b. An RC helicopter
3. Continue developing Daniel Nyren's methods for wind tunnel testing
    a. Scaled Tricon container
    b. Scale sling legs
    c. Scale cargo hook
4. Utilize instrumentation for acquiring the following data
    a. Six degree of freedom force transducer
    b. Force in three directions acting on hook
    c. Torque in three directions acting on hook
5. Develop quantitative and visual metrics for stability

3 Methodology

3.1 Overall Test Conceptualization

The wind tunnel experimental design continued the work of Daniel Nyren and simulated a sling load suspended beneath a cargo hook, similar to those on military helicopters. The hook was attached to a force transducer, which measured forces and moments and all tests were captured on video. A diagram of the test setup is shown below in Figure 11 with a scaled Tricon container (flow from right to left). The hook is connected to the simulated clevis, which is connected to the payload by the sling legs. The following sections of the paper will detail the remainder of the experimental conceptualization.

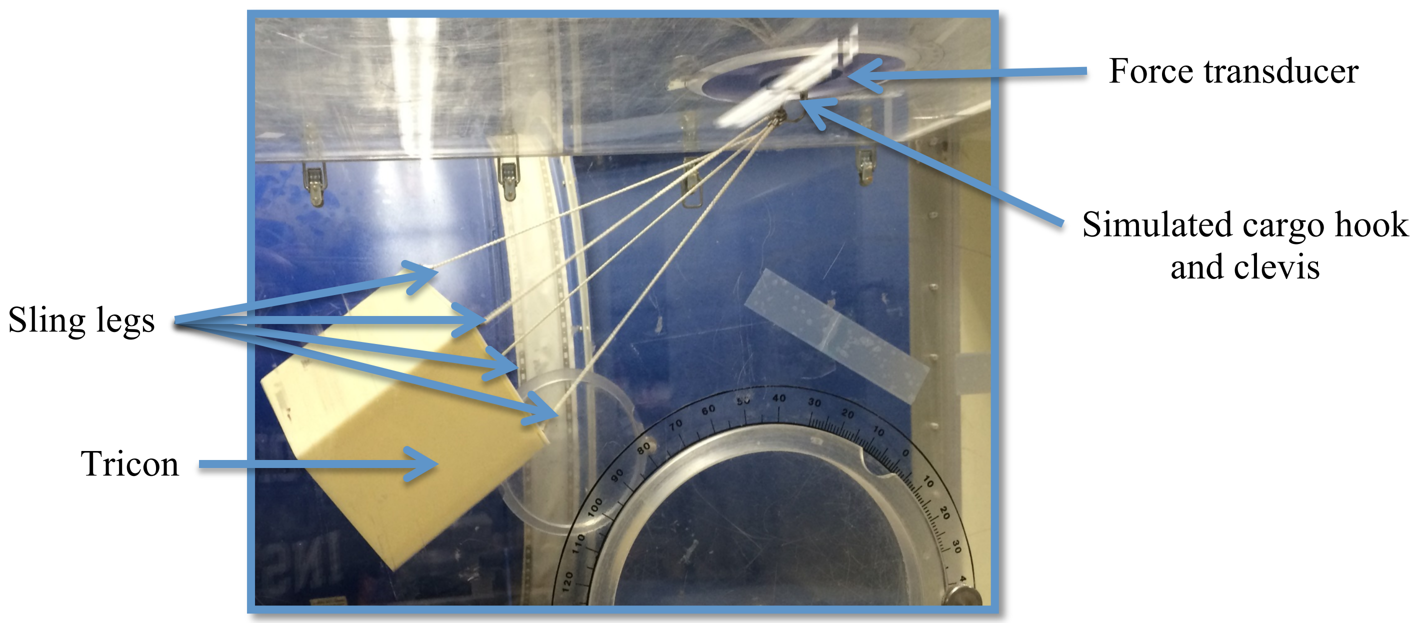


Figure 11: Scaled Tricon Container in Wind Tunnel

3.2 Model Scaling

As testing a full-scale passive stabilization prototype was not feasible, the team settled on 1/17th scale models for the Tricon container and its stability designs. This particular scale was determined using information gathered from Nyren's report along with some preliminary discussion and calculations.

It was not necessary to use Reynolds Number scaling for the Tricon container, as it was a "bluff body" object, meaning that air or any other fluid's streamlines do not attach to its surface. Froude Number scaling however, does not depend on how smooth the airflow around a "bluff body" object is, so it was clear that this was a more reasonable scaling method.

Another important consideration when scaling the Tricon was its area. If the Tricon blocked too much area in the wind tunnel's cross section, the boundary effects from the walls of the wind tunnel would skew the results. From Nyren's report, the scaled container should only block about 5% of the wind tunnel's cross section to provide ample space between the container and the walls of the wind tunnel.

Using a constant Froude Number of 17, the wind tunnel's scaled airspeed was determined to be 41.7ft/s or 12.7 m/s to accurately model a Black Hawk helicopter's full-scale cruise speed when carrying a slung load [1]. A quick speed to frequency ratio calculation determined the operating frequency for the wind tunnel that would give this airspeed.

3.3 Scale Models

3.3.1 Design of a Scaled Tricon Container

A Tricon container is a corrugated metal shipping container used in many cargo transportation operations. The scaled Tricon container used for testing was modeled in SolidWorks and 3D printed at WPI's rapid prototyping center. Scaling was determined similarly to the previous WPI project using a Froude number of 17. It is not necessary to use the Reynolds number for this because the Tricon container is a bluff body.

3.3.2 HMMWV Model

Given the extensive use of this vehicle in military operations a scale model High Mobility Multipurpose Wheeled Vehicle (Humvee) was purchased in order to observe the effectiveness of our designs on another shape of slung load. Due to the more complicated shape of the Humvee it was not possible to manufacture and instead more practical to purchase a 1:25 scale model (Figure 12).

FIGURE 12: MODEL HUMVEE [15] ©2015 REVELL

This scaling is different from the 1:17 used for the Tricon but was one of the few sizes available. The team also needed a model small enough to fit into, and have space to move around in the wind tunnel during testing. The difference in scaling necessitated separate versions of the two stabilization methods and sling legs be constructed in sizes especially for this model.

When transporting a Humvee via helicopter the military typically uses a single point configuration for the sling legs, these are attached to the Humvee via four hooks mounted at points on the vehicle itself. The first attempt to attach sling legs to the model used loops of string placed under the wheel wells, while simple and this design is not like the attachment method used in real life.

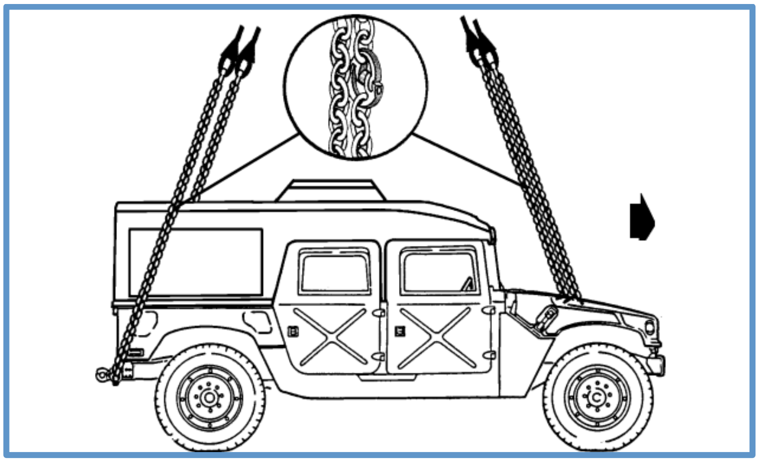


FIGURE 13:HUMVEE SLING ATTACHMENT POINTS [16]

After researching pictures and diagrams of the actual Humvee sling leg mounting points it became obvious that there are two hooks built into the hood and two hooks on the rear bumper, that are to be used specifically for sling loading the Humvee. However a 1:25 scale model is too small to include anything more than engravings of such fine details; holes were drilled in the location of the sling leg attachment points on the hood and rear of the Humvee, hooks were fashioned out of thin wire, and ¼" braided nylon cord tied on in order to mount the sling legs. After performing a baseline test in the wind tunnel it was apparent that the ¼" cord was too thick and rigid to allow the Humvee to move freely. The cord was then replaced with #18 AWG Twisted Mason Line, which allowed proper movement of the model.

3.4 TEST FACILITY

In order to measure the instabilities of the scaled sling loads, testing was performed in WPI's Higgins Labs basement wind tunnel. The wind tunnel has a 2ft x 2ft test cross-section and is capable of wind speeds between 0 and 135mph. The wind tunnel is also equipped with a heat exchanger and temperature monitor to prevent any heat from its motor from affecting any testing. The lab space itself has a desktop computer with ATI's Data Acquisition System software already installed. This computer also has all of the necessary serial input ports required to communicate with the force transducer. The computer desk provided adequate space to prepare all scaled models for testing, along with appropriate tools for assembling and disassembling the force transducer module and housing.

3.5 Instrumentation

All scaled model wind tunnel testing was performed using the NSRDEC's ATI Industrial Automation "Legacy Mini" force transducer module. The force transducer measured forces in the x, y, and z directions, along with torques around each of these axes. This was possible through the use of complex electrical circuitry that changed the transducer's output voltage depending on what forces and moments it was experiencing. A special program developed by ATI was used to translate the output voltages into accurate force and moment readouts. These readouts were saved as "comma separated values" files, which could be read and analyzed in Microsoft Excel.

The force transducer module was container in a circular housing, the same size as the access port on the top of the wind tunnel. A scaled cargo hook was mounted to the module that allowed the scaled sling load models to hang beneath it. The scaled Tricon container was placed in the wind tunnel with the operation panel set to 15.9Hz, this translated to an airspeed of 12.7m/s, the scaled cruise speed of a helicopter, and baseline force and moment data was gathered. Next, the model Humvee and the Tricon's elevated fin modification were placed under the same conditions, and relevant data gathered. This first Humvee test raised some questions however, because its scaling was not appropriate for this wind tunnel speed. At 1/25 scale, 12.7 m/s would not accurately represent a typical slung load cruise speed. The actual test speed was later determined to be 8.36 m/s (10.5Hz on the operation panel) and accurate testing was conducted later.

3.6 Radio Controlled Helicopter Testing

In order to verify the wind tunnel test results, the prototype passive stabilization designs should be tested in real-world conditions. The motivation behind this type of experiment was essentially to overcome the limitations of the wind tunnel environment. Testing with a radio-controlled helicopter allowed for the simulation of many conditions for example turns, sudden elevation changes, crosswinds, and downwash effects. This approach made it possible to use previously fabricated models and designs.

When it came to choosing the specific helicopter, independent research combined with suggestions from local hobby stores were considered to arrive at the particular model that would suit our needs: the Align T-Rex 700E.

FIGURE 14: ALIGN T-REX 700E RC HELICOPTER [17]

Shown above in Figure 1, this particular model from Align was the second largest of the T-Rex models. At 1342mm (52.83 in.) long and 424mm (16.69 in.) high and a flying weight of approximately 5200 grams, the T-Rex 700E was one of the largest, most capable options available and certainly powerful enough to execute any maneuver necessary for our testing. The full list of helicopter-related components is tabulated below.

Table 1: RC Helicopter Components

Transmitter:	• Spektrum DX8 w/ AR8000
Telemetry System:	• TM1100 DSMX Fly-by Aircraft Telemetry Module
	• Aircraft Telemetry Airspeed Indicator(pitot system with sensor)
Power:	• Two 5000mah 6S 45~90C Lipo Packs
GPS:	• SkyRC GPS Standalone

As far as the test setup, there were a few things that had to be modified surrounding the RC helicopter so that it was test-worthy. First, the T-Rex 700E was a kit and did not contain any cargo hooks similar to those found on transport helicopters that carry sling loads. During the assembly of the helicopter, a mounting setup for the hook was devised in order to ensure sling loads hung below the center of gravity securely. Furthermore, the speed of the T-Rex 700 helicopter had to be known during tests so that tests could be conducted at a proper-scaled wind speed (the same speed as the wind tunnel testing). The helicopter did not come with features to be able to do this. For a full list of included components see Appendix B. After consulting RC helicopter enthusiasts and pilots, it become apparent that a simple pitot tube sensor system with a telemetry system could be used to measure instantaneous airspeed of the helicopter. The selected Spektrum Aircraft Telemetry Airspeed Indicator is shown in Figure 15.

FIGURE 15: SPEKTRUM AIRCRAFT TELEMETRY AIRSPEED INDICATOR [18] ©2015 SPEKTRUM RC

In addition, every experiment requires some form of measurement aspect of the stability of the load. In lieu of mounting an Inertial Measurement Unit (IMU) inside of the payload, the test would be captured by a high-definition video camera and used for analysis of stability design usefulness. In order to do this, a rugged Go-Pro camera was mounted just in front of the cargo hook underneath the T-Rex 700. This camera faced downwards at the cargo in order to best capture yaw and sway instabilities. The same mount that will hold the cargo hook was also used to hold this camera.

For good experimental practice, it is important to plot the path of the test and log important velocity data to be used in conjunction with test videos during our analysis. The best way to log velocity and GPS data is a standalone GPS unit. The SkyRC GPS Speed Meter was chosen because of its small size and low weight.

FIGURE 16: SKYRC GPS UNIT [19] ©2015 SKYRC

The SkyRC is able to output this data (comma separated value file) to a program such as Google Earth in order to view the flight information superimposed over a satellite image. Since it is so small and lightweight, the SKYRC was mounted with robust Velcro to the side of the helicopter frame. This method allows easy removal for data collection.

A problem with testing sling loads with an RC helicopter is taking off and landing. The helicopter could crash by landing on top of the container or getting tangled win the sling legs. While in military practice, soldiers can hook up sling loads while the helicopter hovers above, this strategy would be dangerous in scaled testing. The T-Rex 700 is an extremely powerful machine capable of reaching speeds close to 100 miles per hour and not to be confused as a toy. Two strategies were proposed as solutions to this problem: (1) a test stand or undercarriage or (2) a detachable sling set.

The basic idea behind the test stand or undercarriage was to elevate the helicopter over the Tricon container and stability designs for takeoff and landing. After reviewing several DSLR camera mount stands that others had designed, the best option was to pursue a 4-legged design that would allow the helicopter to take off and land without damage to itself, the payload, or the stabilization design being tested. Several materials were experimented with during the construction of the undercarriage. These included PVC, threaded steel rods, and zinc-plated steel sections. For ease of construction, strength of design, and bolt-together ability, the frame-structure was made of steel. The undercarriage was affixed to the existing landing skids on the RC helicopter and would remain as such throughout the duration of testing.

FIGURE 17: SIDE VIEW OF EXPERIMENTAL UNDERCARRIAGE ON T-REX 700

FIGURE 18: FRONT VIEW OF EXPERIMENTAL UNDERCARRIAGE ON T-REX 700

This allowed the camera and cargo hook to be attached as well as the pitot tube. A concern with the steel was the weight. A specific value for lifting capacity of the T-Rex 700 was not provided by the manufacturer and a rather unusual measurement in the RC helicopter community and was therefore difficult to pinpoint. A few enthusiasts ensured weights ranging from five to fifteen pounds. These values could only be verified after the first flight test. Another concern was the battery life of the 2 5000mAh batteries. Shown in the figure below, these two Lithium Polymer batteries were recommended by the RC enthusiast community and were wired in series to power the helicopter brushless motor.

FIGURE 19: ZIPPY 6S 5000MAH LIPO BATTERY PACK [20] ©2015 ZIPPY

Unfortunately, these batteries provide about six to eight minutes of battery life, which does not allow for much testing. In addition, the auxiliary weight of the undercarriage, camera, container, and stability design prototype also contribute to increased battery drain and shorter tests.

In response to the issues with the previous design, a simple load-detachment strategy was envisaged. This method involved a servo-controlled cargo hook that could drop the payload and sling legs with the flip of a switch on the DX-8 transmitter. This would allow the helicopter to land normally without interference from cargo. Without a bulky undercarriage, the helicopter would handle more reliably and predictably. Additionally, drag would be decreased as well as the strain on the battery to keep those extra few pounds in the air. This alternative setup meant increased testing times and the added ability of ditching dangerously unstable sling loads. The capability to detach loads could save the helicopter from an expensive crash.

3.7 DESIGN OF PASSIVE CONTROL CONCEPTS

3.7.1 POTENTIAL STABILITY DESIGNS

After reading through other sling load stabilization studies, a few original designs were generated. These included designs based solely on literature, and others based on properties of proven aerodynamic designs.

There were four initial designs, two developed from literature and the other two were original concepts. The first idea came from Raz's study and consisted of two raised fins on the back of the container, with the smallest side of the container facing into the oncoming airflow [14].

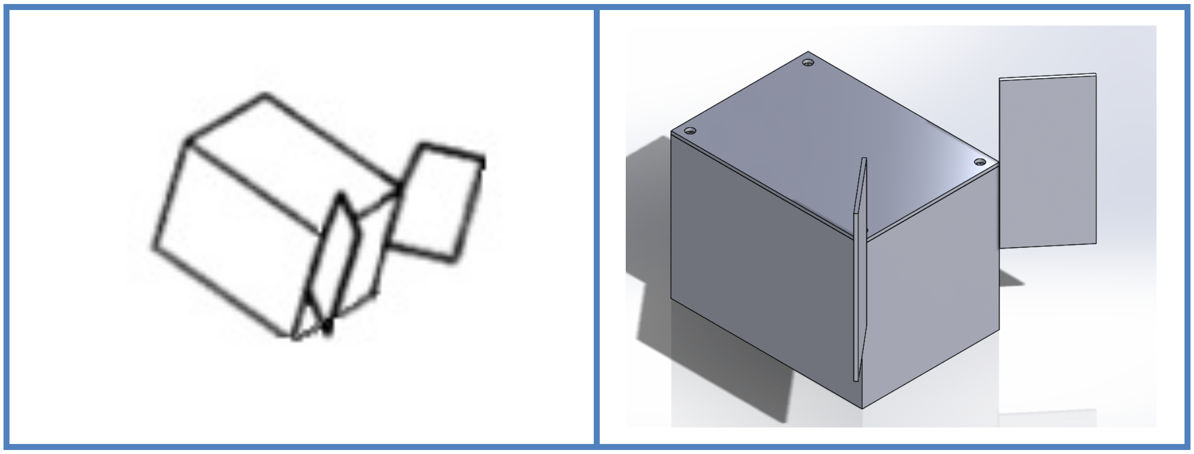


FIGURE 20: ELEVATED FIN DESIGN

The second design was developed from Nyren's drogue chute. This design consisted of a drogue chute affixed to the back of the box by a "kite-tail" line. The line and the drogue chute would have weights affixed to certain points that would keep the chute from becoming unstable and getting caught in the tail rotor of the helicopter.

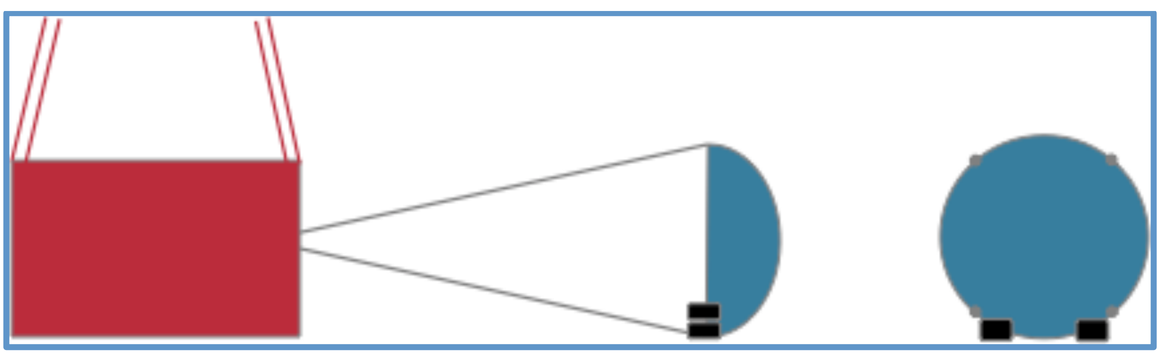


FIGURE 21: DROGUE CHUTE DESIGN

The third design was a purely original design based on a parafoil kite. The design consisted of two layers of fabric draped over the Conex container and affixed at the edges and corners. There would be sets of lengthwise fins between the two fabric layers to form tunnels, which would direct airflow parallel to the container to stabilize it in flight.

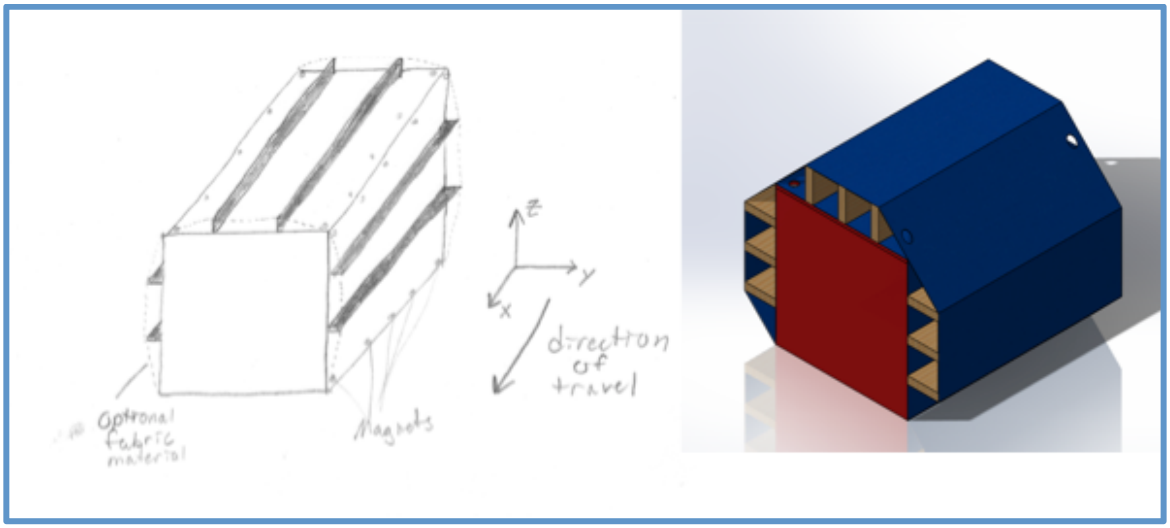


FIGURE 22: FINNED FABRIC DESIGN

The final design was another original idea that consisted of three triangular fins mounted to the rear of the Conex container and a curved structure mounted on the front of the Conex. The fins at the back of the Conex would provide stabilizing moments for any yaw motion of the container, while the curved surface at the leading edge of the Conex would smooth flow around the Conex, preventing yaw and sway motion.

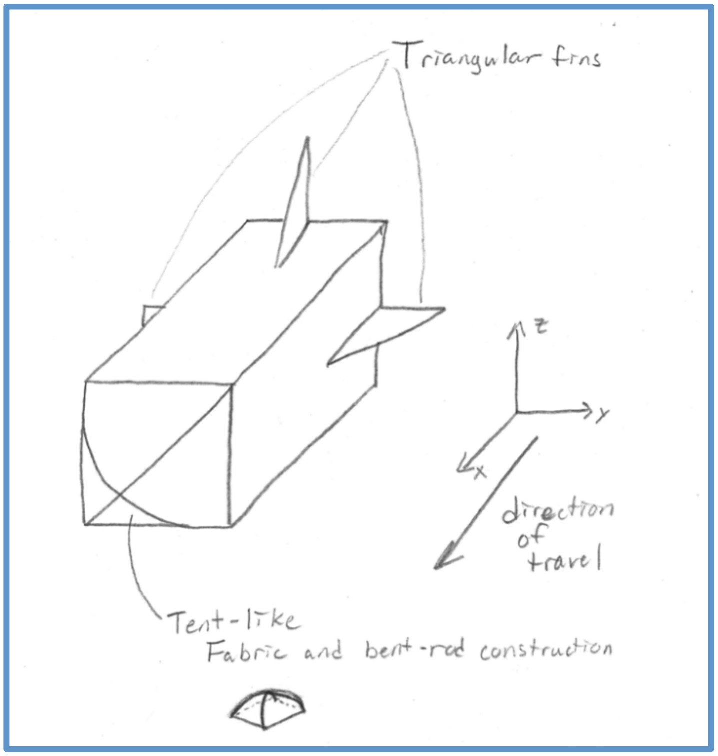


Figure 23: Shuttle Design

After a meeting with the Natick Soldier Research, Development & Engineering Center (NSRDEC) representative of this project, Daniel Nyren, it was decided that one literature based design and one original design would be tested, the “elevated fin” and the “finned fabric” respectively. It was also decided that the analysis would be performed using a model Tricon container (8ft x 8ft x 6.5ft), not a Conex container.

3.7.2 Designs Tested

Two designs for passive stabilization were tested to determine the effectiveness of the (1) Elevated Fin and (2) Finned Fabric designs in stabilizing the Tricon container. The first was a previously tested concept and the second was an original design. Throughout the design process, full-scale concepts were considered in order to ensure adaptability of these designs to a variety of payloads. Testing scaled designs involved comparison with a baseline: a Tricon container without any stabilizing designs.

3.7.3 Elevated Fin Design

The elevated fin design uses two vertical fins mounted to the back of the model with half their height above the top of the container and initially set at a 40 degree angle to the sides. This design is based on ones described in a report by Raz et al.[14]. Separate models were made for both the Tricon container and the Humvee. The first model was constructed out of 1/4” thick balsa wood with a single hook used to attach over the rim of the scaled model, hinges allowed the fin angle to be changed however in order to set the fin angle a connecting bar was fixed in place between the fins which combined with an excess of glue which ran into the hinges rendered the model incapable of movement. Upon inspection of the designs it was determined that the thickness of the wood would interfere with the aerodynamics of the design so a second model was constructed using thinner wood.

3.7.4 Finned Fabric Design

The idea behind the Finned Fabric design was to direct airflow around the slung load, decreasing its “bluff body” aerodynamic effects and its total drag. As air flowed through each fabric channel, any yawing of the load would impart a force on each fin, turning the Tricon into its optimal flight direction. The entire stability design was to be constructed out of fabric specifically because it would greatly reduce the weight of the final structure, and it could be easily folded for storage when not in use. The fabric components would also make it very easy to affix it to many different loads, as it would conform to any shape that is was laid across, without the necessity of modifications.

The scaled Finned Fabric design was constructed out of black fabric and the fins were cut from thin PVC packaging plastic. For all following prototypes, the fins were cut out of thin boxboard, as it was much easier to acquire than the PVC and was thin enough that any effects from the differing thicknesses could be neglected.

The base fabric layer was cut into a 5.64 inch by 15.87-inch rectangle, such that it could be draped over the width and two side heights of the Tricon model. The PVC sheet was cut into 8 0.56-inch wide, 5.64-inch long strips. The base fabric layer was then marked at evenly spaced intervals for each of the Tricon’s surfaces and the PVC strips were glued at these points. The strips were aligned with the length of the Tricon model and glued so they stood perpendicular to the fabric surface. Another piece of fabric was cut 5.64 inches wide, with excess length so it would form a shell around the base fabric layer and fin construction. The two fabric layers were sewn together at the vertices of the Tricon container, and the entire construction was affixed to the Tricon model with clear scotch tape. The tape sealed all possible airflow paths besides the designed finned fabric channels.

After preliminary discussion and testing, a few modifications were made to the finned fabric design. Further analysis of forces and moments about the Tricon's center of mass pushed these modifications, as the "full length" finned fabric design would not have a moment arm to produce a yaw-correcting moment. These modifications included shortening the channeled shell around the Tricon so it only covered the back portion of the Tricon, increasing the desired vertical stabilizer ("weathervane") effect. Half-length shells of different fin heights were also constructed, including one with 1.13-inch fins and another with fins that sloped from 1.13-inches to 0.56-inches, and a quarter-length shell with 1.13-inch fins was also tested to further increase the vertical stabilizer moment.

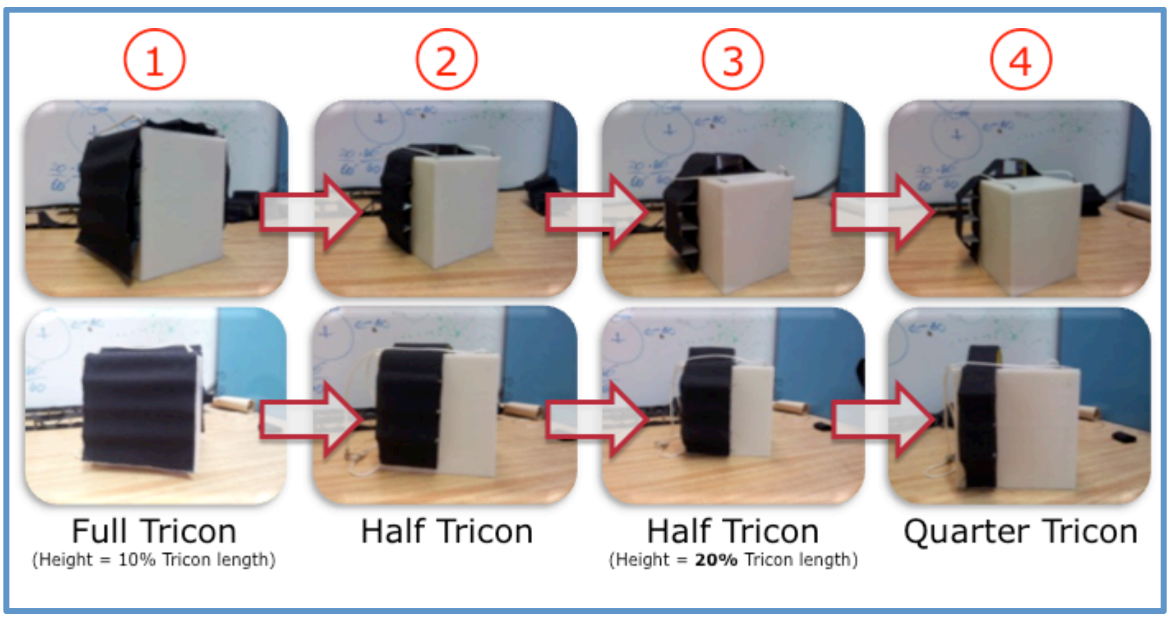


FIGURE 24: FINNED FABRIC ITERATION STEPS

4 Findings & Discussion

4.1 Tricon Baseline Test

Below is the Tricon's baseline test force transducer data. This test was performed with the Tricon in the wind tunnel with the tunnel's frequency set to 15.9 Hz, equivalent to 12.7 m/s airspeed. This was the approximate scaled cruise speed of the Blackhawk helicopter, which is the primary sling-loading helicopter currently in use by the US Army and NSRDEC. The force transducer's positive Y-axis direction was in the direction of airflow in the wind tunnel. The positive Y-axis direction was perpendicular to the direction of airflow, and pointing away from the wind tunnel's recirculating section. Finally, the positive Z-axis was pointing straight downward from the transducer.

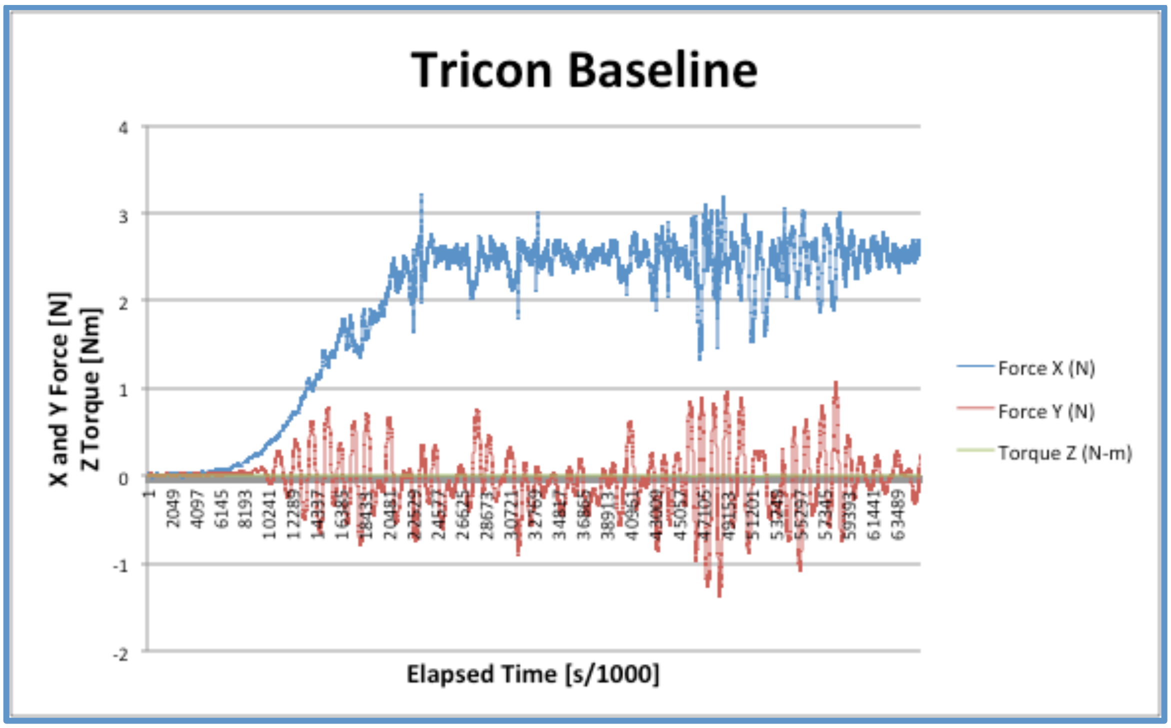


Figure 25: Tricon Baseline Test Results

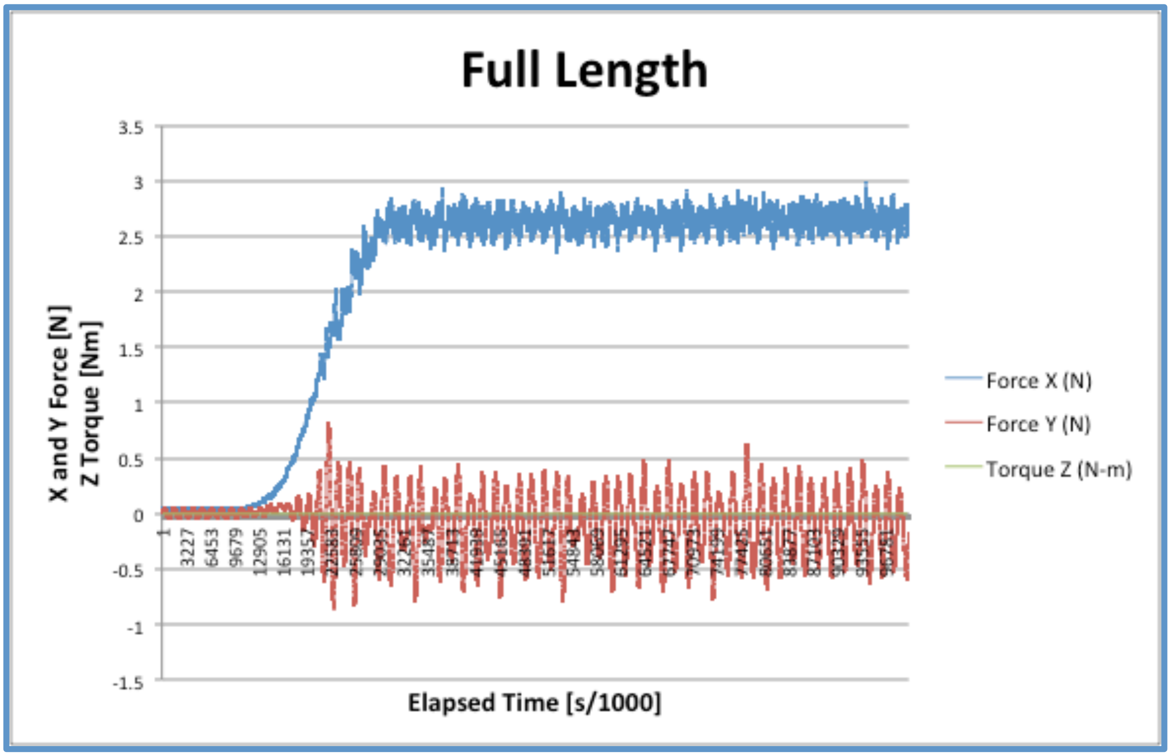
This data clearly shows the inherent instabilities of the Tricon without the use of any stabilizing apparatus. The torque about the Z-axis was relatively low compared to the forces in the X and Y directions. The forces along the X-axis oscillated around about

2.5 N as the container was pushed in that direction by the airflow. The forces along the Y-axis oscillated about the 0 N value as the Tricon swayed back and forth.

4.2 Finned Fabric Tests

4.2.1 Full Length

The first Finned Fabric model's test data is displayed below:



This graph shows that the full Tricon length Finned Fabric model stabilizes the Tricon in the x direction, as it does not show large oscillations about the 2.5 N value. The Y axis forces oscillated in a more predictable fashion than those from the Tricon baseline, but these forces were still relatively large compared to the damped X axis forces. This result showed that the first Finned Fabric model did not sufficiently reduce sway motion.

4.2.2 Half Length

The second iteration of the Finned Fabric design shortened the fin length to half of the length of the Tricon, with hopes to increase the moment arm about the Tricon's center of mass. This not-insignificant moment arm would provide larger moments that would correct the Tricon's yawing motion and, in turn, dampen its swaying along the Y axis.

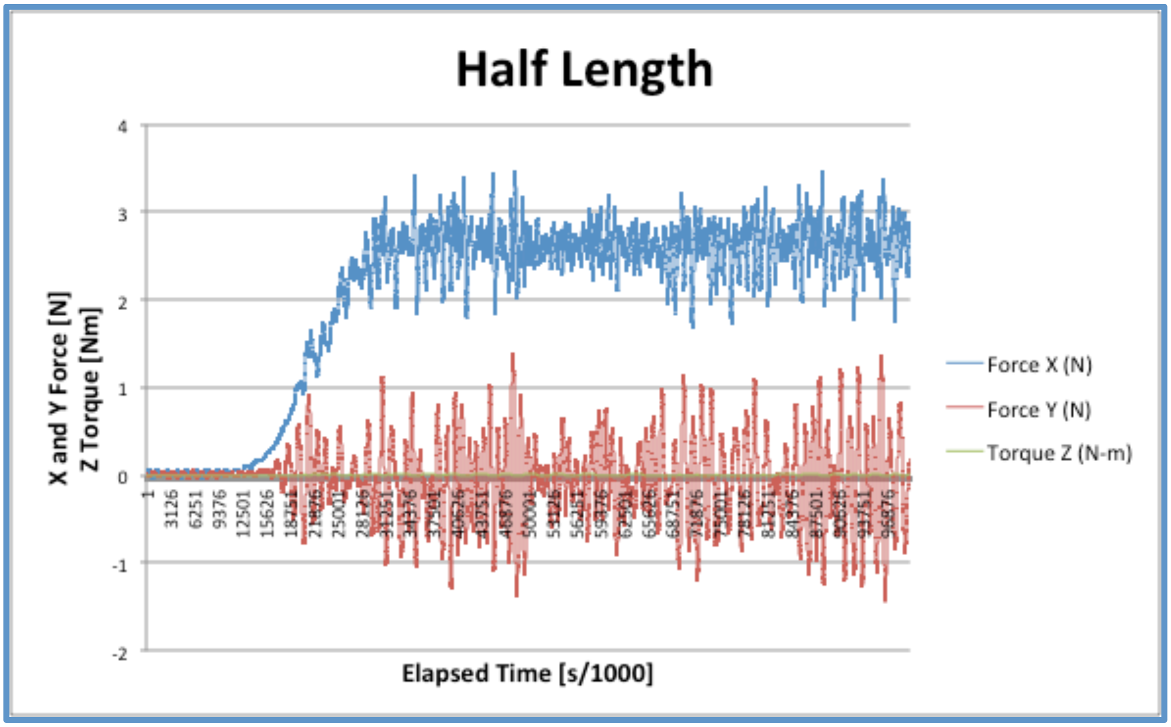


FIGURE 26: FINNED FABRIC TEST RESULTS: HALF LENGTH

The graph above shows that the half-length Finned Fabric design did not stabilize the motions in the X or Y directions as much as the full-length design did.

4.2.3 Half Length, Double Fin Height

The third iteration of the Finned Fabric design increase the height of its fins to 20% of the Tricon's length, as opposed to the previous designs' 10%. This was done to increase the available fin area to provide larger correcting forces, and also minimize the boundary effects that the previous designs' outer fabric shells may have experienced.

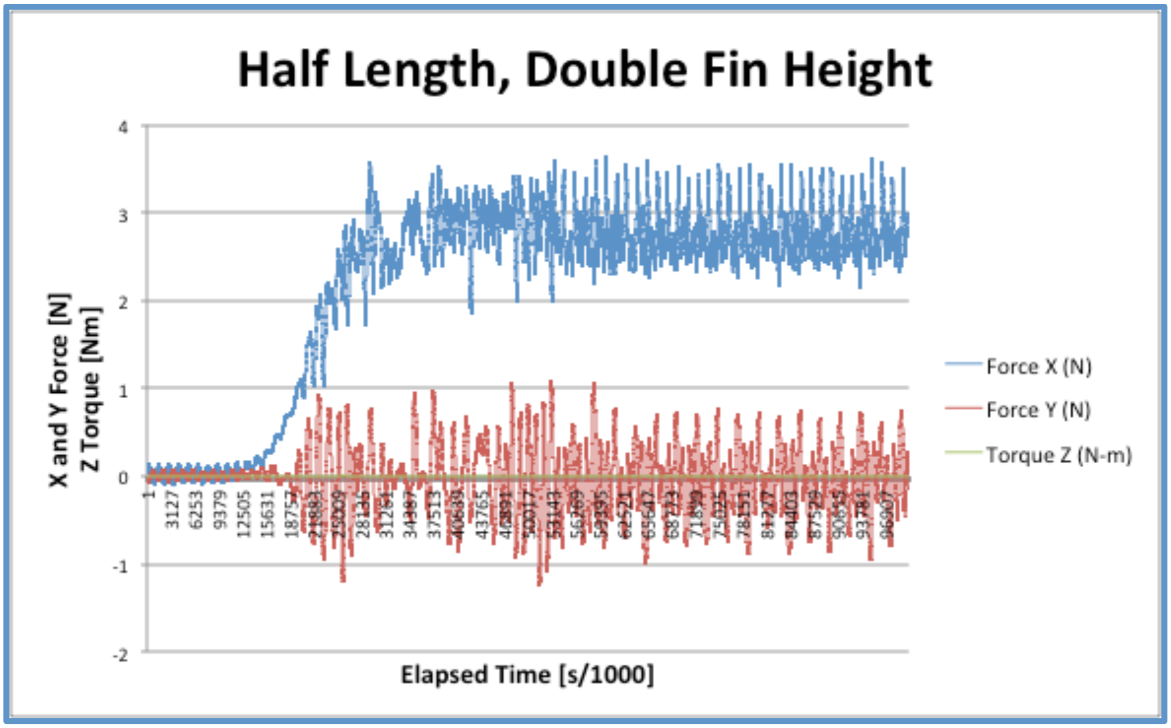


FIGURE 27: FINNED FABRIC TEST RESULTS: HALF LENGTH, DOUBLE HEIGHT

The X and Y-axis forces for this iteration oscillated in a more predictable fashion that it's shorter finned counterpart, while the Y axis forces were also decreased overall. However, the forces and oscillations were still too large, and a visual inspection of the Tricon during this test would show that the Tricon was still relatively unstable.

4.2.4 QUARTER LENGTH

The final iteration of the Finned Fabric design was to further shorten the length of the fins such that they only covered the rear portion of the Tricon. This was again done in pursuit of maximizing the available moment about the Tricon's center of mass to provide correcting moments and decrease yaw and sway motion.

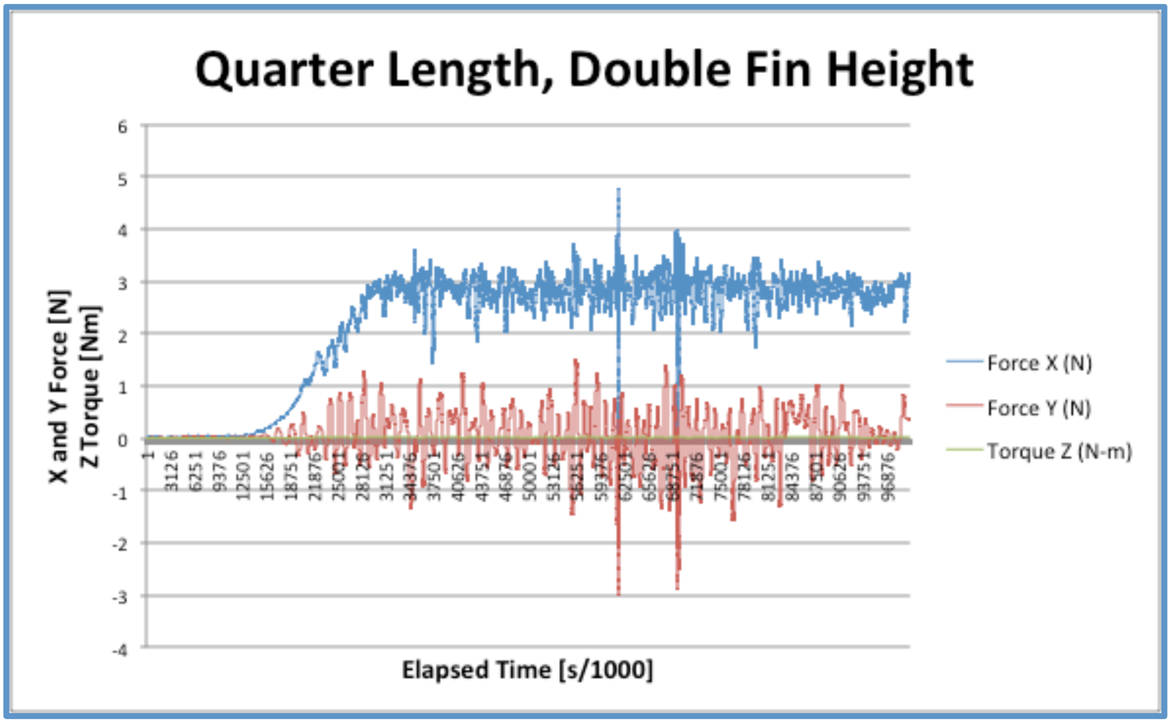


FIGURE 28: FINNED FABRIC TEST RESULTS: QUARTER LENGTH, DOUBLE HEIGHT

The graph above shows that the forces in the X and Y directions were a bit more stable and predictable than those of the half-length, double fin height design. However, the Tricon did hit the wall of the wind tunnel about one minute into the test. Again, from a purely visual inspection of the Tricon's motion during this test, the quarter length Finned Fabric design also did not stabilize the Tricon significantly.

4.2.5 FUTURE FINNED FABRIC CONSIDERATIONS

As the above data shows, shortening the Finned Fabric design such that it covers less of the Tricon and produces larger moments about its center of mass does not provide significant stabilizing effects. However, given the behavior of the full length Finned Fabric model, it may be possible to further increase the effectiveness of this model in a different way. It is possible that increasing the height of the full-length design's fins could stabilize the Tricon even more than the 10% Tricon length fins did. Also, removing the outer fabric shell on this design could possibly improve the stability rather than detract from it, as previously thought. While the outer fabric shell clearly defines the flow path of the air, it also dramatically increases the drag for the entire stability system. If the outer shell were removed, it would lower the drag, while still providing a reasonable stabilizing effect.

This last point is exemplified in the two graphs below.

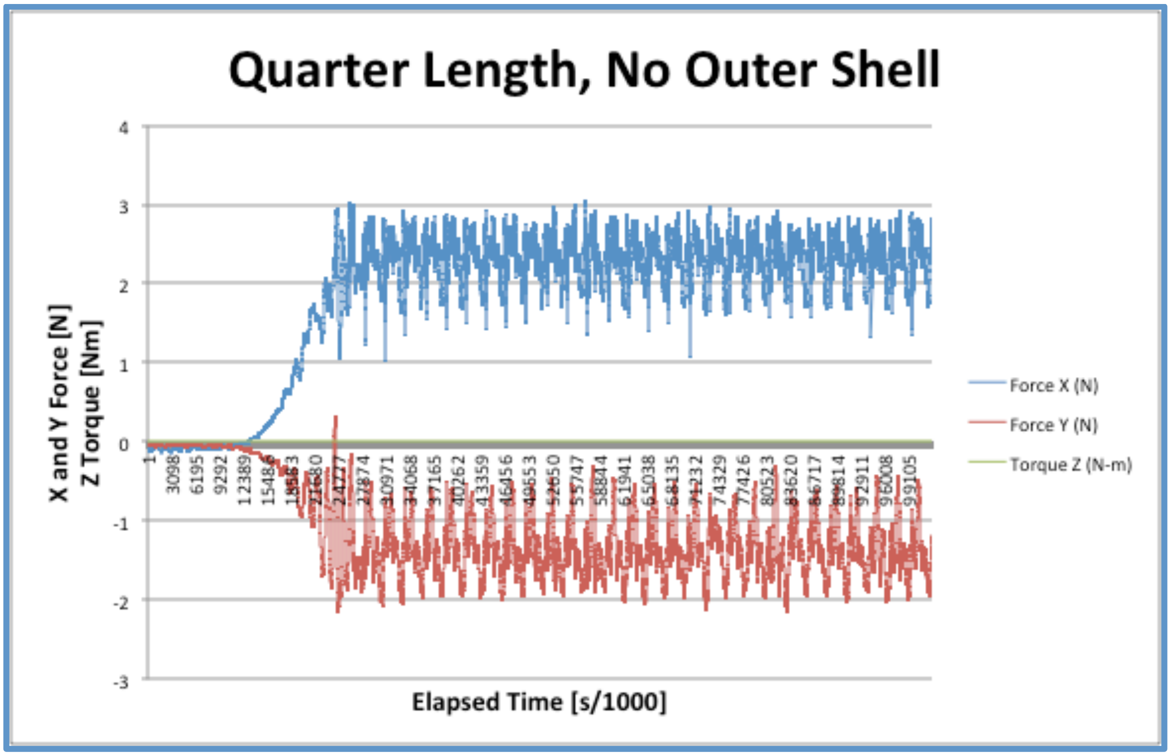


FIGURE 29: FINNED FABRIC TEST RESULTS: QUARTER LENGTH, NO OUTER SHELL

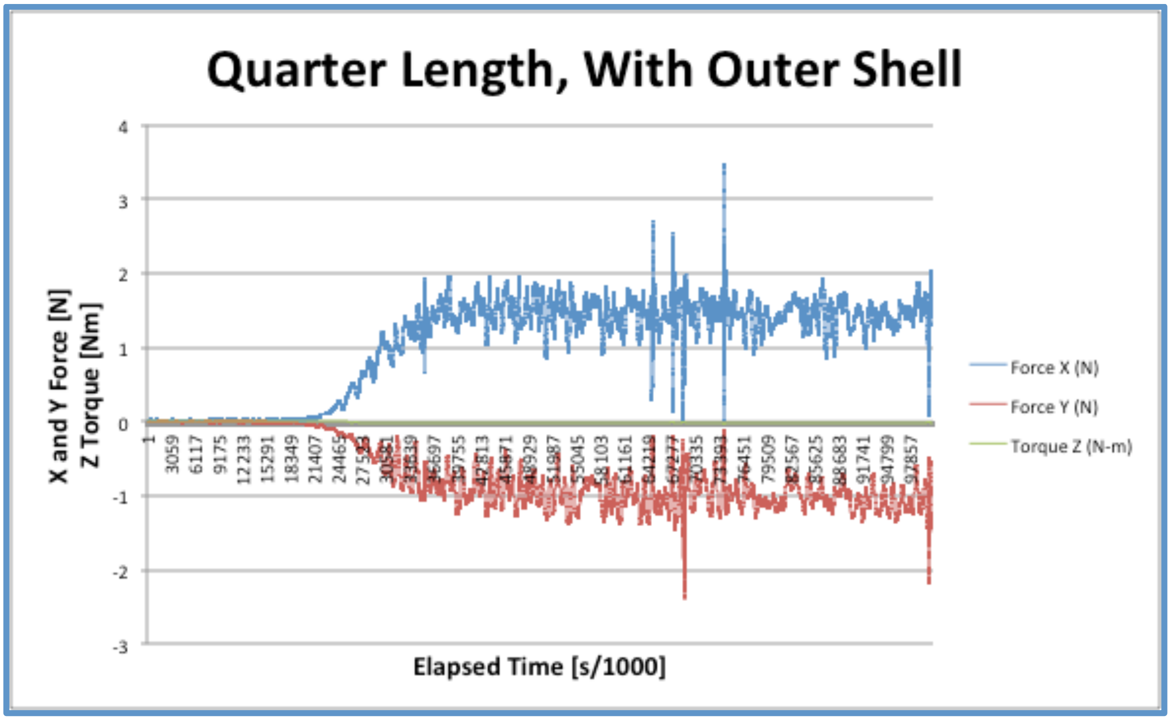


FIGURE 30: FINNED FABRIC TEST RESULTS: QUARTER LENGTH, WITH OUTER SHELL

*There was a problem during the calibration of these two tests, which is why the results for the quarter length only included another proper test with the outer shell, as it was fully assembled at that point.

From these two graphs, it seems that the outer fabric shell decreases the overall magnitude of the forces, but leaves the Tricon's oscillating motion rather unpredictable. Removing the outer fabric shell increases the magnitude of the forces on the Tricon, but its oscillations are much more predictable and could possibly be dampened with fins that span a larger percentage of the Tricon's length.

4.3 ELEVATED FIN TESTS

The elevated fin design was not tested as extensively as the Finned Fabric design, as it had already been previously tested and proven to be inherently stable by Raz et al.'s study in 2010. However, an unmodified elevated fin stability test was run at the scaled 12.7 m/s wind tunnel speed and video was captured for qualitative analysis. This test also utilized the force transducer for quantitative measure, but a mistake was made in the initial setup on that test day, so the force transducer's axes were not properly aligned with the wind tunnel's airflow direction, and the data did not accurately portray the elevated fin's stabilizing effects. Below is the resulting graph from that test day.

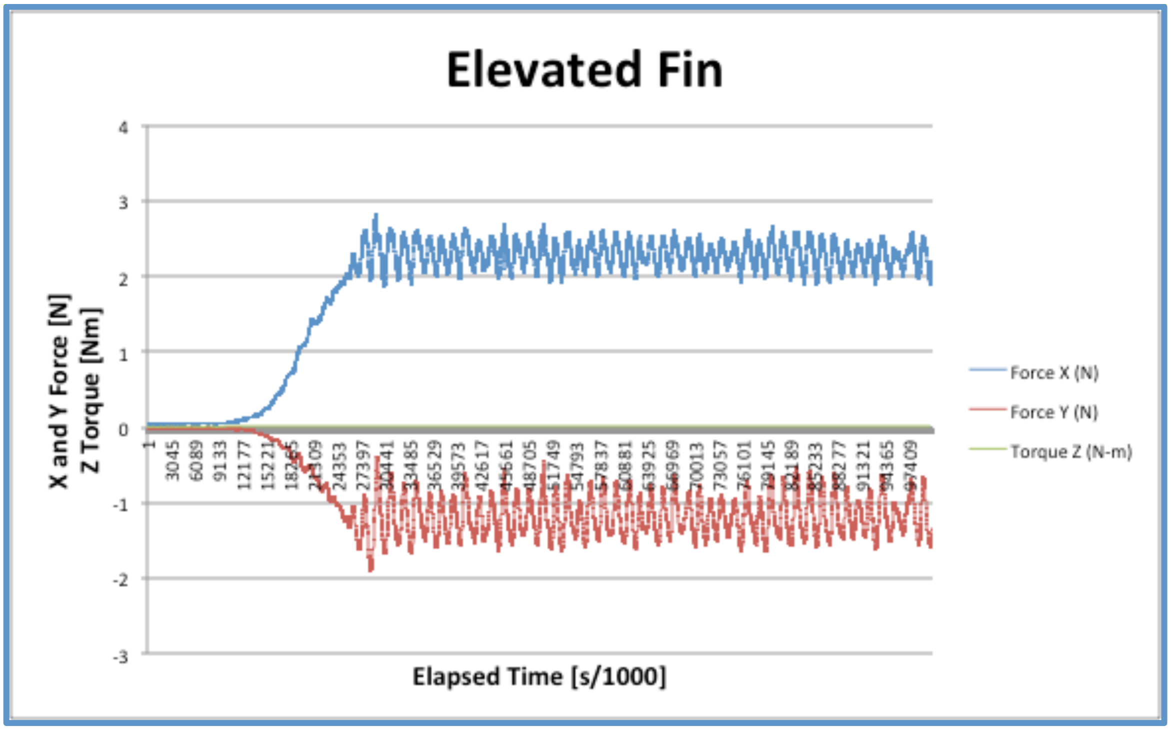


FIGURE 31: ELEVATED FIN RESULTS (SKEWED AXES)

As seen from the graph above, the scaled Tricon's oscillations in the X and Y directions were decreased significantly from the un-stabilized baseline Tricon tests. Although the torque values for all tests remained very low, this test saw a negligible amount of torque on the force transducer's Z-axis, as the Tricon did not yaw to any significant degree compared to the Finned Fabric design.

Further testing of optimized forms of the elevated fin design was planned, but never came to fruition, and is suggested as the base for further research. Options for this optimization include decreasing the elevated fins' areas in order to minimize cost and the required mounting scheme's strength, as well as changing the fins' shape and angle to maximize stabilizing effects. These two strategies were discussed and planned out in length, however, the responsible parties were not able to complete construction or test them.

4.4 Humvee Testing

4.4.1 Humvee Baseline Testing

The results from the scaled Humvee test are shown below. Its responsible party did not do additional testing after the force transducer's axes were realigned, so the forces shown do not accurately represent its motion compared to the traditional wind tunnel axes.

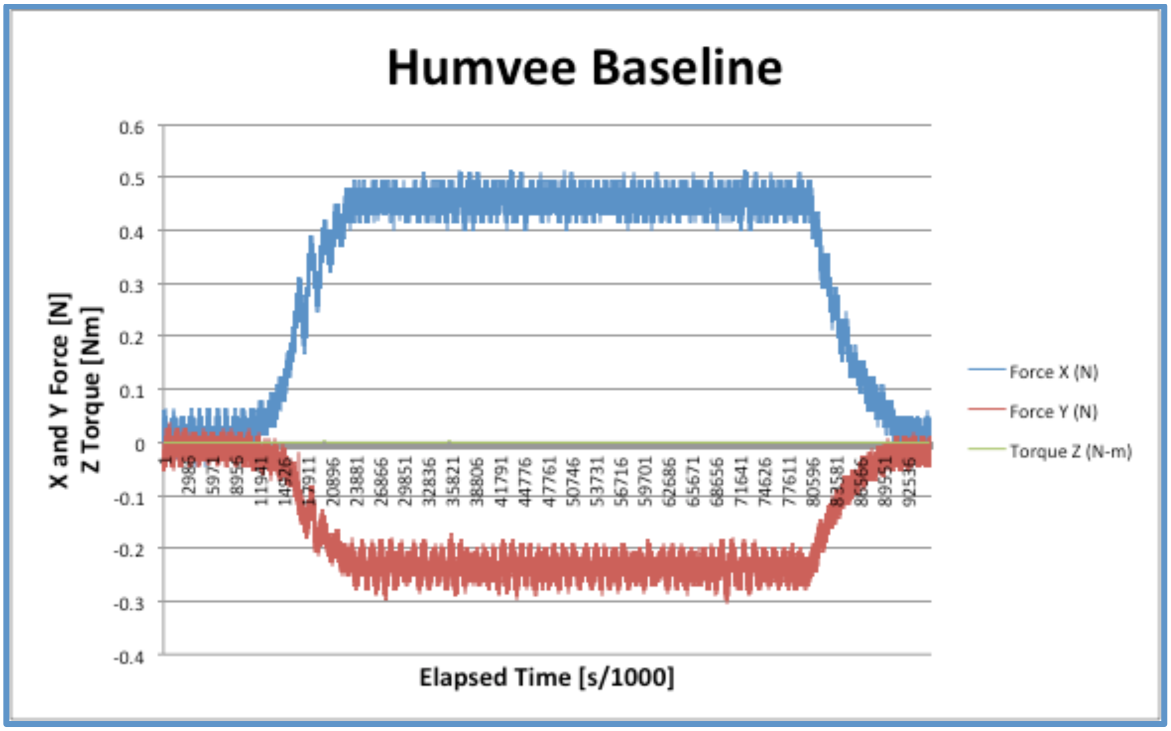


Figure 32: Model Humvee Baseline Testing

This data shows that the scaled Humvee was rather unstable, and it finally settled to a completely horizontal flight configuration, with the broad side of the Humvee facing into the airflow.

4.4.2 Humvee Elevated Fin Testing

A rough model of the Elevated Fin was constructed and tested on the Humvee. Below are the data that correspond to this test.

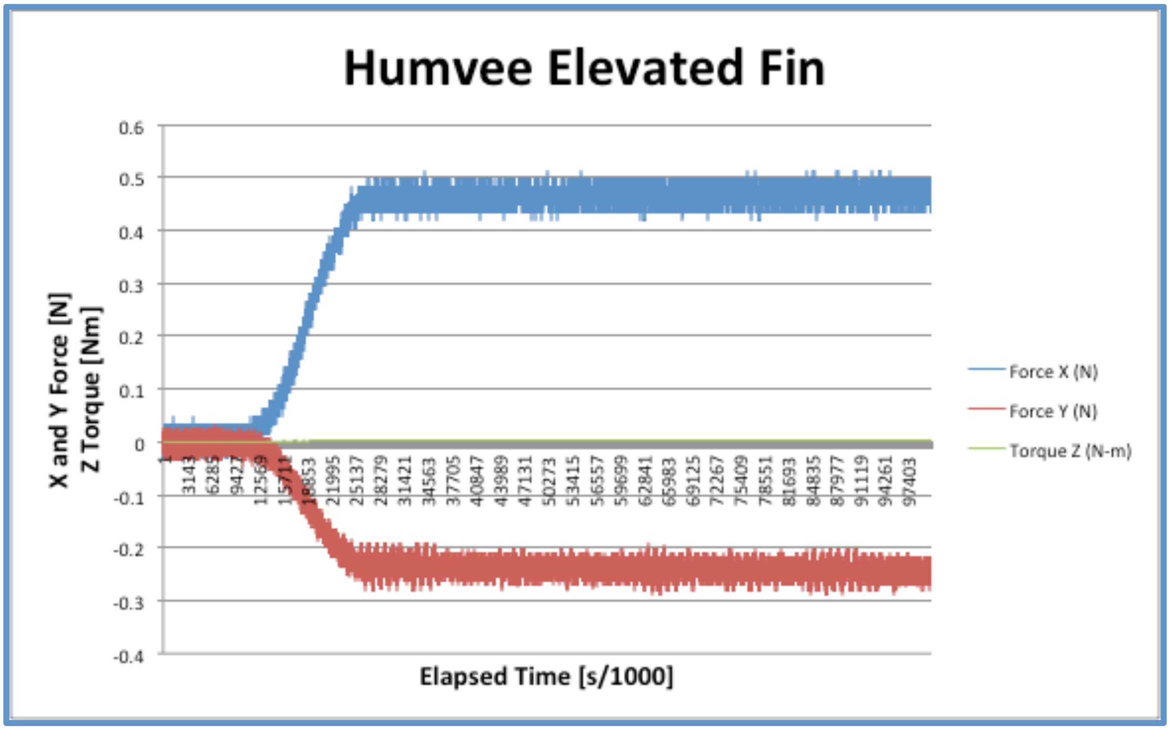


FIGURE 33: MODEL HUMVEE ELEVATED FIN TESTING

The Elevated Fin is a viable method of stabilizing the Humvee, as it remained stable, facing into the airflow for the entire test, with minimal sway and yaw motion.

4.4.3 Humvee Finned Fabric Testing

As there were many more iterations of the Finned Fabric design to be tested on the scaled Tricon, and the initial test results from the Finned Fabric were not promising, the team agreed that scaled Humvee testing for the Finned Fabric design was not needed. Also, as the project proceeded through its final stages the responsible parties were not able to deliver the scaled Humvee on testing days, and therefore made it infeasible to design and test Humvee Finned Fabric designs.

4.5 Full Scale Mounting Plans and Discussion

As all the above research was done on small-scale prototypes affixed with clear Scotch tape, a real-world stabilizing and attachment strategy is yet to be researched by the US Army. A feasible option would be to use neodymium or "rare-earth" magnets. These super-strong magnets come in many shapes and sizes, and the larger ones can produce a very large holding force when placed on a steel surface. Specifically discussed during the infancy of the Finned Fabric design, the idea of utilizing magnets to affix stability schemes has grown to encompass many different stability prototype applications for the team.

Specific magnetic forces were estimated using "The Original K&J Magnet Calculator" offered on the K&J Magnetics website (https://www.kjmagnetics.com/calculator.asp). From these estimates, it was concluded that a circular magnet of 3 inches in diameter and 1 inch thick would provide 400 pounds of holding force when placed on a flat steel surface. And at $173.09 per magnet, these magnets are a reasonable option for easy attachment and detachment of full-scale sling load stability prototypes.

5 Conclusions and Recommendations

5.1 Finned Fabric and Elevated Fin

A few future recommendations can be drawn from the data expressed above. First, further research on the Finned Fabric design is necessary. The given data does not show a significant improvement in load stability from this prototype. This includes optimizing the fin heights, fabric shell usage, and construction materials to more effectively use the aerodynamic forces on it. Second, the elevated fin model provided the most passive stability from this project, however it had already been proven and focus should be put into optimization; specifically to find the smallest fin area that will still provide stabilizing effects. Other angles for the elevated fin should also be explored, as the 40-degree angle was relatively arbitrary and based the report by Raz et al.. Finally, testing and stability prototype mounting strategies for the Humvee model should be researched, as there wasn't enough time or availability of the physical model to fully test it.

5.2 RC Helicopter

Although scaled RC helicopter testing did not come to fruition, development of the RC helicopter testing leaves future researchers with a place to start. The promise of real-world testing has caused many evolutions in the experimental setup of the T-Rex 700 and special interest should be taken into improving the undercarriage design and fabricating the detachable sling hook. In order to test for longer periods of time, future researchers should purchase several battery packs to enable more design testing per trial. Above all, operators should be safe with these powerful machines and always pilot with great caution.

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7 Appendices

Appendix A: Tricon Container Specifications



Features

- All CORTEN steel monocoque construction
- Three-way forklift pockets
- 10,000 lbs. rated "E" track system for shoring and shelving options
- Full-width access doors on one side of container
- 26-2,000 lbs. rated lashing points
- Over 5.5 tons (12,000 lbs.) payload capacity
- ISO tested and CSC approved by Lloyd's Register for use in the 20' module configuration
- Over 9.6 cubic meters (346 cubic feet) of internal capacity
- Easily repaired (essentially same construction as a 20'/40' steel container)
- 1-Year Warranty on materials and workmanship

Specifications (Tricon I)

External Length	2,438 mm	96"
External Width	1,968 mm	77.5"
External Height	2,438 mm	96"
Internal Length	2,299 mm	90.5"
Internal Width	1,882 mm	74.06"
Internal Height	2,262 mm	89.06"
Door Opening Width	1,874 mm	73.75"
Door Opening Height	2,164 mm	85.187"
Maximum Gross Weight	6,759 kg	14,900 lbs
Tare Weight	1,134 kg	2,500 lbs
Payload Weight	5,625 kg	12,400 lbs
Internal Volume	9.9 cu.m	346 cu.ft
Fork Pocket Height	118 mm	4.65"
Fork Pocket Width	356 mm	14.02"
Fork Pocket Centers	902 mm	35.5"

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TREX 700E INSTRUCTION MANUAL

使用說明書

KX018E06T

F3C

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Contents

Thank you for buying ALIGN products. The ***T-REX 700E F3C*** is the latest technology in Rotary RC models. Please read this manual carefully before assembling and flying the new ***T-REX 700E F3C*** helicopter. We recommend that you keep this manual for future reference regarding tuning and maintenance.

承蒙閣下選用亞拓遙控世界系列產品，謹表謝意。進入遙控世界之前必須告訴您許多相關的知識與注意事項，以確保您能夠在學習的過程中較得心應手。在開始操作之前，請務必詳閱本說明書，相信一定能夠給您帶來相當大的幫助，也請您妥善保管這本說明書，以作為日後參考。

3.EQUIPMENT REQUIRED FOR ASSEMBLY 自備設備

ALIGN

RADIO TRANSMITTER AND ELECTRONIC EQUIPMENT REQUIRED FOR ASSEMBLY 自備遙控及電子設備

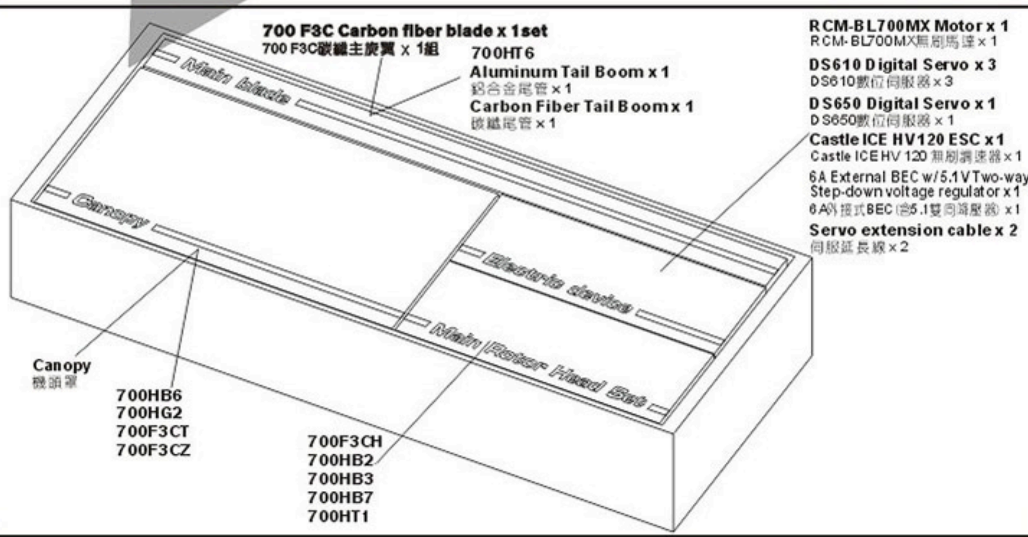
 Transmitter (7-channel or more,helicopter system) 發射機(七動以上直昇機模式遙控器)	 Receiver(7-channel or more) 接收機(七動以上)	 Li-Po Battery Charger Li-Po電池充電器
 22.2V 6S 4500~5200mAh Li-Po Battery x 2pc 22.2V6S 4500~5200mAh Li-Po電池 x 2	 Receiver battery 7.4V 2S 1900~2300mAh Li Po x 1pc 接收機電池7.4V2S 1900~2300mAh Li-Po x 1	 Dial Pitch Gauge x 1pc 旋轉式螺距規 x 1

ADDITIONAL TOOLS REQUIRED FOR ASSEMBLY 自備工具

 Scissors 剪刀	 Cutter Knife 刀子		 Diagonal Cutting Pliers 斜口鉗	 Needle Nose Pliers 尖嘴鉗
 Oil 潤滑油	 CA 瞬間膠	 AB Glue AB膠	 Hexagon Screw Driver 六角螺絲起子 3mm/2.5mm/2mm/1.5mm	 Philips Screw Driver 十字螺絲起子 ф3.0/ф1.8mm

4.PACKAGE ILLUSTRATION 包裝說明

ALIGN



5.SAFETY CHECK BEFORE FLYING 飛行前安全檢查重要事項

CAREFULLY INSPECT BEFORE REAL FLIGHT 請嚴格執行飛行前之檢查義務

☆Before flying, please check to make sure no one else is operating on the same frequency for the safety.
☆Before flight, please check if the batteries of transmitter and receiver are enough for the flight.
☆Before turn on the transmitter, please check if the throttle stick is in the lowest position. IDLE switch is OFF.
☆When turn off the unit, please follow the power on/off procedure. Power ON- Please turn on the transmitter first, and then turn on receiver. Power OFF- Please turn off the receiver first and then turn off the transmitter. Improper procedure may cause out of control, so please to have this correct habit.
☆Before operation, check every movement is smooth and directions are correct. Carefully inspect servos for interference and broken gear.
☆Check for missing or loose screws and nuts. See if there is any cracked and incomplete assembly of parts. Carefully check main rotor blades and rotor holders. Broken and premature failures of parts possibly cause resulting in a dangerous situation.
☆Check all ball links to avoid excess play and replace as needed. Failure to do so will result in poor flight stability.
☆Check if the battery and power plug are fastened. Vibration and violent flight may cause the plug loose and result out of control.
☆Be sure to use the carbon fiber main rotor blades durable with 2800RPM(or faster) 700mm length. Please do not use the carbon fiber main rotor blades with durability lower than 2800RPM and wooden or glass fiber main blades to avoid any unpredictable damage.

★每次飛行前應先確認所使用的頻率是否會干擾他人，以確保你自身與他人的安全。
★每次飛行前確定您發射機與接收機電池的電量是在足夠飛行的狀態。
★開機前確認油門搖桿是否位於最低點，熄火降落開關，定速開關(IDLE)是否於關閉位置。
★關機時必須遵守電源開關機的程序，開機時應先開啓發射機後，再開啓接收機電源；關機時應先關閉接收機後，再關閉發射機電源。不正確的開關程序可能會造成失控的現象，影響自身與他人的安全，請養成正確的習慣。
★開機請先確定直昇機的各個動作是否順暢，及方向是否正確，並檢查伺服器的動作是否有干涉或崩齒的情形，使用故障的伺服器將導致不可預期的危險。
★飛行前確認沒有缺少或鬆脫的螺絲與螺帽，確認沒有組裝不完整或損毀的零件，仔細檢查主旋翼是否有損壞，特別是接近主旋翼夾座的部位，損壞或組裝不完整的零件不僅影響飛行，更會造成不可預期的危險。注意：每次飛行前的安全檢查、保養、及更換損耗零件，請確實嚴格執行以確保安全。
★檢查所有的連桿頭是否有鬆脫的情形，過鬆的連桿頭應先更新，否則將造成直昇機無法操控的危險。
★確認電池及電源接頭是否固定牢靠，飛行中的震動或激烈的飛行，可能造成電源接頭鬆脫而造成失控的危險。
★**主旋翼務必使用耐轉速2800RPM以上的 700mm長度碳纖槳，嚴禁使用耐轉速低於2800RPM的碳纖槳、玻纖槳或木製槳。**

Standard Equipment 標準配備				
 700HC2	 700F3CH	 700HB1	 700HB2	 700HB3
 700HB6	 CNC Slant Thread Main Drive Gear 700HB7	 700HG2	 700F3CT	 700HT1
 700HT6	 700F3CZ	 700 F3C Carbon Fiber Blades x 1set 700 F3C碳纖主旋翼 x 1組	 RCM-BL700MX 470KV Brushless motor x 1 RCM-BL700MX 470KV無刷馬達 x 1	 M4x4 Set Screw x 2 M4x4 止付螺絲 x 2 Motor Slant Thread Pinion Gear 12T x 1 馬達斜齒輪 12T x 1
 DS610 Digital Servo x 3 DS610數位伺服器 x 3 CNC Metal servo horn CNC金屬伺服器舵角片 x 3	 GP780 Head Lock Gyro Combo x 1 GP780鎖定式陀螺儀組(GP780+DS650) x 1	 Castle ICE HV 120 ESC x 1 Castle ICE HV 120 無刷調速器 x 1	 6A External BEC w/5.1V Two-way Step-down voltage regulator 6A外置式BEC(含5.1V雙向降壓器)	

When you see the marks as below, please use glue or grease to ensure flying safety.
標有以下符號之組裝步驟，請配合上膠或上油，以確保使用之可靠度。

CA : Apply CA Glue to fix.
AB : Apply AB Glue to fix.
R48 : Apply Anaerobics Retainer to fix.
T43 : Apply Thread Lock to fix.
OIL : Add Grease.

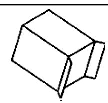
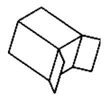
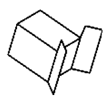
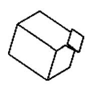
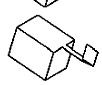
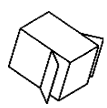
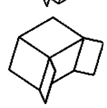
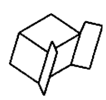
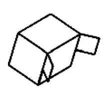
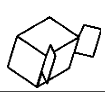
CA：使用瞬間膠固定
AB：使用AB膠固定
R48：使用金屬管狀固定缺氧膠固定
T43：使用螺絲膠
OIL：添加潤滑油

R48 metal tubular adhesive (eg. Bearings). T43 thread lock, apply a small amount on screws or metal parts and wipe surplus off. When disassembling, recommend to heat the metal joint about 15 Seconds. (NOTE : Keep plastic parts away from heat.)
R48 為強力金屬管狀(如軸承)接著劑，T43為螺絲膠，膠合螺絲或金屬內外徑請務必少量使用，必要時請用手去除多餘膠量，欲拆卸時可於金屬接合部位熱烤約15秒。(注意！塑膠件避免接近熱源)

When assembling ball links, make sure the "A" character faces outside.
各項塑膠製連桿頭扣接時，A字請朝外。

APPENDIX C: CONFIGURATIONS TESTED BY RAZ ET AL.

Table 2. Wind tunnel test configurations and results

Conf. No.	Drawing	Description	Weight	Fin Angle (deg)	Dominant Dynamic Behavior
1		Narrow fins on the narrow side	2K	0	±180° yaw oscillations with some longitudinal oscillations
			2K	10	±180° yaw oscillations with some longitudinal oscillations
			2K	20	±180° yaw oscillations with some longitudinal oscillations
			2K	30	±180° yaw oscillations
			2K	40	±180° yaw oscillations
2		Fins on the narrow Side	2K	0	Divergent three axis oscillations with large longitudinal motion
			2K	10	Divergent three axis oscillations
			2K	20	Divergent three axis oscillations
			2K	30	Divergent yaw/lateral oscillations
			2K	40	Divergent yaw/lateral oscillations
			4K	30	Divergent yaw/lateral oscillations
3		High fins on the narrow side	2K	0	Large yaw/lateral oscillations
			2K	30	Divergent yaw/lateral oscillations at low speed. Stable above 60 kt
			4K	30	Divergent yaw/lateral oscillations at low speed. Stable above 70 kt
4		Single fin on the narrow side	2K	0° Short arm	±180° yaw oscillations with large longitudinal oscillations
			2K	0° Long Arm	Unstable oscillations in three axes up to 90 kt. Almost stable above 90 kt
5		Side fins	2K	35	Yaw/lateral oscillations at low speed. Nonuniform spin at high speed
6		Fins on the broad side	2K	40	Yaw/lateral oscillations up to 60 kt. Stable above 60 kt
			4K	30	Yaw/lateral oscillations up to 85 kt. Stable above 85 kt
			4K	40	Yaw/lateral oscillations up to 80 kt. Stable above 80 kt
7		High fins on the broad side	2K	30	Small yaw/lateral oscillations up to 60 kt. Stable above 60 kt
			2K	40	Small yaw/lateral oscillations up to 60 kt. Stable above 60 kt
			4K	30	Small yaw oscillations up to 70 kt. Stable above 70 kt
			4K	40	Small yaw oscillations up to 60 kt. Stable above 60 kt
8		Short fins on the broad side	4K	30	Yaw oscillations up to 70 kt. Stable with low damping above 70 kt
9		Elevated fins on the broad side	4K	30	Small yaw oscillations up to 60 kt. Stable above 60 kt

1) The model was suspended in the tunnel and the tunnel speed was increased from zero to a maximum value and then decreased to zero (accel/decel run). During the run, the sensor outputs (longitudinal, lateral, and yaw angles) and wind tunnel speed were recorded continuously at 30 Hz. Accel/decel runs simulated the acceleration from hover to cruise speed and deceleration from cruise to hover. In addition, important information was obtained on the load trail angle (average longitudinal swinging angle; see Fig. 1) as a function of airspeed. In the flight tests, trail angle was limited to 45° for safety reasons. Thus the trail angle may limit the speed envelope, particularly for light loads.

2) During the second wind tunnel run, the tunnel speed was stabilized at a few discrete values. At each tunnel speed, the model was initially