PORTABLE RECOVERY SYSTEM FOR AN UNMANNED AIRCRAFT WITH A STRAIGHT WING AND A TRACTOR PROPELLER

By

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PORTABLE RECOVERY SYSTEM FOR AN UNMANNED AIRCRAFT WITH A STRAIGHT WING AND A TRACTOR PROPELLER

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Abstract:

The recovery system development effort for an unmanned aircraft (UA) has been documented and examined. The development effort existed to satisfy a customer's need to recover an 80 lb aircraft on unimproved terrain. The recovery system had to be able to be transported in a small portion of the bed of a pickup truck, set up in less than 15 minutes, and operated by highly tasked individuals. The customer was willing to accept impacts to aircraft performance, but impacts were to be minimized to the greatest extent possible. Multiple iterations of designs were developed and tested, starting from a previously established arresting wire recovery system design, evolving through many barrier net configurations. Testing was conducted by suspending an analogue aircraft from a truck-mounted aircraft recovery simulator mechanism, pushing an aircraft through the recovery system, launching an unpowered aircraft into the recovery system, and flying a fully functional aircraft into the recovery system during flight testing. The current design is a barrier system that secures the airframe and decelerates it via two disk brake dissipaters. All of the on-runway recoveries of the mature designs resulted in successful recoveries of the aircraft. Some of the off-runway recoveries resulted in damage to the aircraft. Design changes were implemented to avoid future malfunctions. Additional improvements are proposed for consideration.

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CHAPTER I

MOTIVATION

The ability of an aircraft to perform a mission is influenced by what locations are viable for recovery; just as an aircraft’s endurance, payload capacity, signatures, etc. influence what missions are achievable. The infrastructure and terrain requirements for recovery restrict the locations that are viable for an aircraft’s recovery. The location of recovery affects transit time, time on target, and detectability. The influence of the recovery location on achievable flight paths and predictability of operations account for the potential impact on detectability. The importance of recovery location is evident in the existence of aircraft carriers, temporary runways, and many unmanned aerial system (UAS) designs. The customer’s requirements were driven by the understanding that UAS capability increases as the number of viable recovery locations expands.

CHAPTER II

GOALS

The goal of this thesis is to document and examine the development, fabrication, and testing of UAV recovery system developed during a UAS development project. This document details the design process, fabrication, testing, analysis, and system specifications for iterations of the recovery system.

In addition to recording the development effort, the required capabilities and characteristics of the UAV recovery system are listed early in order to inform the reader’s perspective. A recovery system was developed to satisfy a portion of a contract for the development of a UAS. The UAS was to be capable of landing the aircraft in a small section of flat, unimproved terrain. The recovery system was to be capable of being transported in a small portion of a pickup truck bed. The recovery system was to be capable of being unloaded, set up, operated, disassembled, and packed up by two operators. The recovery system was to limit damage to the aircraft during recoveries. The contract was for a full UAS; therefore, the aircraft’s design could be influenced to accommodate recovery system. The unmanned aircraft developed by Oklahoma State University had a straight wing and a tractor propeller. While modifying the aircraft’s design was an option, design modifications that would negatively affect the aircraft’s performance should be avoided. Discoveries were made during the recovery system’s development process. This paper documents and explains these discoveries in hopes that future researchers can avoid this project’s missteps and build on its successes.

CHAPTER III

RATIONALE

Recovery systems designs' potential for fulfilling requirements and feasibilities were initially considered for an 80 lb, straight wing taildragger with a tractor propeller. This aircraft was being developed in parallel with the recovery system. No extra airframes were constructed solely for the purpose of recovery testing. All recovery testing would have to be done on analogues, the deliverable's predecessors, or one of the deliverable aircraft themselves.

An existing, but minimally tested, recovery system: a steel rope arresting wire run between 2 hydraulic disk brake dissipaters caught by an onboard hook, had been previously developed by OSU. The hook was to be on a detachable mount on the tail, with cables running from the hook itself to a structurally sufficient point near the gear mount. Because this system was previously developed to meet the goals of this effort, this project began with testing of the existing design.

CHAPTER IV

BACKGROUND

Recovery System Concepts and Methods

Recovery methods and recovery systems configurations were compiled through a survey of existing systems and paper designs.

Arresting Wire

An arresting wire recovery method uses a wire or rope that is captured by a hook or clip on the aircraft. The energy is dissipated by either a dampening mechanism attached to the wire or rope, an elastic rope, or a combination of the two methods. This method requires an onboard hook or clip to be carried by the aircraft.

Recovery Net, Barrier, or Barricade

A net, barrier, or barricade system is similar to an arresting wire method, except that a net, barrier, or barricade contacts and conforms to the airframe of the aircraft instead of the being captured by a hook or clip. Identical to the arresting wire method, the energy is dissipated by either a dampening mechanism attached to the net, an elastic net, or a combination of the two methods. No onboard hook or clip is required; however, the aircraft recovery loading locations are dependent on the how net contacts the aircraft.

Aircraft Flaring

Some aircraft flare before landing to increase drag and temporarily increase lift. This change in aerodynamic forces decreases ground speed and temporarily decreases descent rate. Gusts will have a greater impact on touchdown location accuracy due to slower airspeeds.

Onboard High Lift and/or Drag Device

Some aircraft have flaps that can be deployed before landing to augment lift and drag. This change in aerodynamic forces decreases ground speed and affects descent rate. Gusts can have a great impact on touchdown location accuracy due to slower airspeeds.

High/Directed Thrust

Some aircraft have additional or overpowered propulsion systems that augment the thrust line or improve performance of High Lift devices. The weight of such systems typically results in degraded endurance, payload capabilities, etc.

Onboard impact reduction and ground motion dissipaters

Some aircraft have onboard shock absorbers or onboard airbags to allow for impacting the ground at higher vertical speeds. Aircraft sometimes have onboard brakes to slow the aircraft after it is on the ground.

Belly landing capable

Some aircraft land on the underside of the fuselage and/or wing. This can allow for the use of terrain with small imperfections for recovery of the aircraft, where aircraft with landing gear could risk catching the gear on a divot.

Expendable Aircraft

Expendable aircraft are aircraft that fly missions without the requirement of recovery. The cost of the aircraft is low, and the supply of the aircraft is adequate enough that the aircraft can crash and the mission is still considered a success.

Existing Recovery Systems

RQ-7 Shadow / RQ-5 Hunter / X-47B

The RQ-7 Shadow, RQ-5 Hunter, and X-47B use arresting wires to shorten the length of runway required for recovery. The Shadow and Hunter touchdown on a runway and roll for multiple seconds before engaging the arresting wire. Both arresting wires are elevated off the ground by rubber doughnuts. Both aircraft have hooks that attach to the main gear structure. The Shadow uses DGPS for more reliable location data during recovery. Sometimes, multiple redundant arresting wires are set up do increase the chance of a successful capture.

Figure 1 : Shadow Arresting Wire System

Figure 2 : Hunter Tailhook

The arresting wire recovery method of the Shadow and Hunter, the multi-second pre-capture roll, would not satisfy this effort's requirement of recovering on unimproved terrain.

The Shadow has a barrier system that engages the nosewheel if the wire arrest is unsuccessful. This barrier must have the potential of damaging the aircraft; otherwise, the arresting wire(s) and hook would not be used.

Figure 3 : Shadow Barrier System

The X-47B deploys flaps and performs a late flare during an arresting recovery. The X-47B captures the arresting wire immediately after touchdown. Many US Navy aircraft also capture the arresting wire immediately after touchdown, including the F-18 and the F-35B.

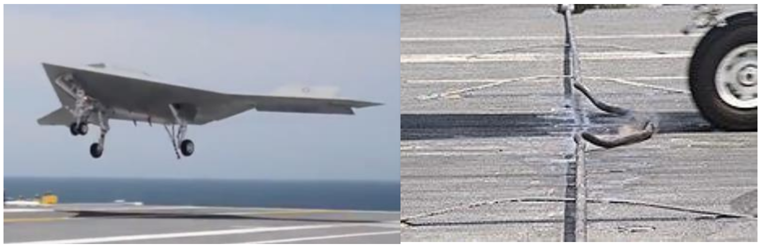


Figure 4 : X-47B Arresting Wire System

The X-47B hook is attached to the aft of the aircraft, similar to the tailhooks of many US Navy aircraft. If the X-47B's hook misses the arresting wires, the X-47B performs a touch and go. A touch and go would be a hazardous act from an unimproved terrain, where an unpredictable moment could be imparted to the aircraft by uneven terrain.

MQ-27B ScanEagle / RQ-21 Blackjack

ScanEagle and Integrator both use vertical arresting wires recovery systems. Vertical wire systems require DGPS, or an alternate navigation system that provides more reliable location data than satellite-based GPS. Vertical wire recovery systems have historically required a trailer transported structure. A structure that could not fit in a portion of pick-up truck would conflict with this effort's portability requirement.

Figure 5 : ScanEagle Skyhook

Figure 6 : Integrator Skyhook

A developmental system, Flying Launch and Recovery System (FLARES), greatly increases portability of the vertical wire recovery system. FLARES uses an electric multi-rotor to suspend the vertical wire. A portable vertical wire system may have fulfilled all of this effort's requirements, but the barrier system and aircraft were already developed and flight tested before the development team became aware of this method of suspending the arresting wire.

T-20 / Jump 20

An inflatable net and landing pad recovery system was developed for the Arcturus T-20. Padding, inflatable or solid, could be used to achieve the goals of this effort, but when used extensively, would negatively impact portability. In the case of inflatables, reliability and set-up tasking would be negatively affected.

Figure 7 : T-20 Net System

Alternatively, the T-20 can belly land on runways and well-maintained paved roads. Belly landing on unimproved terrain would require a retractable camera, foldable propeller, and strengthened fuselage. Belly landing on unimproved terrain might result in increased frequency of aircraft damage.

Figure 8 : T-20 Belly Landing

A VTOL variant of the T-20, the JUMP 20, eliminates the need for the inflatable recovery system or a location suitable for belly landing. The VTOL system, electric multi-rotor, negatively impacts endurance/payload capacity. A VTOL system would not satisfy this effort's requirement of minimizing impact to the aircraft's performance.

Figure 9 : T-20 VTOL (JUMP 20)

Husky A-1C-180

High lift devices, oversized engines, tundra tires, and significant suspension systems allow STOL aircraft, such as the Husky bush plane, to takeoff and land on small, unimproved patches of ground. The same features that make the Husky capable of short takeoffs and recoveries create drag, reducing the Husky's range and payload capacity. The same features that make bush planes STOL aircraft could contribute to meeting all the recovery requirements except the minimization of the recovery system's impacts to aircraft performance.

Figure 10 : Husky Unimproved Terrain

Puma/Raven

Some aircraft deploy high lift devices or flare before landing to increase lift and drag in order to decrease horizontal velocity and descent rate. Both the RQ-11 Raven and the RQ-20 Puma perform an early and severe flare before recovery, greatly reducing horizontal velocity making it possible to belly land within a small, unimproved area. The reduction in airspeed is great enough to reduce lift greatly, resulting in an increased descent rate before impact. The Raven and Puma both have detachable wings that separate and tumble to dissipate energy during violent impacts that result from their deep stall landings. The RQ-5 Hunter deploys flaps and performs a late and slight flare before a conventional touchdown on a conventional runway. RQ-7 Shadow uses flaps before touchdown during arresting wire recovery on short, improved runways. The X-47B deploys flaps and performs a late flare during an arresting recovery. A severe flare would allow for recovery in a small unimproved area but could require an energy dissipation system. Either flaps and/or a slight flare would decrease the horizontal velocity in order to reduce impact energy and increase approach angle.

Figure 11 : Raven Deep Stall

SD-2 Overseer / SD-5 Osprey / Rheinmetal KZO

Parachute recovery systems would greatly impact the aircraft design, due to the weight, volume, deployment, and vertical impact speed considerations.

Figure 12 : Rheinmetal KZO Parachute

RQ-2 Pioneer / Aerosonde -30/40 / Fury / FULMAR

The Pioneer, Aerosonde, Fury, and Fulmar are examples of aircraft that use net recovery systems. The net designs vary greatly amongst these systems.

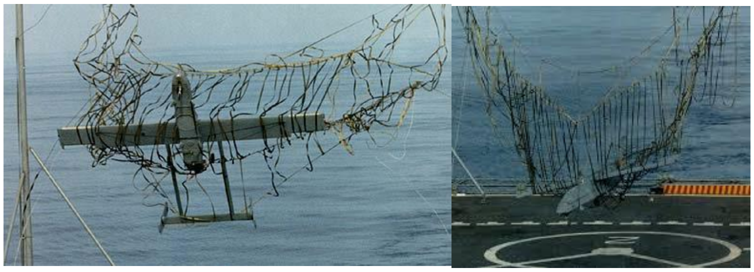


Figure 13 : Pioneer Net System

Figure 14 : Aerosonde Net System

Figure 15 : Fury Net System

Figure 16 : FULMAR Net System

Figure 17 : FULMAR Water Landing

C-130 retro rockets

The C-130 was modified to recover in a soccer stadium. Forward and downward facing rockets were installed for rapid deceleration during landing. The impact of carrying rockets for recovery on aircraft performance might be significant. The logistical impact of maintaining an adequate supply of rockets for sustained UAS operations would be burdensome.

Figure 18 : C-130 Retro-Rockets

Aircraft Carrier Barrier Recovery

Aircraft carrier capable airplanes typically use barrier systems for recovery during an arresting hook malfunction. These barrier systems are more likely to damage the aircraft than arresting wire systems used on aircraft carriers.

Figure 19 : Carrier Barrier System

Switchblade / Hero-30

The Switchblade and Hero-30 are examples of aircraft that are meant to be expendable. The cost and supply of the aircraft are appropriate for single missions before loss of the aircraft. The Switchblade can be recovered into a net, but typically is not.

Figure 20 : Expendable Switchblade and Hero-30

CHAPTER V

FINAL DESIGN

Barrier System

The final system is a barrier system comprised of ten straps, a top rope, a bottom rope, a weighted rope, two shear-pin systems, two uprights, two dissipater ropes, and two dissipaters. The aircraft flies or rolls into the net, causing the shear-pins to release the top rope while the net conforms to the aircraft. The dissipaters then dispense the dissipater ropes and dissipate the kinetic energy of the aircraft. The development of this recovery system is described in later sections. This section describes the components of the final system.

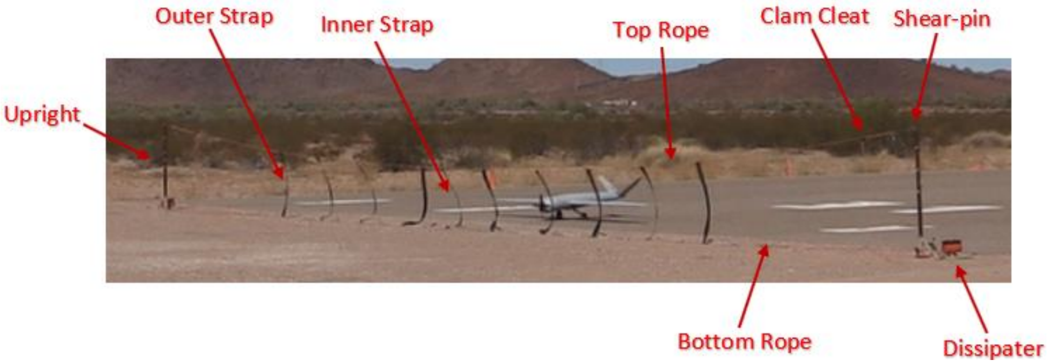


Figure 21 : Final Net Design

Dissipater Bases

The dissipater bases consist of the dissipater ropes which are wound around the dissipater reels, the braking systems, dissipater rope guides, the structure required to support the uprights, and the stakes

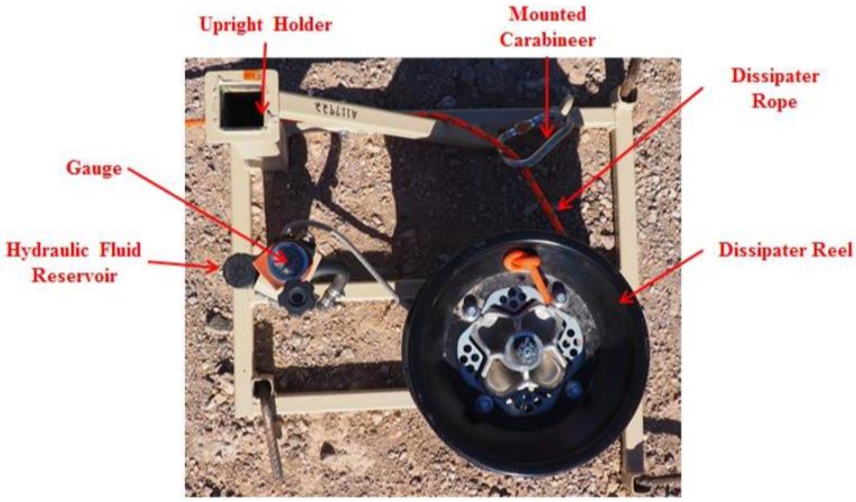


Figure 22 : Final Dissipater Base

Braking System

The dissipater reel dispenses the dissipater rope connected to the net after the net engages the aircraft. The dissipaters slow the aircraft more gradually than if the net was anchored. The dissipater reel is an ATV wheel on a spindle and brake. ATV brakes allow the rate at which the energy of the aircraft and net is dissipated to be adjusted. By adjusting the master cylinder, the pressure on the brake pad can be varied, resulting in the desired force profile during recovery. ATV brakes are also already developed and will always be available to purchase off the shelf. A problem of using a hydraulic braking system is that the hydraulic pressure of the brake fluid drifts as temperature varies, causing the operator of the recovery system to confirm the pressure before every recovery. Using ATV brakes as the dissipaters also requires that maintenance personnel to have the ability, parts, and consumables required to service and maintain the ATV brakes. The ATV brakes required repair multiple times during testing. The dial on the dissipater base indicates the hydraulic pressure which can be quickly checked by the operator. The dials used in the current system are specifically for systems using brake fluid of the type used in the ATV braking system. The system’s brake fluid rendered multiple corrosive-resistant pressure gages, not specifically designed for brake fluid, inoperable after a few months of testing. The knob next to the dial can be turned by the operator to move the master cylinder, thereby adjusting the hydraulic pressure. The brake line contains the brake fluid between the master cylinder and the brake. Stainless steel tubing was used on previous designs of braking system. Flexible line was selected to eliminate the time and skill required for fabrication of this component.

Dissipater Rope Guidance

The carabiner is hooked through a steel eyebolt which is welded to the dissipater base.   The dissipater rope runs through carabiner. The carabiner keeps the dissipater rope level with the dissipator reel, so the rope cannot slip above or below the reel while dispensing.   The carabiner also guides the dissipater rope safely around the dissipater base structure.

Structure for Upright Support

Each dissipater base has one section of square tubing welded to the base as to allow an upright to slide into and be supported by it. The tubing is supported by additional structure to withstand the inward bending moment the upright and upright holder will see during recovery before the shear-pins break.

Dissipater Immobilization

The stakes fix the dissipater base to the ground. The stakes counter the moment created by the top rope pulling towards the center of the system. The stakes also keep the dissipater base from sliding while the dissipaters decelerate the aircraft. The stakes are hammered through open ended tubing. Stakes are easily transported and stored. The number of sandbags and/or amount weights required to fix the dissipater bases to the ground exceeded the personnel and transportation requirements.

Net

The net is the portion of the recovery system that directly contacts the aircraft. The net consists of ten straps, a top rope, a bottom rope, two rope segments that connect the top and bottom ropes, and carabiners.

Figure 23 : Final Net

STRAPS

The net had only vertical straps. The horizontal straps seen on many nets may have caused the net to engage the aircraft asymmetrically, causing aircraft damage during recovery. When only vertical straps are utilized, the net can slide around the aircraft until the top rope stops the shifting in a position that results in symmetric loading during deceleration. Symmetric loading around the z-axis of the aircraft reduces the amount of yawing during recovery. During deceleration of the aircraft, at least one strap must engage each side of the wing. Any additional straps engaging the wing, fuselage, or propeller are neither required nor detrimental. Straps, which are wider than ropes typically used in netting, result in lower pressures on the skin of the wing.

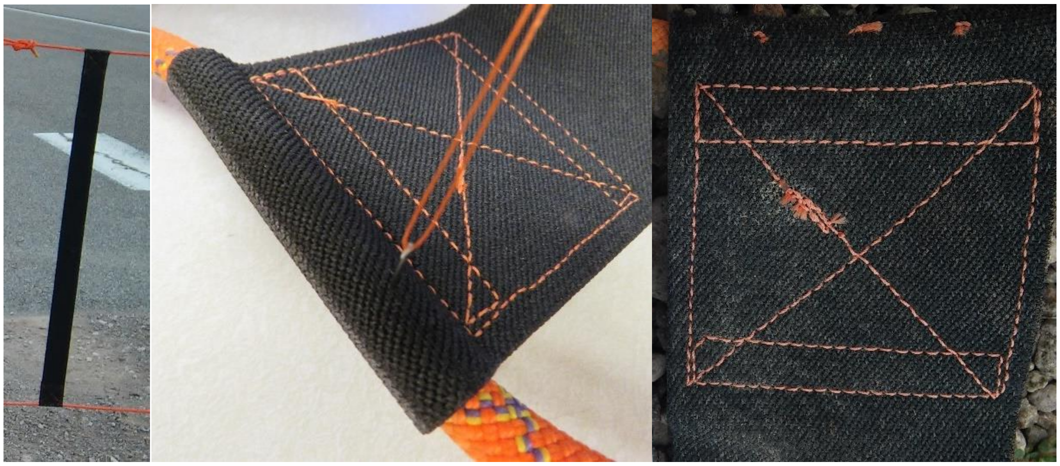


Figure 24 : Final Straps

The higher elasticity of the straps results in more gradual deceleration of the aircraft than a less elastic material, resulting in less jerk imparted to the aircraft during recovery. The length of the straps is limited so they do not damage the antennae or the tail. Two loops were sewed on each end of each strap. One end of each strap was slid onto the top rope and the other end onto the bottom rope. Each strap was sewn to the top and bottom rope to stop sliding. Replaceable straps were considered in order to extend the service life of the net. However, no method for making the straps replaceable was found that didn't also risk the straps catching on the aircraft and stopping them from sliding as needed. Because straps are not replaceable, the whole net should be replaced when the straps stop rebounding to their original lengths.

ROPE

A top rope, a bottom rope, and two rope segments were tied together to hold the straps vertically. The bottom rope is connected directly to the dissipater rope. Two rope segments connect the top rope to the bottom rope. These segments direct tension created by the dissipaters around vertical straps into the top rope, stopping the outermost straps from handling the full force of the deceleration, as the outermost straps would be damaged by the full force of the deceleration.

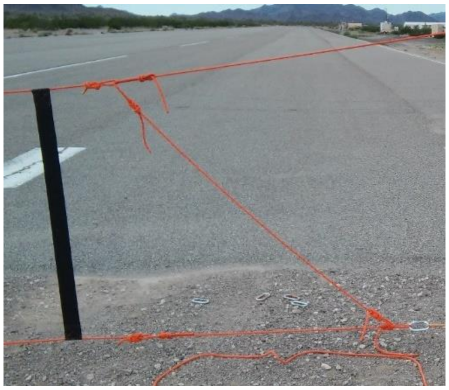


Figure 25 : Final Ropes

The ropes are made of climbing rope. Climbing rope is designed to extend the distance over which a falling climber is decelerated, reducing the jerk imparted to the climber. Climbing rope also has a rebound rate that is sufficiently long as to reduce the amount that the climber rebounds during a fall. Climbing rope was selected for the net as it reduced the jerk imparted to the aircraft while causing less rebound than a material with a shorter rebound period. The top rope is suspended between the two uprights.

WEIGHTED ROPE

During some wind conditions the bottom rope is sometimes lifted off the ground. If the bottom rope was off the ground, it would be possible that the gear would not pass over it. The weighted rope, secured to the bottom rope, increases the wind required to lift the bottom rope off the ground. The climbing rope is much more elastic than the steel and fabric weighted rope. The weighted rope must be able to slide independent of the climbing rope to allow for the climbing rope to stretch as needed. The loops are secured to the climbing rope, but not secured to the weighted rope so that ropes are able to stretch to differing lengths during recovery. Securing the loops to the climbing rope eliminates the need for repositioning of the loops before each recovery. The Velcro loops can be opened and closed to allow for the addition or removal of weight.

Net Support System

Before the aircraft engages the net, the top rope must be suspended. After the aircraft engages the net, the top rope must be released so the dissipater rope can be dispensed from the dissipater. The shear-pin system provides two points for the top rope to be suspended between the uprights before the aircraft engages the net. The shear-pins proved to be a reliable, repeatable release mechanism for the top rope. The shear-pin system consists of a shear-pin, a shear-pin holder, a washer, paracord, a climbing O-ring, and a clam cleat. The shear-pin runs through the top hole in the shear-pin holder, through the washer, and through the bottom hole of the shear-pin holder. The washer is tied to the paracord, which is tied to the climbing O-ring. The O-ring is a smooth loop used to transfer tension from the shear pin system to the top rope. The washer and shear-pin holder break the shear-pin once the aircraft creates high tension in the top rope.

Figure 26 : Final Shear-pin System

In order to suspend the top rope, the shear-pin system requires a loop on each end of the top rope. Over time, the top rope will stretch and require re-tensioning, and clam cleats allow for easy re-tensioning. Clam cleats provide a quick and repeatable method of creating loops and setting tension in the top rope. The top rope is fed through the holes of the clam cleat, fixing the clam cleat to a spot of the rope. Then the top rope is fed through the O-ring, back under the peg of the of the clam cleat, and into the teeth of the cleat.

Figure 27 : Final Clam Cleat

As previously stated, before the aircraft engages the net, the top rope must be suspended. The uprights hold the shear-pin system, which provides two points for the top rope to be suspended. The uprights are square tubing with equally spaced holes which allow the height of the shear-pin system holders to be easily raised and lowered.

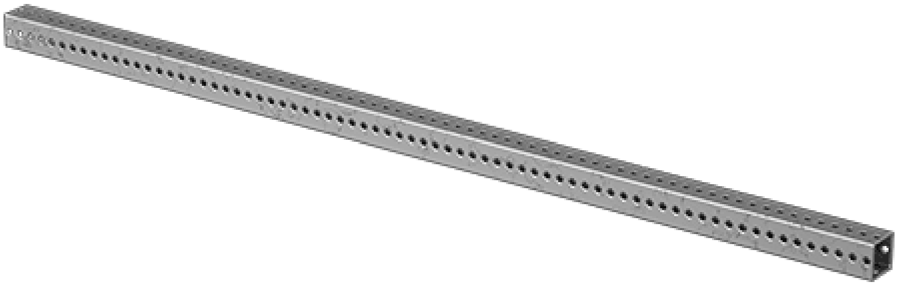


Figure 28 : Final Upright

The uprights are removeable for ease of storage and relocation of the system. The uprights slide into square tubing on the dissipater bases.

CHAPTER VI

DEVELOPMENT

In the course of development of the recovery system, prototypes were designed, fabricated, and tested. These iterations and testing results are documented and discussed in this chapter.

Damper Arresting Wire System

The original arresting wire system consisted of a steel rope, 2 dampers, and 2 wooden spacers. The steel wire ran between the dampers and was elevated off the ground by wooden spacers. Each velocity damper consisted of a shuttle moving through a cylinder filled with water. Each end of the steel wire was attached to a shuttle.

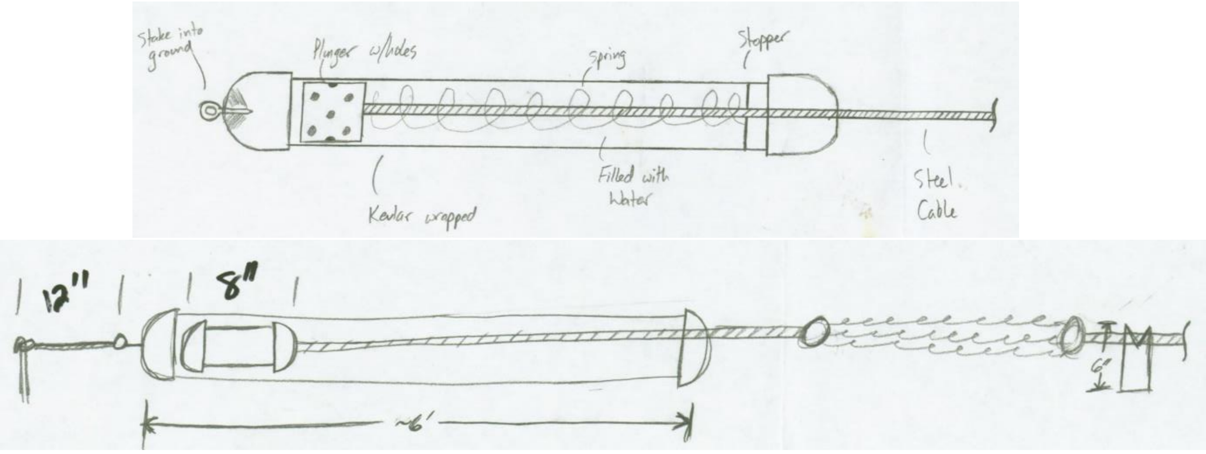


Figure 29 : Wes Combs' Damper Design

The aircraft was to have a hook that reached down below the aircraft's landing gear. The hook was to be on a detachable mount on the tail, with cables running from the hook itself to a structurally sufficient point near the main gear mount. The aircraft was to maintain an above ground level altitude that would result in the hook snagging the wire. As the hook pulled the wire, the shuttles in the dampers would be pulled through the water, transferring the aircraft's kinetic energy to the water. The force of the wire on the hook would flare and decelerate the aircraft, bringing it to rest on its landing gear. Preliminarily, this design appeared to have many benefits and the insufficiencies were not yet evident. The original design was extremely simple and portable. It did not require the aircraft to be capable of touching down within a certain error. The aircraft simply had to maintain AGL and a ground track. It was considered that the aircraft might flare due to the force of the wire on the hook. The flare would have maintained lift as the airspeed was reduced by the arresting system. Because the wire would be perpendicular to the recovery path of the aircraft when the hook engaged the wire, the load would be gradually applied to the aircraft by the arresting wire. The ratio of the component of tension in the wire that contributed to deceleration of the aircraft to the total tension in the wire would increase as the wire dispensed from the damper. The component of the tension in the wire applied to the hook could be estimated using the equation:

$$\frac{F_{Hook}}{T} = \frac{L_x}{\sqrt{L_x^2 + L_y^2}}$$

Figure 30 : Force on Hook Eq.

Where, T is the tension in the arresting wire, F_{Hook} is the component of the tension in the direction of the aircraft's deceleration, L_x is the distance between the hook's current location and the hook's location upon engaging the wire, L_y is half the distance between the 2 dampers. This equation assumes the arresting system acts in only the xy plane and tension in the arresting wire can be predicted by static analysis. The validity of these assumptions is examined with the results of arresting wire recovery system testing. This equation was used to indicate load on the hook, as a function of tension in the wire and length of wire dispensed.

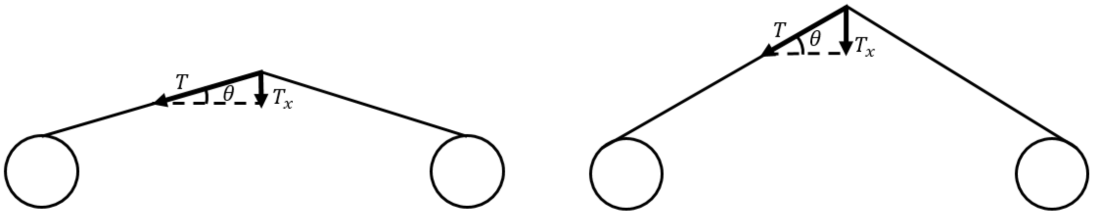


Figure 31 : Force on Hook Illustration

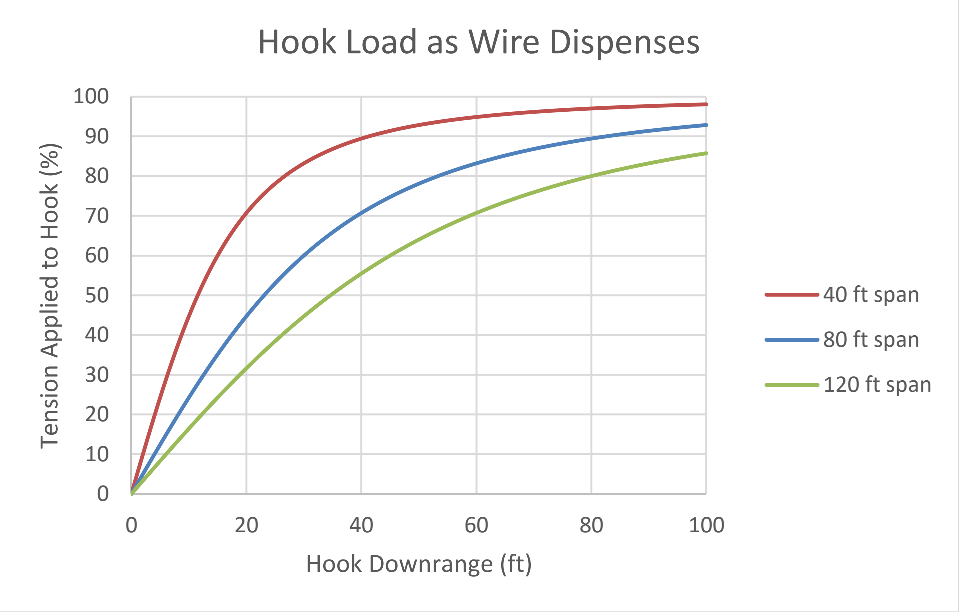


Figure 32 : Force on Hook Chart

This equation only predicts the load on the hook based on the tension in the wire and the amount of wire dispensed. The drag on the shuttle in the damper and the velocity of the hook engaging the wire produce the tension in the wire. After testing the damper, it became evident that the damper was a poor choice for this recovery system. With the damper, the tension on the wire was proportional to the square of the difference between the wire's velocity and the velocity of the fluid surrounding the shuttle in the damper:

$$T \propto (V_{shuttle} - V_{fluid})^2$$

Figure 33 : Damper Tension

Where, T is tension in the wire, $V_{shuttle}$ is the velocity at which the wire is being dispensed, and V_{fluid} is the velocity at which the fluid surrounding the shuttle is moving in the direction the shuttle is moving. This would result in a high initial tension that would taper off during recovery. From an aircraft structural perspective and recovery dynamics perspective, an ideal force profile on the hook would increase during recovery. To achieve this profile, a damper/dissipater that would apply a more consistent tension on the rope would be selected for the next iteration of the arresting wire system. If the tension in the wire was consistent, the geometry of the wire as it dispenses would result in an increasing loading on the hook.

Disc Brake Arresting Wire System

SYSTEM DESIGN

For the second iteration of the arresting wire system, disc brakes replaced the dampers. The disc brakes were Yamaha YFZ450-2007 ATV rear brakes. The brakes were mounted to a steel base that could either be weighed down or staked down. The steel rope was wound around the wheel hubs and attached to the wheels. The steel rope was linked together by two carabiners so that the two dissipaters could be detached for storage. The master cylinder on the dissipaters could be depressed by a knob to vary the pressure on the disks. By varying the pressure on the disks, the force applied to the steel rope could be varied. The pressure would need to be adjusted based on the weight of the aircraft, the speed of the aircraft, and the distance desired for stopping. The hook design and approach method did not change from the last iteration.

Figure 34 : Arresting Wire System

While the disc brakes are more complicated than the dampers, the disc brakes do not have the problem of wire tension being proportional to velocity squared. The tension profile with the disc brakes was expected to be more constant throughout recovery. This change was an attempt to have the hook loading increase with time. While the torque applied by disc brakes generally decreases as velocity increases, the 2nd derivative of tension vs wire velocity is much lower than it is for the damper.

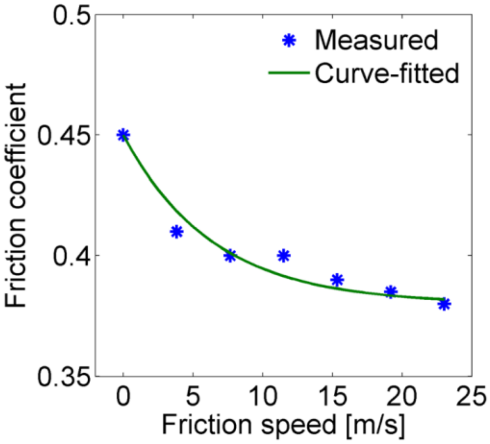


Figure 35 : Disk Brake Friction Chart

Above is an example of coefficient of friction vs velocity for disc brakes. Tension in the wire is proportional to torque, which is proportional to coefficient of friction:

$$T \propto \tau \propto c_f$$

Figure 36 : Tension from Disc Brake Eq.

Where, T is tension in the wire, τ is torque applied by the disc brake, c_f is the coefficient of friction. The relationship of the tension to the velocity of the wire, paired with the effects of wire geometry during recovery, was expected to result in a more gradual and sustained load being applied to the hook. This system maintains the benefits of not having to touchdown in a specific area and the potential for hook force induced flare. The gradual application of the deceleration force on the hook, due to the wire geometry during recovery, persists from the previous iteration. The system had been previously proven to be capable of capturing a precisely placed hook and stopping a mass connected to the hook.

The relationship between pressure and force for the dissipaters was found using a crane scale.

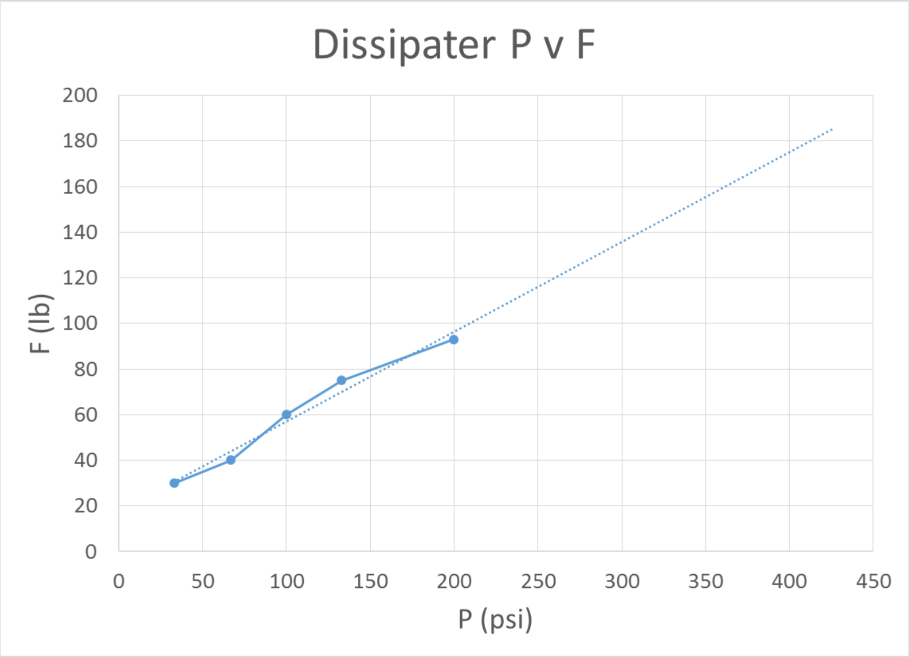


Figure 37 : Dissipater Force vs Hydraulic Pressure

The ATV brakes were bolted to a welded steel base. The ends of the steel wires were secured to the wheels by running the wire through the tire valve stem hole and clamping a wire clamp onto the ends of the wire. The carabiners were attached to loops in the steel wire. The loops were created by thimbles and wire clamps.

TEST APPROACH

An analogue aircraft was constructed for recovery testing. The analogue aircraft consisted of two-by-fours, sandbags, landing gear, paracord, and a recovery hook. The sandbags were distributed to emulate the CG and moments of inertia that were expected for the aircraft. It was found to be highly impractical to match the moments of inertia on all three main axes. Therefore, only pitch and yaw were matched. CG was based on previous models of the aircraft, and moments of inertia were based on a weight and location component buildup. Gear placement and interaction between the detachable hook mount, the hook cable, and airframe were also matched to the actual aircraft.

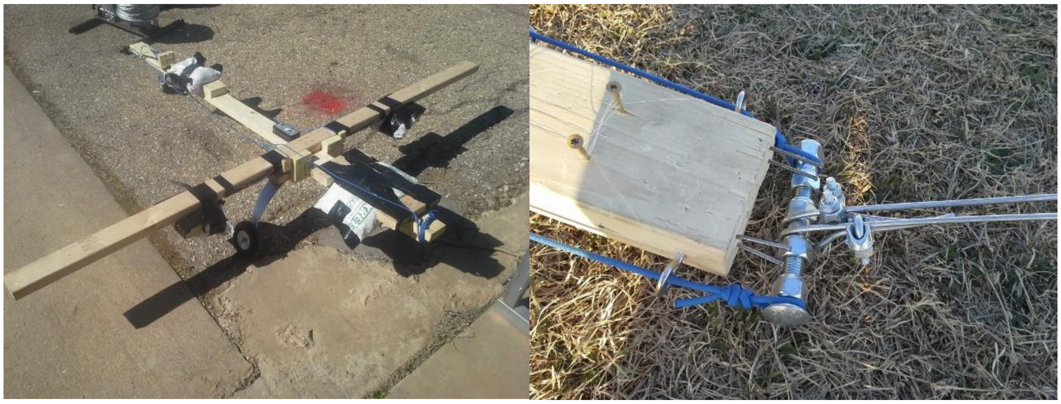


Figure 38 : Aircraft Analogue

The analogue aircraft could not fly; therefore, engagement with the recovery system was achieved via alternative methods. To avoid disturbing the recovery system, the analogue was suspended beside the truck. The analogue could be moved over the arresting wire without the truck disturbing the recovery system.

Figure 39 : Suspension Arm

When the hook would engage the arresting wire, the analogue would be yanked off the suspension arm. The arresting arm was attached to the truck with tie-down straps and S-hooks.

Figure 40 : Securing Suspension Arm

The suspension arm system included two shelves that were attached to the main beam by vertical tubing that held the wings of the analogue aircraft. These vertical tubing could be adjusted to vary the height of the analogue off of the ground for each test. A counterbalance was needed on the opposite side of the suspension arm system to reduce the tilt of the truck. During initial testing we found that a mechanism was needed to hold the analogue on the suspension arm so that it would not fall off due to acceleration and vibration. This mechanism was a 3-ring release with a servo pulled pin attached to different points of the analogue via fishing line.

Figure 41 : Aircraft Analogue Release Mechanism

Fishing line was chosen to be a fail-safe in case the release failed and the hook caught on the wire before release. The fishing line would fail and the test results would be compromised, but the fail-safe would decrease the chances the truck would be damaged.

Figure 42 : Arresting Wire Testing

TESTING RESULTS

Tests were all at least partially unsuccessful due to damage to the analogue aircraft, the vertical descent rate at touchdown being great enough to damage the actual aircraft, the hook not engaging the wire, or the analogue slipping off the test rig before engaging the wire. The test on February 25, 2014 resulted in analogue aircraft falling off the test rig prematurely. Both test 1 and test 3 of February 27, 2014 resulted in the hook bouncing off the wire. On both test 2 and test 4 of February 27, 2014 the main gear were deformed by violent impact due to excessive vertical speed at touchdown. The main gear were 24 in above the ground while sitting on the rig.

Figure 43 : Gear Damage

Test 1 of March 5, 2014 resulted in analogue aircraft falling off the test rig prematurely. Test 2 of March 5, 2014 resulted in the hook bouncing off the wire. On both test 3 of and 4 of March 5, 2014 landing gear did not deform, because the gear had paracord tied to each leg to keep the gear from deforming, violently impacted the ground and bounced due to excessive vertical speed at touchdown. The main gear were 21 in above the ground while sitting on the rig.

Figure 44 : Gear Wire

Test 1 of March 14, 2014 but started falling off rig before engaging wire. resulted in the main gear hitting the wire and catching on the tail gear. The recovery was gentle, but the aircraft was touching down as it engaged the wire. The main gear were 8 in above the ground while sitting on the rig.

Figure 45 : Gear Engaging Wire

Test 2 of March 14, 2014 landing gear did not deform, because the gear had paracord tied to each leg to keep the gear from deforming, violently impacted the ground and bounced due to excessive vertical speed at touchdown. The hook drug on the ground before engaging the wire. The main gear were 10 in above the ground while sitting on the rig.


Figure 46 : Hook Skimming Ground

On the March 15, 2014 test the main gear did not deform, because the gear had paracord tied to each leg to keep the gear from deforming, violently impacted the ground and bounced due to excessive vertical speed at touchdown. The analogue's empennage tilted down before the analogue left the rig. On test 1 of March 19, 2014 the main gear did not deform, because the gear had paracord tied to each leg to keep the gear from deforming, violently impacted the ground and bounced due to excessive vertical speed at touchdown. The analogue's empennage tilted down before the analogue left the rig. The main gear were 20 in above the ground while sitting on the rig.


Figure 47 : Analogue Tilting and Gear Damage

Test 2 of March 19, 2014 resulted in the analogue aircraft falling off the test rig prematurely. The main gear were 20 in above the ground while sitting on the rig. The March 31, 2014 test resulted in the analogue aircraft falling off the test rig prematurely.

CONCLUSIONS

Positive attributes of the original system were that it was incredibly mobile, had a small footprint, and utilized COTS components. The use of the hydraulic braking system makes the overall system scalable to heavier aircraft, as the ATV brakes were oversized for an 80 lb aircraft and the friction could be increased by turning the knob on the master cylinder. It was discovered that the steel wire led to increased setup time because the coil would unwind itself, so it was switched to climbing rope. Climbing rope was easier to wind, and it was also realized that it had elasticity, which would reduce loadings in case of dissipater malfunction. Another benefit is that when arresting first begins, the deceleration due to the arresting wire is miniscule, and it gradually increases, limiting the impulse applied to the aircraft. It did not require the accuracies of DGPS guidance system because the arresting wire could be spanned as wide as possibly necessary, and the aircraft's laser altimeter was supposed to be used to fly at a constant altitude low enough to grab the arresting wire with the tailhook. This recovery approach would have eliminated the need for accurate flight in both horizontal axes. However, a test with the main gear only 10 in AGL resulted in a violent recovery. The aircraft would have to maintain an the AGL within 5 in to avoid hitting the wire with landing gear, or the ground with the hook. Either of these would likely result in damage. Even if the aircraft had gentle recoveries at lower AGL's, it was decided that the maximum AGL errors the aircraft would have to achieve were not feasible.

A real aircraft could have been used in place of the analogue in order to see if the recoveries would have been successful. A real aircraft would have created more lift, thus the vertical descent rate could have been decreased, potentially leading to better recoveries. However, a concern that had no chance of being resolved was that a botched recovery attempt could lead to the aircraft hurdling uncontrolled downrange. It was decided to pursue an alternative recovery method immediately to avoid the risk of a schedule overrun.

Barrier System for Tail-Dragger

DESIGN ITERATION MOTIVATION

Every test conducted of the arresting wire system would have resulted in the damage to the aircraft, even when the recovery AGL was low enough that the aircraft would not be able to achieve the required AGL error. The customer and designers mutually agreed that the arresting wire system was not an adequate solution for the requirements. A new system was designed, adhering to the original requirements. The new design was created with a major goal of not allowing the uncontrolled landing mentioned previously.

DESIGN

A barrier system, similar to those used by aircraft carriers, was selected as an alternative to the arresting wire system. The barrier system solved two major problems: the aircraft no longer needed to maintain an AGL with a small error, and the window which would result in a controlled recovery was increased. The aircraft would be programed to touch down at or in front of the net. Also, a hook bouncing off a wire or engaging the ground were no longer possibilities. An additional benefit of the barrier system was that the aircraft would not have the negative performance impacts of carrying a hook.

The arresting wire system applied load gradually to the aircraft during deceleration. This characteristic was desirable for the barrier system; therefore, a similar dissipater configuration was considered as a frontrunner during the conceptual design process. Unlike the arresting wire system, the barrier system utilized a net to engage the aircraft. The net needed to be developed and required suspension. A method of suspending the net needed development.

Paracord mockups and push-through testing were utilized to determine the validity and feasibility of ideas before a full design was created and tested.

Figure 48: Various Net Mock-ups

Many possible net designs and ways rig the net to secure the aircraft in a non-damaging way, as well as the distance the system would stop the aircraft, and the complexity of setup were considered during the conceptual design process. Non-damaging includes where the aircraft is loaded, unwanted ground contact, and excessive acceleration experienced during the recovery. Loading the plane through the root of the wing was desired, much effort was devoted to finding a way to accomplish this. A single bay net design would have loaded the aircraft through the wing root. As the plane slid into the net, the straps would slide towards the wing root and up against the bottom of the fuselage; however, the width of single bay is limited to less than half the aircraft's 14 ft wingspan. The lateral error due to navigation error, waypoint placement error, and rollout error would have to be less than 3.5 ft to successfully capture the aircraft. It was determined that forgiveness in lateral accuracy was more valued than simplicity and favorable loading of the single bay net design.

Figure 49 : Single Bay Net

In an attempt to maintain the benefits of a single bay net but increase the acceptable lateral error, the next logical step was to make a multi-loop system. In the multi-loop system, if the aircraft goes into a loop, there is contact at the root of the wing, but there is also contact at the tips of the wings by the other loops. If the aircraft's nose hits one of the loops, it can push the barrier up and go under it. Therefore, this design was not successful during push through testing. Cinching methods were considered for sliding the contacting restraints towards the root of the leading edge, but this extended the distance before the aircraft significantly started to decelerate. Placing the dissipater directly up-range of the barrier and attaching it to the center of the bottom rope was considered to reduce the distance before the barrier significantly decelerated the aircraft. Unfortunately, this eliminates the gradual application of the loading that was seen by flanking dissipaters, as referenced in the original arresting wire description. Another difficulty with this was that if there is error in the touch down and hit an outboard portion of the barrier, then the distance before significant deceleration occurs is greatly increased.

The barrier system selected incorporated climbing ropes as the horizontal net components, the component that linked the net to the dissipater wheel, and the component that allowed the transfer of tension from the dissipater rope to the bottom rope. Climbing rope was chosen because it was lightweight and elastic.

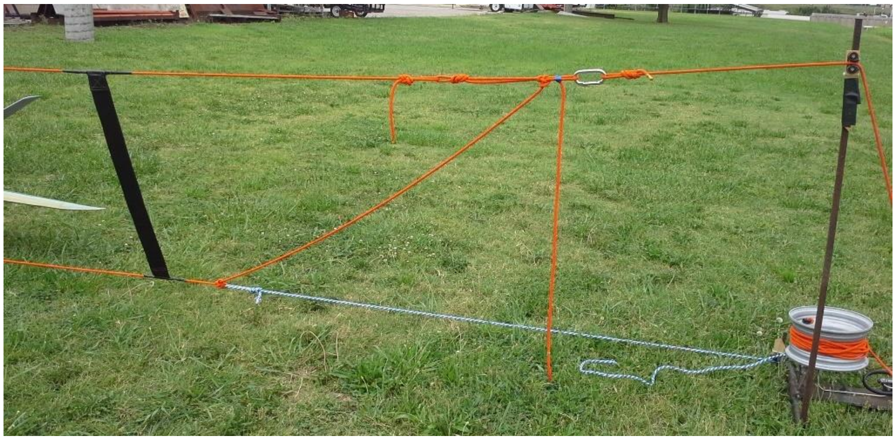


Figure 50 : Net Rope

There were straps of three-inch elastic sewn to the top and bottom ropes. Elastic was used because if non-elastic straps were used, only the outboard straps would be load bearing. Elastic straps result in a portion of the load being borne by the inboard strap. For inelastic straps, $T_r \sin\theta_2 \propto T_{s2}$ and $T_r \sin 0 = 0 = T_{s1}$. For elastic straps, $T_r \sin\theta_2 \propto T_{s2}$ and $T_r \sin\theta_1 \propto T_{s1}$.

Where T_r is the tension in the rope, T_{s2} is the tension the outboard strap, T_{s1} is the tension in the inboard strap, θ_2 is 90 degrees less than the obtuse angle between the rope and the outboard strap, and θ_1 is 90 degrees less than the obtuse angle between the rope and the outboard strap.

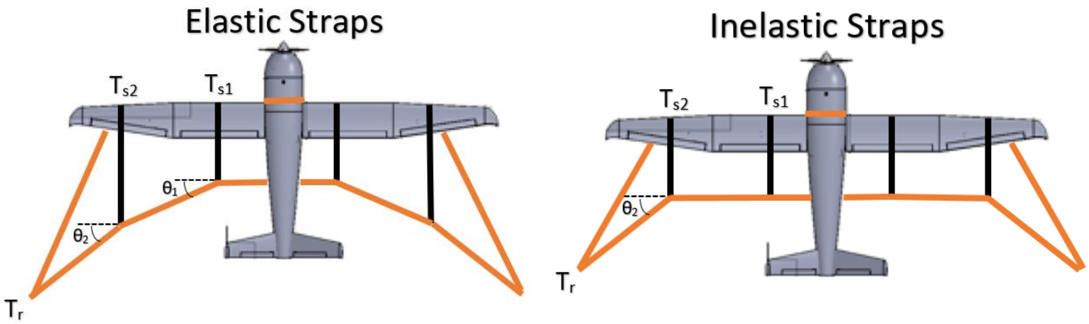


Figure 51 : Elastic Straps vs Inelastic Straps

Elastic vertical straps also allow for a gradual application of the loading during recoveries. The spacing of the vertical straps was designed to avoid the case where there was a single vertical strap on a half-span near the tip of the wing. The spacing that was used would always result in either one strap near mid-span or two straps on a half-span where one was near the tip and one was near the root.

Figure 52 : Strap Spacing

The same brake hardware was used for the dissipaters, but was installed on an improved base that had an adjustable slant arm with a cam cleat on it for holding the loose end of the bottom rope. This adjusted the amount of slant on the net by pulling the bottom rope back, so that the wheels would go over the bottom rope before the aircraft significantly impacted the barrier.

Figure 53 : Net Slant

It was uncertain if the slant was necessary. However, it was known through push-through tests that as the plane went through the barrier, the bottom rope would be pulled up against the bottom of the fuselage and forward to the leading edge of the wing. It was understood that the camera would be safe if the bottom rope got behind the main landing gear of the aircraft. The lengths rope segments that connected the top and bottom rope were selected so that when the barrier wrapped around the aircraft, the straps, not the climbing rope, would be pushing on the leading edge of the wing.

A detachable upright tube had a cam cleat attached that could be used to adjust the height of the top rope. The height was adjustable because the top rope would need to be at different heights depending on the span of the distance between the dissipaters. Cam cleats were utilized for holding the rope taut while allowing it to release when a downrange force was applied from the aircraft.

The stretched length of the vertical straps was limited to the distance from the bottom of the fuselage to the leading edge of the wing plus the distance from the leading edge of the wing to the tail. The width of the barrier was based on GPS error. The minimum dissipater spacing is driven by $2 * (GPS_{maxErr} + LateralGuidance_{maxErr} + b/2)$, where b is wing span. The maximum dissipater spacing is limited by the height of the top cam cleats that that hold the top rope.

The bottom rope was weighted so that it would not be lifted by the wind. Discrete weights were undesirable because they could damage the plane. Ideally, the weight would be distributed evenly, and it should be padded so that the weight does not damage the aircraft. Also, the diameter of the weight needs to be small enough so that the main gear wheels can easily roll over it. Three-eighths inch steel wire reinforced nylon rope was chosen for this. The nylon covered steel was secured to the bottom rope with Velcro. It was crucial that the wind-weight rope could slide as the climbing rope stretched during recovery.

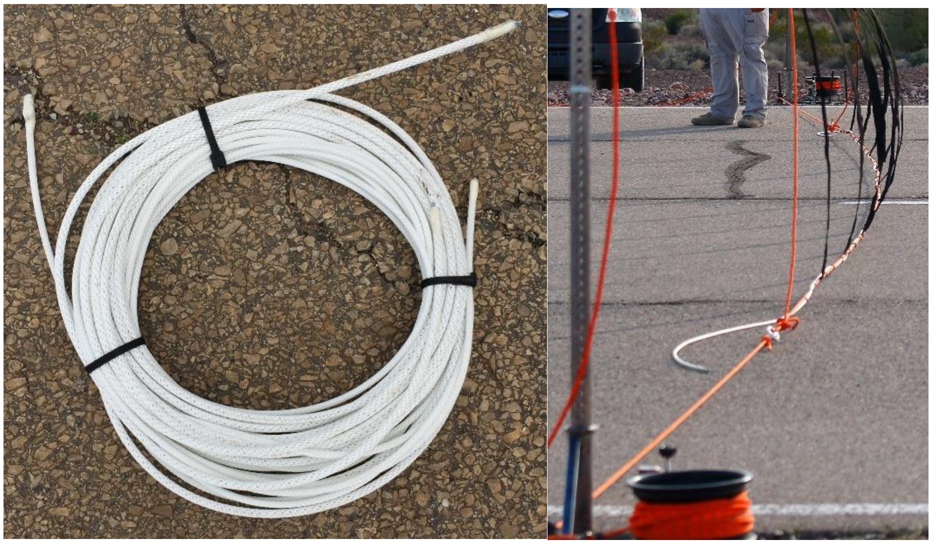


Figure 54 : Weighted Wind Rope

Wind Speed (mph)	Wind Weight (lb)	Add Ropes (2.5 lb each)
10	0.8	1
15	2.9	2
20	5.9	3
25	9.8	4
30	14.5	6

Figure 55 : Weighted Wind Rope Table

TEST APPROACH

A launcher was designed for another portion of this contract, so it was decided that this would be an efficient way to test the barrier. The barrier was tested by launching a glider into a prototype barrier. Although the orientation of the plane was not as would be seen during an actual landing, the velocities and plane geometry were similar. Accelerometers were installed on the test airframe during recovery testing utilizing the launcher. Further testing was conducted with fully functional aircraft landing on a runway.

TESTING RESULTS

During the launches where the orientation was nose down, the barrier stopped the aircraft, but damage occurred.

Figure 56 : Pitched Down Recovery Test

From these tests, it was clear that the barrier would be able to stop the aircraft and that the loadings of the barrier would not damage the aircraft. However, it was still unclear from the launcher tests what moments the barrier would impart on the airplane during recovery. Accelerometer data showed that the deceleration was mostly done at the instant the aircraft nosed into the ground. Three tests were conducted during full-functioning aircraft live recovery testing. During the first live recovery test, the bottom rope broke the slant arms after becoming stuck in the cam cleat on the slant arms. Since the plane was landing on a runway, and not nosing into the ground before it reached the net, the tension on the bottom rope increased drastically before the bottom rope popped out of the cam cleats. This bent the slant arm in towards the plane, which changed the angle of the rope in the cam cleat and kept the rope from popping out as it was designed to operate, which bent the slant arms in more until they finally snapped off. The elasticity of the climbing rope and vertical straps prevented the aircraft from being damaged. The following test was then conducted without slant to the barrier. The second test, the aircraft hit before the barrier, then rolled into the barrier. The aircraft was decelerated safely and smoothly. Through this testing it was indicated that slant might not be necessary, as it missed the camera and recovered the aircraft successfully. It should be noted that the bottom rope was still taut in the bottom cam cleats which were now directly below the top cam cleats. The third test, pilot error led to the aircraft clipping the top of the barrier in an engine-out situation, which resulted in severe, but repairable, damage to the airframe.

CONCLUSIONS

The barrier system was capable of stopping the aircraft, and the net loadings would not damage the aircraft. It appeared from the second on-runway recovery that the barrier would decelerate the aircraft in a safe orientation. Additionally, the second on-runway recovery appeared to show that the net no longer needed to be slanted for the bottom rope to roll under the main gear before being pulled up to the fuselage. This system appeared to be adequate for recovering the tail-dragger aircraft. Additional recoveries would need to be conducted to test longevity of components and behavior during extreme recovery conditions.

Barrier System for Trike Gear

DESIGN ITERATION MOTIVATION

For taxiing purposes, the customer requested that the airframe be converted to a tri-gear aircraft. If the recovery system remained unchanged, the moment created by the top rope pushing down on the tail of the aircraft would drive the tail into the ground during recoveries. In order to avoid this, the dissipater ropes would be attached to the bottom rope thus pulling the top rope forward, ultimately pulling down on the fuselage on the leading edge. It would be assumed until proven otherwise that slant was not needed in the barrier because the bottom rope is now being pulled back away from the camera. Since the top rope was being pulled forward instead of towards the tail, there was an opportunity to increase the height of the barrier. Previously the height of the barrier was restricted by the need to not hit the tail with the barrier. Now with the top rope being pulled forward, it was critical to not hit the tail only during the initial impact. It would be beneficial for the top rope to pop out first to avoid hitting the pitot probe on the tail. The aircraft was pushed through prototype third iteration barriers. Top and bottom cam cleats were varied until a complimentary combination resulted in the top rope popping out before the bottom rope.

DESIGN

The bottom cam cleats were moved forward because slant was no longer needed. The slant was no longer necessary because the bottom rope would be pulled back away from the camera; the bottom rope did not need to be behind the gear any longer. The top cam cleats were modified to release the top rope before the bottom rope was released so that the impact of the top rope would be farther forward, missing the pitot probe on the tail. The vertical straps were made longer allowing for the barrier to be taller, giving the aircraft a larger recovery window.

TEST APPROACH

The landing gear of the test airframe was modified to match the customer's preferences. The modified test airframe was launched into the net in more of a nose down orientation than the aircraft would be during an actual recovery. There was only one launch that reflected an accurate orientation that would be expected during landing. Next, more testing was conducted with fully-functional aircraft on a runway. Finally, testing was conducted off-runway on unimproved terrain.

TESTING RESULTS

During the launches where the orientation was nose down, the barrier stopped the aircraft, but damage occurred. From these tests, it was clear that the barrier would be able to stop the aircraft, and that the loadings would not damage the aircraft. The launch into the barrier that resembled an actual landing, resulted in the aircraft being undamaged during recovery.

Figure 57 : Slightly Pitched Down Recovery Test

Runway recoveries were almost entirely successful, regardless of whether the aircraft touched down in front of the net and rolled into it, if the aircraft touched down at the net, or if the aircraft flew into the net just off of the ground. It is important to note that if the aircraft's propeller is caught by the net, this can still result in a successful recovery with a portion of the loading being carried by the wings.

Figure 58 : Strap Catching Propeller

Only three off-runway recoveries on unimproved terrain resulted in the aircraft entering the barrier with significant velocity. Six recoveries resulted in either the aircraft rolling to a stop as it contacted the net or stopping before it reached the net. During the only recovery of July 13th, 2015, the aircraft entered the barrier at high speed, at a level orientation, with a nose gear that appeared un-damaged. The nose gear and one wheel of the main gear rolled over the bottom rope, while the other wheel slipped under and caught the bottom rope. The aircraft yawed in the direction of the left gear that caught the bottom rope and nosed into the ground. Both dissipaters appear to be dispensing rope during the recovery.

Figure 59 : 7/13/2015 Off-runway Recovery with Damage

The 1st and 4th tests on July 13th both resulted in minor damage from touchdown/ground-roll before the aircraft reached the barrier. In both cases, the barrier safely decelerated the aircraft once engaged.

Figure 60 : 7/14/2015 Off-runway Successful Recovery with Minor Damage

CONCLUSIONS

The nose gear damage during off-runway recoveries indicated the need for a more robust nose gear. The variance in longitudinal touch down location, relative to the net, indicated a need for a change in landing logic. Overall, the barrier system recovered the aircraft with minimal or no damage.

Barrier System for Trike Gear with Top Rope Pulley

DESIGN ITERATION MOTIVATION

The top rope was wearing out the teeth of the top cam cleat. It was hypothesized that the teeth were being worn down during setup. In addition, some operators found the task of tensioning the top rope strenuous. A solution to these two problems was desired.

DESIGN

A pulley was added just outside each top cam cleat. During tensioning of the top rope by the operator, the top rope could now be placed on the top of the pulley and pulled down, reducing the effort required for setup and decreasing the possibility of wear on the cam cleat teeth.

Figure 61 : 7/14/2015 Off-runway Successful Recovery with Minor Damage

TEST APPROACH

The aircraft was recovered using the modified system.

TESTING RESULTS

The aircraft was damaged during a February 2, 2016 recovery. Both the starboard dissipater rope and the port side of the top rope jammed during recovery. The aircraft's spar tube was snapped by the high load applied to the wing during the double jam. The net was also damaged during the double jam. The two previous recoveries that were recorded indicated abnormal behavior from the starboard dissipater base. The 4/10/16 recovery ended with the aircraft yawed approximately 45 degrees towards the starboard dissipater base and the dissipater base pulled partly out of the ground. The 4/13/16 recovery ended with the aircraft yawed approximately 45 degrees towards the starboard dissipater base.

Figure 62 : 4/10/16 and 4/13/16 Abnormal Recoveries

2/2/16 Starboard Dissipater Rope Jam

Exposed inner strands of dissipater rope wedged behind the jaws of the bottom starboard cam cleats.

Figure 63 : Starboard Bottom Cam Cleat on 2/2

The dissipater ropes had been damaged prior to 2/2 incident.

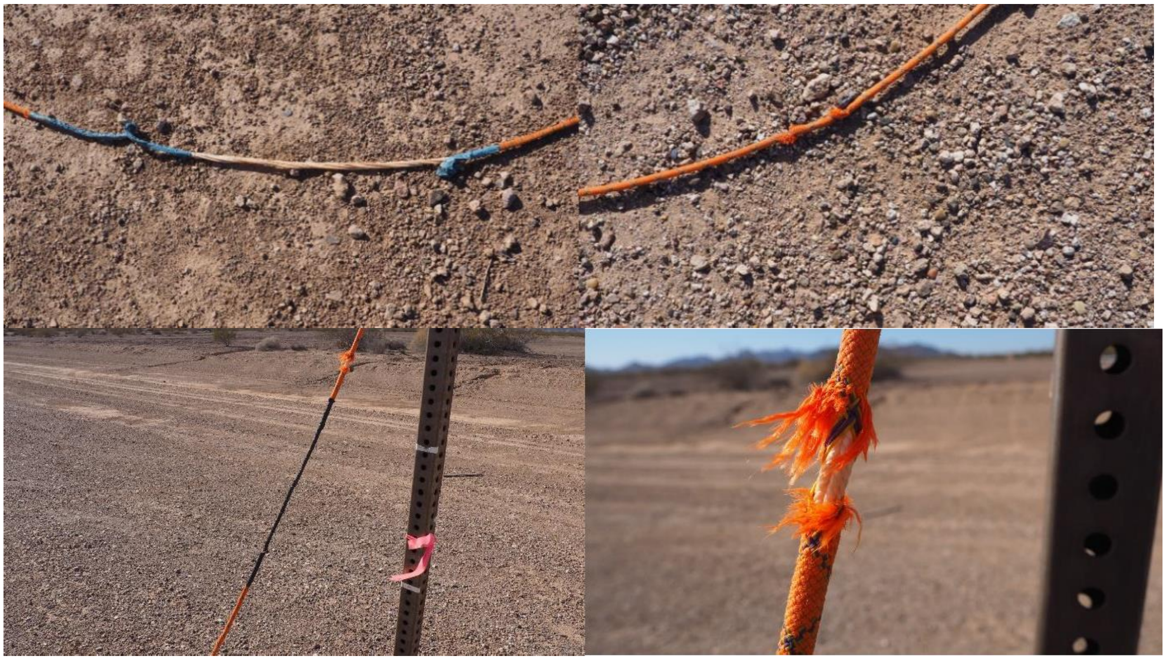


Figure 64 : Dissipater Rope Feb 1, 2016 or Earlier

2/2/16 Port Top Rope Jam

In addition to the bottom starboard cam cleat jamming, the top port rope seems to have momentarily wedged between the pulley and the pulley mount. The end of the port top rope was off camera, and did eventually completely disengage.

Figure 65 : 2/2/16 Video Screenshot

The port side of the net during the recovery did not form a triangle as expected (2 straight ropes from the carabiner to the plane) until after the snap. In order to determine if this was a dynamic rope reaction, or interaction with dissipater structure applying tension to the end of the top rope, the 2/2/16 video was compared to January 2016 recovery videos with comparable camera angles.

During the January recoveries, the net formed the expected acute triangle to the plane after a shorter distance than the 2/2/16 recovery. Some tension on the blue rope could be due to the inertia of the rope, but the fact the red joint stayed significantly far from the green line shows that the tension must have been significant.

Figure 66 : 2/2 Photo of Back Port Stake

Additional proof of the port top rope end interacting with the top of the dissipater structure was evident when the back stake of the port dissipater was found to be pulled up. It was determined that the long moment arm of the upright, paired with the top rope interacting with the top of the upright, was the most likely cause. However, this could have happened even if all the load was through the dissipater spool if the soil happened to be loose. The mar on the pulley mount, indicates the strong possibility that the rope wedged itself between the pulley and the pulley mount after disengaging the cam cleat.

Figure 67 : Pulley Mount Marred

2/2/16 Recovery System Wear and Damage

Dissipater Rope

The dissipater rope was severely frayed in locations that the bottom cam cleat would engage during testing throughout development and testing at OSU and testing at YPG. There was no evidence of fraying in May 2015 after Fall 2014 YPG testing. The damage is approximately equal on both dissipater ropes.

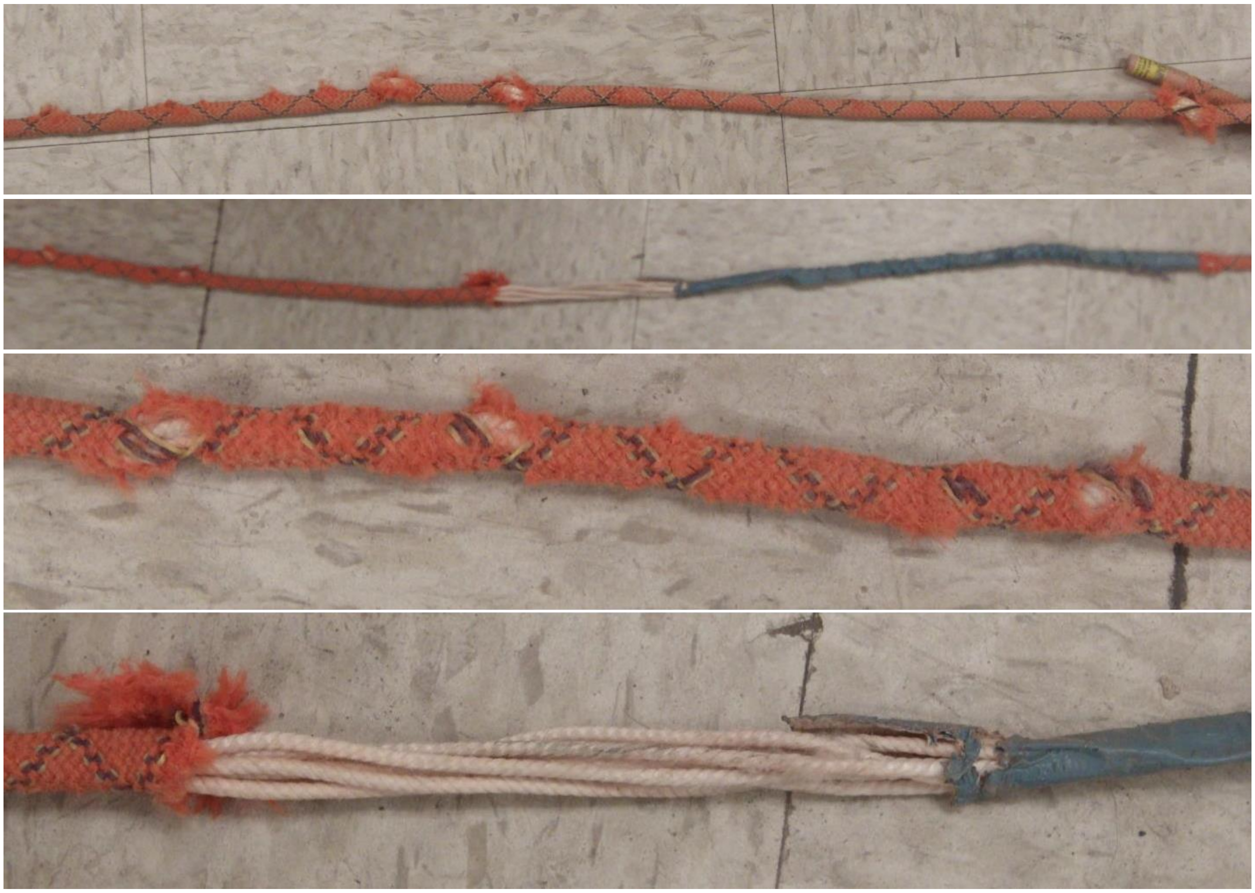


Figure 68 : Examples of Dissipater Rope Damage

Net Bottom Rope

The bottom rope of the net is slightly rough from wear, but the sheathing is completely intact.

This length of rope does not interact with cam cleats.

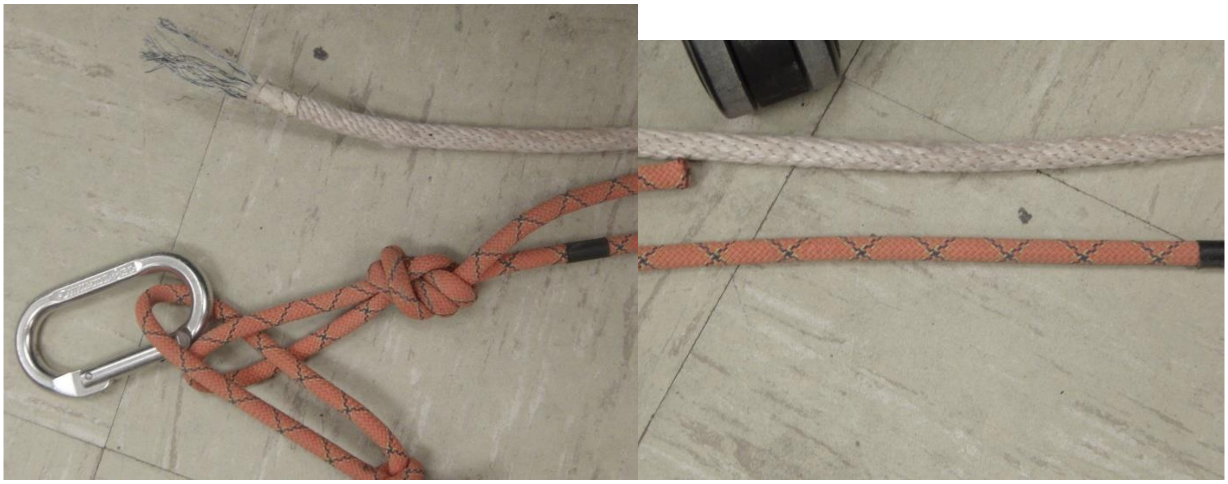


Figure 69 : Example of Bottom Rope

Upon closer inspection, every instance that at first appears to be frayed sheathing is confirmed as stitching from before the trike gear conversion.

Figure 70 : Threads on Bottom Rope Confirmed as Stitching Left After Modification

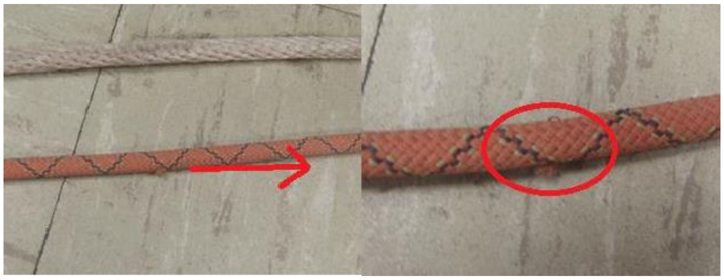


Figure 71 : Addition Example of Stitching Left Over from Modification

Wind Weight Rope Ends

Both ends of the wind weight rope have exposed steel cable. The wind weight rope sheathing shrunk or slid over time.

Figure 72 : Wind Weight Rope Exposed End 1

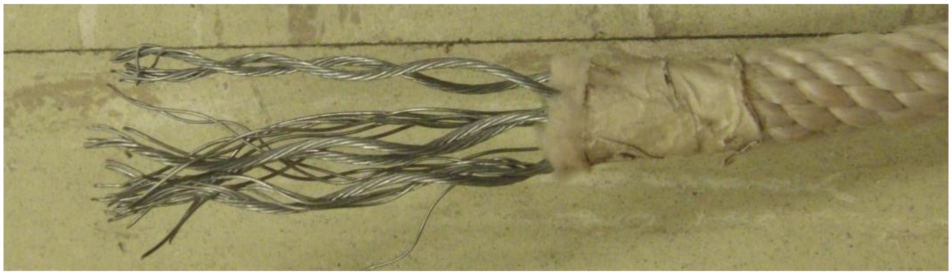


Figure 73 : Wind Weight Rope Exposed End 2

Straps

The net vertical straps had varying levels of wear and damage. Three of the four straps contacted during the 2/2/16 incident had their stitching that secures the strap to the rope ripped free. All other straps were secured to the rope.

Vertical Strap Wear and Damage										
Strap Starting from Starboard as Set Up on 2/2/16	1	2	3	4	5	6	7	8	9	10
Contacted by Aircraft on 2/2/16 (From Video)	No	Contact	Contact	Contact	Contact	No	No	No	No	No
Correctly Secured to Rope OR Free to Slide	Secure	Secure	Free	Free	Free	Secure	Secure	Secure	Secure	Secure
Vertical Strap Lengths - Unstretched (in)	45	46.5	46	47	45	45.5	45	44.5	44.5	44.5

Figure 74 : Vertical Strap Condition

Figure 75 : Example of Secure Strap

Figure 76 : Example of Strap Ripped Free

Strap 4, as defined in the Table 1, had the stitches that create the loop for the rope had minor damage. All the other straps' loop stitching is in perfect condition. The damage to Strap 4 probably occurred during the extreme loading of the double jam on 2/2/16.

Figure 77 : Strap 4 Loop Stitching Damage

Strap 5, as defined in Table 1, has a straight cut or tear. The damage is on the strap 4 side of strap 5. After reviewing the 2/2/16 video and considering the damage/wear observations of the ground crew, the single cut or tear of on the strap is believed to have been inflicted by the aircraft during the double jam on 2/2/16.

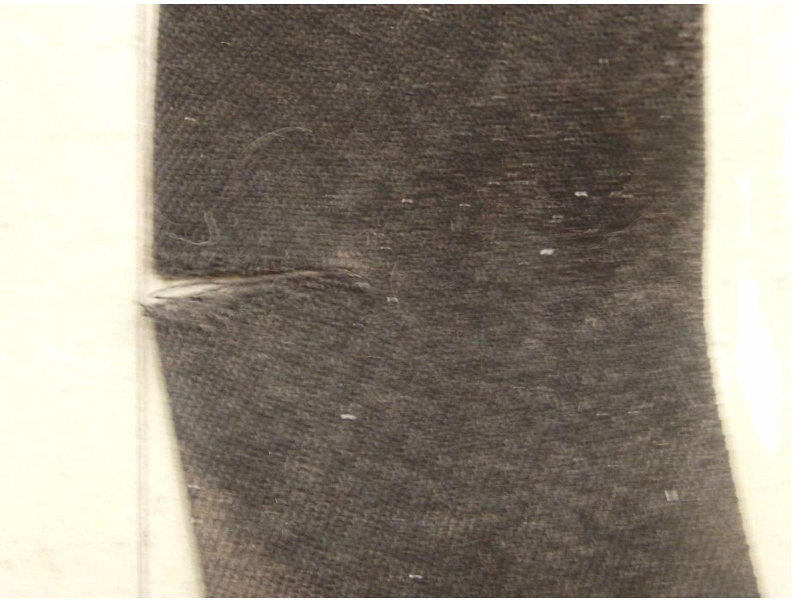


Figure 78 : Strap 5 Damage

Top Rope

The only damage or wear to the top rope is one frayed spot near the damage to strap 5, between strap 5 and 6. As it was inspected, the fraying worsened quickly, potential indication the it was a recent laceration. After reviewing the 2/2/16 video and considering the damage/wear observations of the ground crew, the single point of damage on the top rope is believed to have been inflicted by the aircraft during the double jam on 2/2/16. This section of the rope slipped off of the port wing of during the double jam on 2/2/16.

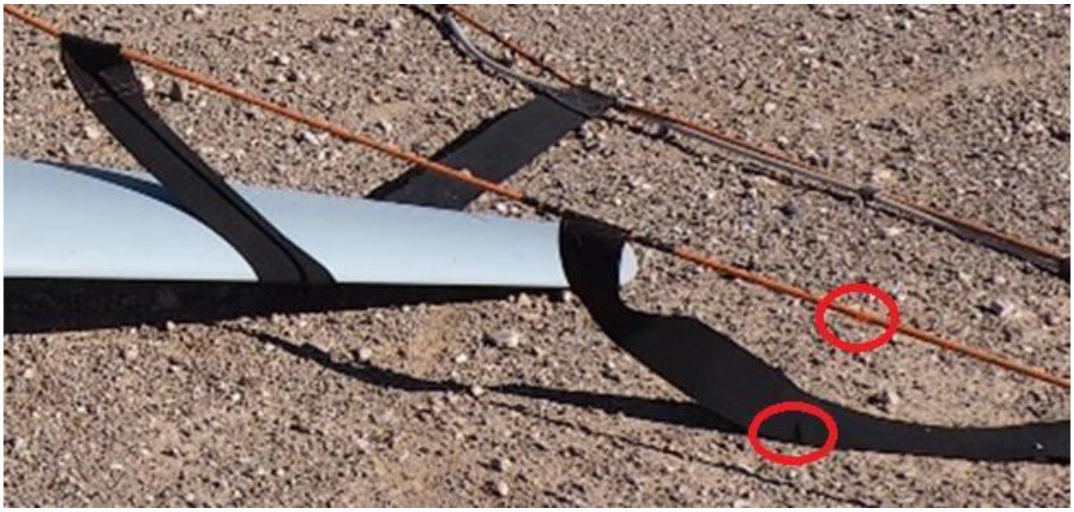


Figure 79 : Location Relative to Damaged Aircraft

Figure 80 : Top Rope Damage Location

Figure 81 : Close-up of Top Rope Damage

Top Rope Ends

The ends of the top rope that interact with the top cam cleat and sometimes contact the rest of the dissipater structure were slightly rough from wear, but the sheathing was still completely intact. The ends of top rope were new rope when installed on May of 2015 during the net conversion for a trike gear aircraft.

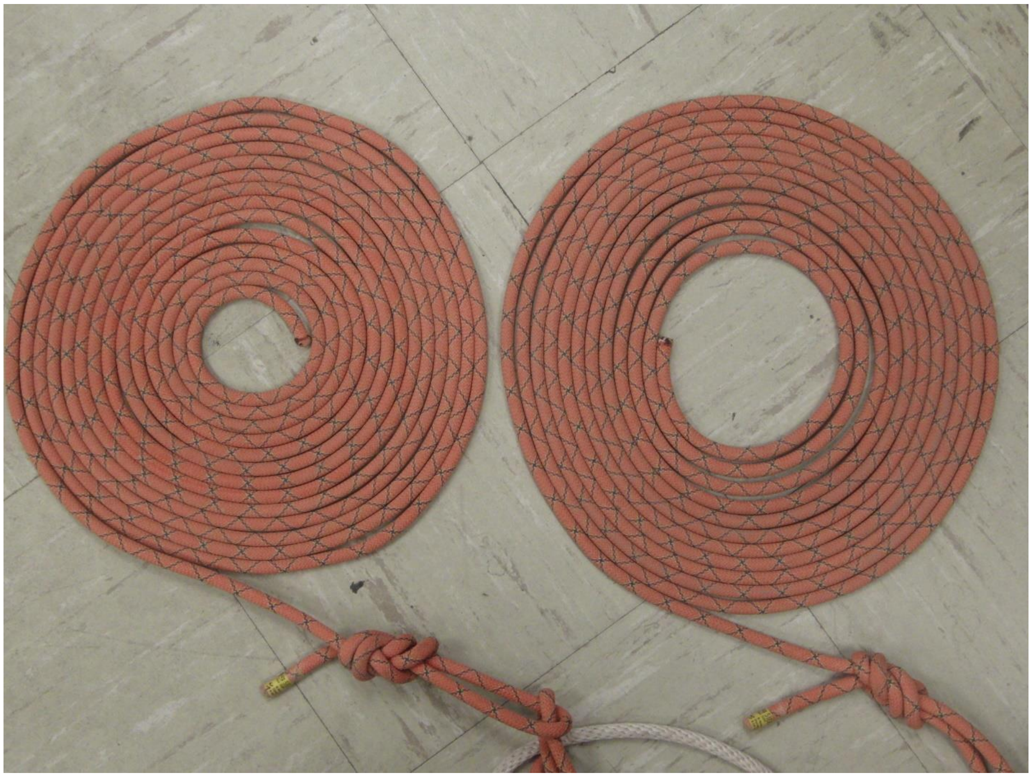


Figure 82 : Top Rope Ends, Fine Condition

Top Cam Cleat and Pulley

The top cam cleat teeth were worn from the top rope. The teeth were still able to hold the weight of the rope over an 80 ft span, before being contacted by the aircraft. The springs in the top cam cleat were still functioning sufficiently. The problem of the bottom spring in the top cam cleat wearing out due to forces encountered during set up has apparently been solved by the addition of the pulley as a rope guide.

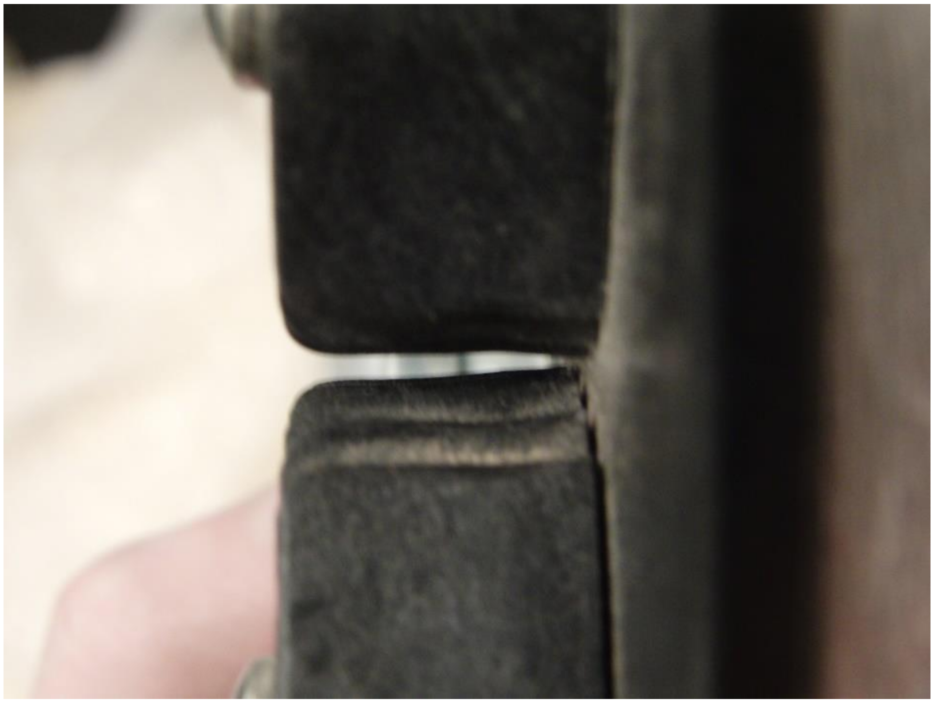


Figure 83 : Top Cam Cleat Teeth Wear

The Port Pulley Mount has a mar where it appears the end of the top rope wedged between the pulley and the pulley mount.

Figure 84 : Mar on Pulley Mount

Dissipater Base and Dissipater

The Bottom Cam Cleats are in fine condition.

Figure 85 : Bottom Cam Cleats

The Bottom Cam Cleat Mount has been rotated to a slight angle.

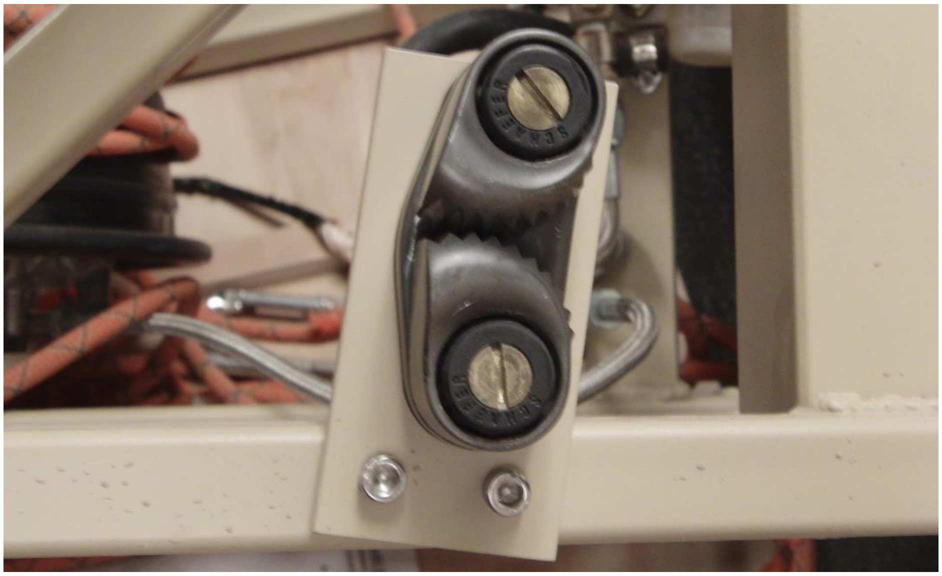


Figure 86 : Bottom Cam Cleat Mount

The holes on the dissipater base, used to secure the bottom cam cleat mount to the base, show no signs of damage or wear.

Figure 87 : Bottom Cam Cleat Mount Dissipater Base Holes

The holes on the bottom cam cleat mount show slight wear from the heads of the bolts.

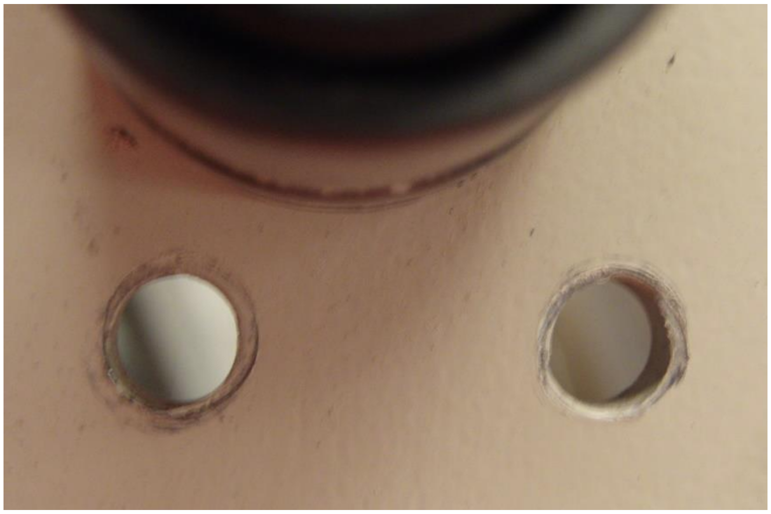


Figure 88 : Bottom Cam Cleat Mount Holes

The threads of the bottom cam cleat mounts were undamaged.

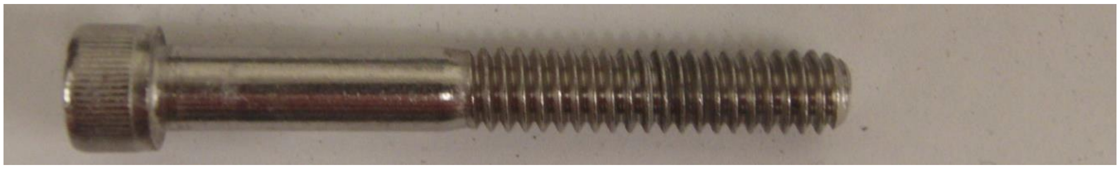


Figure 89 : Bottom Cam Cleat Mount Bolt

The stake holes were slightly bent; the stake holes should be watched for further wear/damage as testing continues.

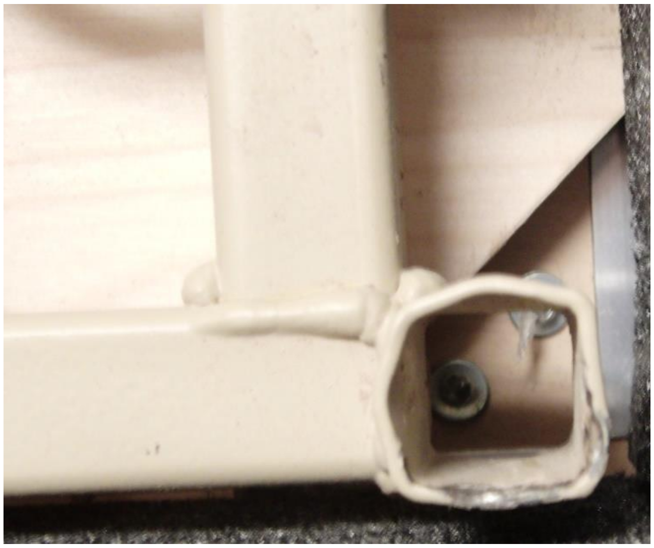


Figure 90 : Slightly Bent Stake Hole

CONCLUSIONS

The top pulley should be removed and the problems it solved should be solved by alternative methods. A peg where the pulley was located could make setup easier. The top cam cleats could be replaced once the teeth were worn to the extent that tension in the top rope could not be sustained due to slippage. The climbing rope could be replaced with abrasion-resistant and UV-resistant rope. Rope used for hauling up traps by the commercial fishing industry is a potential source of an appropriate replacement rope. Alternatively, the climbing rope could be kept out of the sun when not in use and the dissipater ropes and outer sections of the top rope could be replaced before fraying occurs. If frayed rope was not used or the pulley was not installed, the design utilizing cam cleats would have likely been the final design, as a single jam would not have caused the significant damage that a jam on each side did.

Barrier System for Trike Gear with Magnetic Release

DESIGN ITERATION MOTIVATION

Replacing the climbing rope with abrasion-resistant and UV-resistant rope, or periodically installing new climbing rope for the dissipater ropes and outer sections of the top rope, were deemed to be inadequate solutions. The fact that the cam cleats clamp down on the dissipater ropes, and the outer sections of the top rope, as tension increases shortly after the aircraft engages the net became apparent. This fact motivated a search for alternative release mechanisms that did not encounter as extreme of stresses shortly after the aircraft engaged the net.

DESIGN

Magnetic release systems replaced the top cam cleats and the bottom cam cleats were removed. The magnetic release system consisted of a magnet, a steel plate, a climbing O-ring, two lengths of paracord, a clam cleat, an eyebolt, and a carabiner. The magnet is attracted to the steel plate and should stay attached until the aircraft engages the net. One length of paracord links the magnet to the O-ring for the outer segments of the top rope to loop through. The clam cleat creates a loop at an end of the top rope and allows for tension to be easily applied to the top rope.

The magnet would occasionally separate from the steel plate while the operator added tension to the top rope and be flung towards the operator. A carabiner was linked by paracord to an eyebolt on the upright. The carabiner was hooked to the O-ring while the operator added tension to the top rope. The carabiner was removed after the operator was out of the path that the magnet could take during a premature separation. JB-Weld was applied to the surface of the magnet to fill divots and keep metal shavings from accumulating on the face of the magnet. Any grit on the magnet or steel plate increased the chance of premature separation.

Figure 91 : Magnet with Divots Filled with JB-weld

TEST APPROACH

The aircraft was recovered using the modified system.

TESTING RESULTS

The magnetic release system successfully maintained tension in the top rope until the aircraft engaged the net. The aircraft was damaged during a recovery when the nose gear snagged on the top rope.

Figure 92 : 4/17/17 Nosewheel Snag

The magnets often landed near the aircraft during recovery.

Figure 93 : Magnet Flying Toward Aircraft

The carabiner and eyebolt safety system, used to ensure the magnets did not hit the operator during top rope tensions, was sometimes used incorrectly.

CONCLUSIONS

The potential for the magnets to damage the aircraft or the camera was a concern after recovery testing with the magnetic release system. When the safety system was used incorrectly, it either put the operator at risk during tensioning of the top rope, or it would have stopped the aircraft suddenly during recovery. Solutions to these problems can be seen in the final design, in the form of the shear-pin release system.

CHAPTER VII

CONCLUSIONS

There were at least 21 on-runway recoveries which were all successful. Off-runway recoveries, the reason to have a barrier as opposed to an arresting wire, were not as successful. The bottom rope slipping over one side of the main gear, turning the plane and damaging the nose gear, is a significant concern for this recovery system. Two potential solutions are: re-introducing slant to the barrier and/or modifying the gear with larger diameter tires. If the barrier was slanted, the bottom rope would be behind the main gear before the aircraft impacting the vertical straps could pull the bottom rope up. Larger diameter tires would allow the aircraft to roll over the bottom rope even if it was off the ground the distance of half the tire radius. Increased accuracy and precision of the longitudinal touchdown location would reduce the rollout before engagement of the net and reduce the chance of snagging the nose wheel on the top rope. Instances of damage during off-runway recoveries could be reduced by larger diameter tires, shock absorption in the gear, and/or landing closer to the base of the net.

CHAPTER VIII

POTENTIAL FUTURE WORK

Spanning Wider Runways

There is an optional method for use of this system on a runway. There should be a detachable hook that attaches to the main gear mount and a rope with donuts to be used as an arresting wire. Instead of attaching the barrier to the dissipater ropes, the arresting wire with donuts will be attached to the dissipater ropes. It would still be necessary to have dissipaters on each side of the runway, but the uprights and net are no longer necessary for this configuration. The aircraft would land in front of the wire and would catch the wire as it rolls over it. This configuration would require less time for setup and is the only option for runways wider than 80 ft.

Upscaling

The design of the barrier system could be scaled up for larger, heavier aircraft.

NET AND UPRIGHT SIZING

The wing fuselage and tractor prop size would dictate the spacing of the verticals. The vertical straps’ spacing will not affect the rest of the system sizing much. The location of the most outboard vertical straps will affect the height and strength of the uprights. With the higher forces seen with heavier planes, it would be suggested to have as many straps on the wing as possible, so it is inadvisable to move the outboard straps towards the center. If the outboard straps were shifted outwards, it would greatly increase the top rope tension, height of uprights, or lower the height of the center of the net. The height of the plane and its max bounce height should set the minimum height of the middle of the net. The distance from tail to leading edge will drive the length of the straps. The tail, external payloads, or communication hardware might limit the max vertical strap length. The strap length and dissipater spacing will drive the sizing of the uprights. The 8.4mm dynamic rope is rated by mountain climbing industry to fail after 6 falls with an impact force of 1460 lbs. Climbing rope would cease to be suitable once forces in the system become too great.

DISSIPATER BRAKES

A MathCAD code previously develop can be used to find the dissipation force required. The inputs are dissipater spacing, weight, speed, and G's or stopping distance. COT hydraulic brakes should be capable of stopping much heavier aircraft than the 80 lb aircraft developed during this project.

DISSIPATER STRUCTURE

Uprights must be tall enough for the net and strong enough for the moment created by the max top rope tension. The base must be large enough for the brake, strong enough for the moment created by the max top rope tension, strong enough for the dissipation loading, and securable.

DETERMINING STRENGTH OF UPRIGHTS

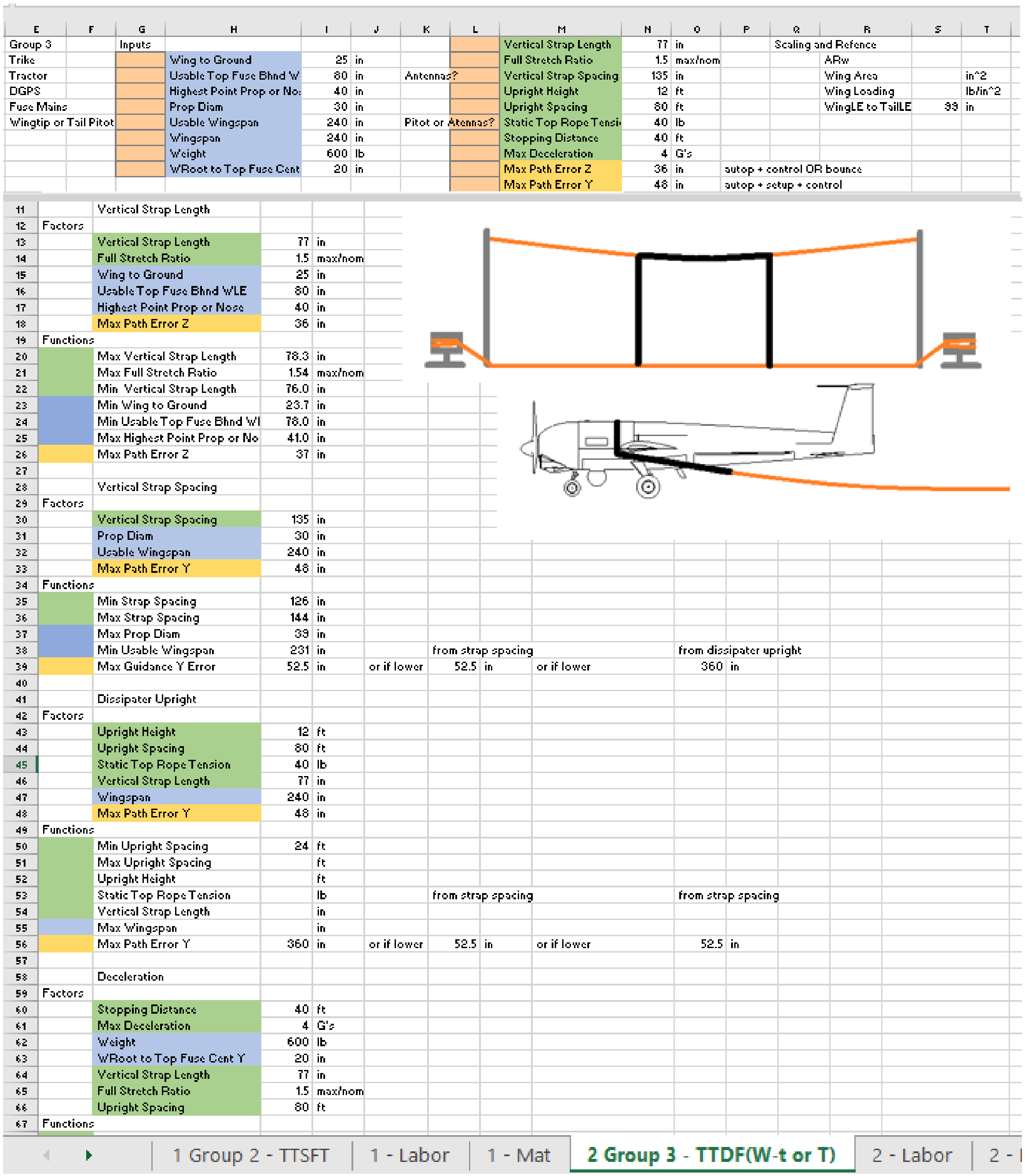
The required strength of the uprights is driven by the max bending moment, which occurs after the plane has contacted the net and before the top rope releases from the upright. This max bending moment will be the max top rope tension times the upright height. Weight of the airplane will not greatly affect the max top rope tension. The max top rope tension will be higher than the static top rope tension. Regardless of the method used to calculate the required strength of the uprights, the static top rope tension should be found as a sanity check of the upright strength.

SET UP

Depending on the height of the dissipater uprights and dissipater spacing (major contributor to top rope tension), a reach extender and/or pulley system might be required for setup. If stakes are used to secure the base to the ground, the stake slots should be stronger than the rest of the dissipater base, as the current stake slots are deforming.

DESIGH SPREADSHEET

A spreadsheet intended to guide the design of barrier recovery systems was created. The spreadsheet is incomplete, but could assist with some designs, and could be completed to support more design types.



E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Group 3		Inputs						Vertical Strap Length	77	in		Scaling and Refence			
Trike			Wing to Ground	25	in			Full Stretch Ratio	1.5	max/nom			ARw		
Tractor			Usable Top Fuse Bhnd W	80	in	Antennas?		Vertical Strap Spacing	135	in			Wing Area		in^2
DGPS			Highest Point Prop or No:	40	in			Upright Height	12	ft			Wing Loading		lb/in^2
Fuse Mains			Prop Diam	30	in			Upright Spacing	80	ft			WingLE to TailLE	99	in
Wingtip or Tail Pitot			Usable Wingspan	240	in	Pitot or Atennas?		Static Top Rope Tensi	40	lb					
			Wingspan	240	in			Stopping Distance	40	ft					
			Weight	600	lb			Max Deceleration	4	G's					
			WRoot to Top Fuse Cent	20	in			Max Path Error Z	36	in	autop + control OR bounce				
								Max Path Error Y	48	in	autop + setup + control				

11		Vertical Strap Length								
12	Factors									
13		Vertical Strap Length	77	in						
14		Full Stretch Ratio	1.5	max/nom						
15		Wing to Ground	25	in						
16		Usable Top Fuse Bhnd WLE	80	in						
17		Highest Point Prop or Nose	40	in						
18		Max Path Error Z	36	in						
19	Functions									
20		Max Vertical Strap Length	78.3	in						
21		Max Full Stretch Ratio	1.54	max/nom						
22		Min Vertical Strap Length	76.0	in						
23		Min Wing to Ground	23.7	in						
24		Min Usable Top Fuse Bhnd Wl	78.0	in						
25		Max Highest Point Prop or No	41.0	in						
26		Max Path Error Z	37	in						
27										
28		Vertical Strap Spacing								
29	Factors									
30		Vertical Strap Spacing	135	in						
31		Prop Diam	30	in						
32		Usable Wingspan	240	in						
33		Max Path Error Y	48	in						
34	Functions									
35		Min Strap Spacing	126	in						
36		Max Strap Spacing	144	in						
37		Max Prop Diam	39	in						
38		Min Usable Wingspan	231	in		from strap spacing			from dissipater upright	
39		Max Guidance Y Error	52.5	in	or if lower	52.5	in	or if lower	360	in
40										
41		Dissipater Upright								
42	Factors									
43		Upright Height	12	ft						
44		Upright Spacing	80	ft						
45		Static Top Rope Tension	40	lb						
46		Vertical Strap Length	77	in						
47		Wingspan	240	in						
48		Max Path Error Y	48	in						
49	Functions									
50		Min Upright Spacing	24	ft						
51		Max Upright Spacing		ft						
52		Upright Height		ft						
53		Static Top Rope Tension		lb		from strap spacing			from strap spacing	
54		Vertical Strap Length		in						
55		Max Wingspan		in						
56		Max Path Error Y	360	in	or if lower	52.5	in	or if lower	52.5	in
57										
58		Deceleration								
59	Factors									
60		Stopping Distance	40	ft						
61		Max Deceleration	4	G's						
62		Weight	600	lb						
63		WRoot to Top Fuse Cent Y	20	in						
64		Vertical Strap Length	77	in						
65		Full Stretch Ratio	1.5	max/nom						
66		Upright Spacing	80	ft						
67	Functions									

Figure 94 : Tab of Design Spread

REFERENCES

1. Combs, James W. DESIGN AND DEVELOPMENT OF A QUIET UNMANNED AIRCRAFT SYSTEM. Thesis. Oklahoma State University, 2013

2. Gundlach, Jay. Designing Unmanned Aircraft Systems: A Comprehensive Approach. Reston, VA: American Institute of Aeronautics and Astronautics, 2012. Print

3. Wiesel, William E. Spaceflight Dynamics. Third ed. New York: McGraw-Hill, 2010. Print.

4. Nam-Jin, Lee. The Effect of a Variable Disc Pad Friction Coefficient for the Mechanical Brake System of a Railway. PLOS ONE, 2015

5. Mutlu, Ibrahim. The effects of porosity in friction performance of brake pad using waste tire dust. Polimeros, 2015

APPENDICES A

RECOVERY SYSTEM TECHNICAL OVERVIEW

Recovery

1.1 SYSTEM

1.1.1 Design Motivation

The AV was required to be recovered to a site with limited geographical space and without a runway. The recovery system was required to be transportable by a small section of a vehicle and be able to be set up by two individuals in under 15 minutes. No single component was to weigh more than 100 pounds, including shipping / transportation cases. The unimproved terrain and portability requirements drove development to the final design.

1.1.2 System Type Selection

Due to unconventional requirements, a survey of existing systems included both unmanned and manned aircraft operations. The design that proved to most completely fulfill the requirements is similar to an aircraft carrier emergency barricade system. An arresting wire system was attempted first, but fulfilling the unimproved terrain requirement was determined through testing to be futile.

System Types				
	Limited Space	Unimproved Terrain	Extremely Portable	Rapid Set-up
Tower/Vertical Wire	Yes	Yes	No	Yes
Above Ground Net	Yes	Yes	No	No
Arresting Wire	Yes	No	Yes	Yes
Barricade Net	Yes	Yes	Yes	Yes

The consideration of using a barricade net for a straight wing, puller prop AV raised concerns about loading the prop and wing during recovery. A net recovery imparts high loads to the wing tips of an un-swept wing. The elasticity of the vertical straps distributes some of the load to the inboard section of the wings. It was a concern that the prop/engine mount could be damaged or heavily worn by the net. The wide spacing of the vertical straps decreases the percent of the time the straps engage the prop. Prop/engine mount damage/wear was not found to be the case during testing. A benefit of the barricade net is that in the case where a runway is available, a low impact recovery method can be employed. The runway recovery method with a barricade net should be to touchdown early and roll into the net. The 80 ft span ensures that if the AV can turn during extended ground rolls and still be successfully captured.

1.1.3 Further Design Justifications

Stakes were chosen for the method for immobilizing the dissipator bases, because it would require too much weight, violating the portability requirement.

Hydraulic braking system was chosen for momentum dissipation. Ease of variation of dissipation force is beneficial, because if new, heavier iterations of the AV are developed, the dissipation force can be increased by turning a knob. By choosing COTS ATV brake parts, relatively cheap and accessible reparment parts were ensured.

Climbing rope was chosen for its low weight and for the feature of being a failsafe jerk reducer. The failsafe jerk reduction was proved its value during one recovery test.

Cam cleats hold tension in the net until the AV pulls the net downrange, popping the rope out of the cam cleats. The net is easily insert into the cam cleats and pulled tight during set-up.

Heavy rope was used to weigh down the bottom rope to ensure that a wind gust could not raise the bottom rope and allow the nose gear to slip under. The ropes are allowed to slide length wise realitive to each other to allow the load bearing climbing rope to stretch

.

1.1.4 Specifications

Recovery System Specifications	
System Type	Barricade Net
Dissipation Type	Hydraulic Disk Brake
Dissipator Span	min 55 ft / max 80 ft
Middle Net Height	3 ft 6 in
Guidance System	GPS (NO GPS) + Laser Alt

1.1.5 System Overview

The recovery net minimizes the geographical space required for the AV to land, while enabling the AV to be land without a runway or DGPS.

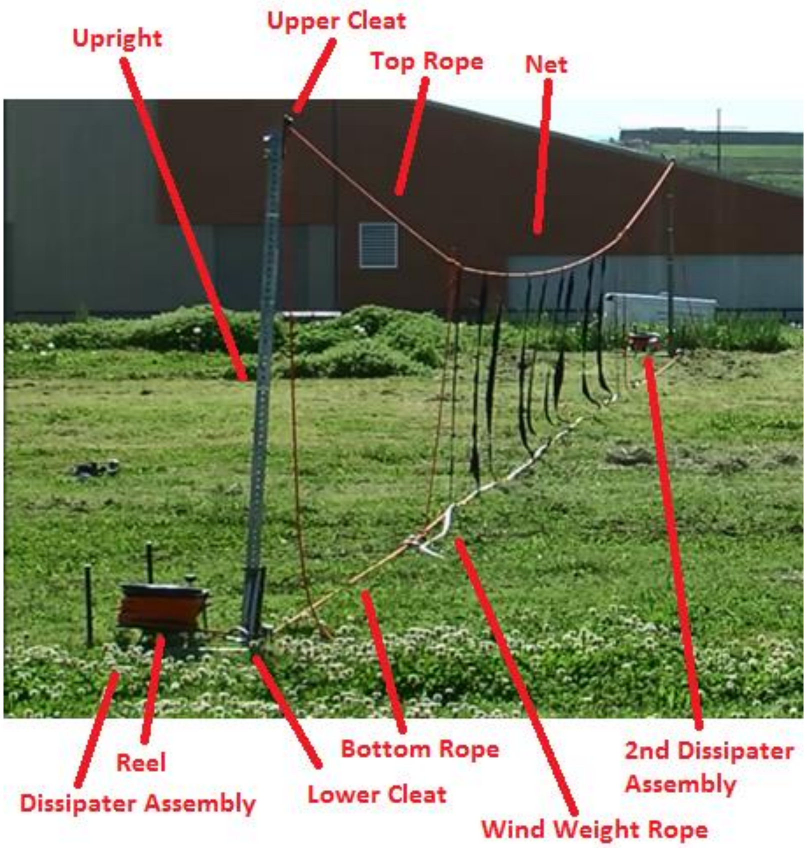


Figure 0-1 Recovery Net

The recovery net captures the AV. The two dissipaters slow the AV upon net capture. The net is held in place by 4 cleats. 1 cleat on both both dissipater bases hold the bottom rope. 1 cleat on both uprights hold the top rope.

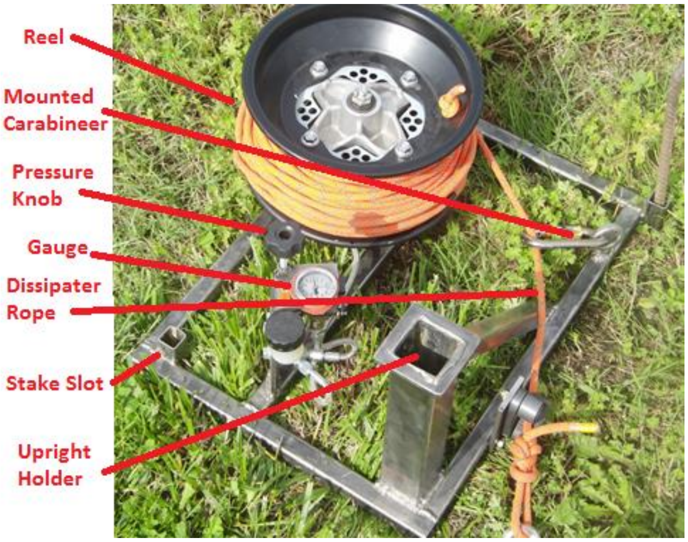


Figure 0-2 Dissipater Base

Uprights slide out of the bases' upright holders to become easily portable.

Figure 0-3 Recovery

When the AV contacts the net, the top rope is pulled from the upper cleats. Next, the bottom rope, attached to the dissipaters, is pulled from the lower cleats and continues to slow the AV.

1.2 PROCEDURES

1.2.1 Setup

1. Select the recovery site.

NOTE

> **When selecting a recovery site, ensure there is 60 ft of open ground downrange of the net and ensure location is flat (no berms, boulders, or ditches).**

2. Place net
    a. To help with the placement of the dissipaters, unwind the net onto the ground where it will be erected

Figure 0-4 Net Stored on Spool

3. Place a dissipater base on each side of net on stakeable ground
    a. Orient dissipater bases relative to landing direction so that the upright mounts are downrange and inside

Figure 0-5 Dissipater Orientation

4. Insert uprights

Figure 0-6 Dissipater with Upright

   a. Orient uprights so that upper cleats face down range and will hold net taunt

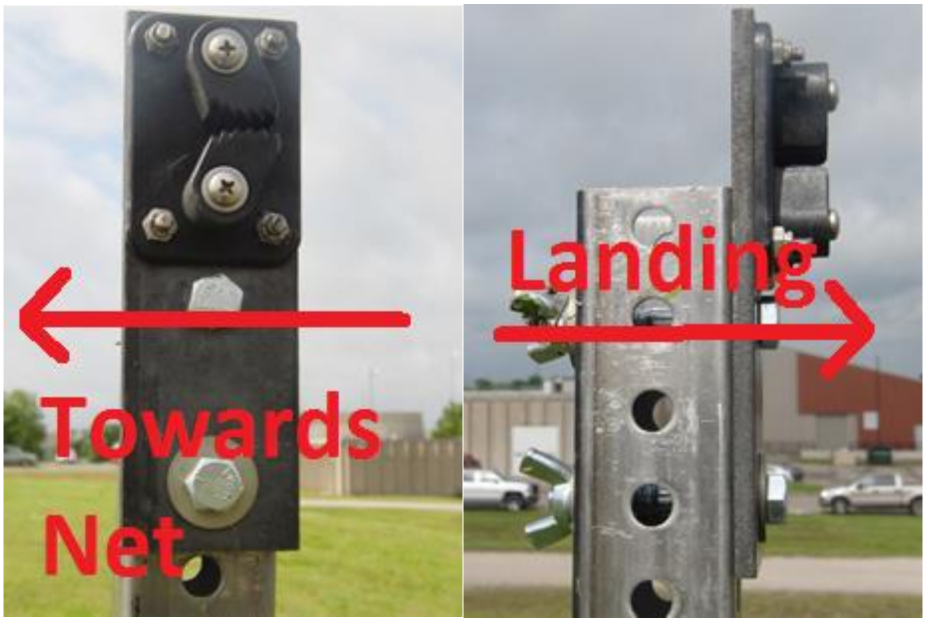


Figure 0-7 Upper Cleat Orientation Relative to Landing Direction

5. Set upper cleat height (if different dissipater span than last setup)
   a. Upper cleat height depends on dissipater spacing
      i. 55 ft spacing = 5’2” upper cleat height
      ii. 80 ft spacing = 6’2” upper cleat height (1 hole down from highest placement)
         (1) Height defined at cleat teeth
6. Stake down dissipaters
   a. Choose large straight or small L stakes depending on soil condition

Figure 0-8 Stakes

b. Drive stakes with sledge hammer into stake slots

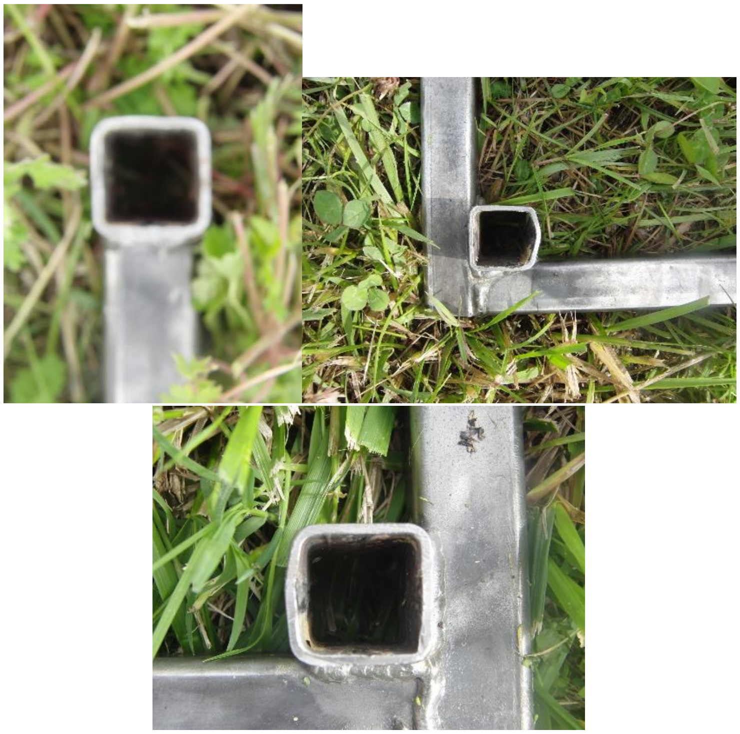


Figure 0-9 Stake Slots

   i. Drive large straight stakes until 8 inches of each stake remains above each stake slot
   ii. Drive small stakes till flush with stake slot

Figure 0-10 Driving Dissipater Stakes

7. Mount Net
    a. Attach an end of bottom rope to each of two the dissipater ropes using carabiners

Figure 0-11 Connecting Net to Dissipater Ropes

    b. Run dissipater ropes through their dissipater base’s mounted carabineer

Figure 0-13 Dissipater Rope through Mounted Carabineer

c. Place dissipator ropes in lower cleats

Figure 0-14 Dissipater Rope through Lower Cleat

d. Place top rope in each upper cleat

Figure 0-15 Top Rope through upper Cleat

e. Check net

  i. Orientation

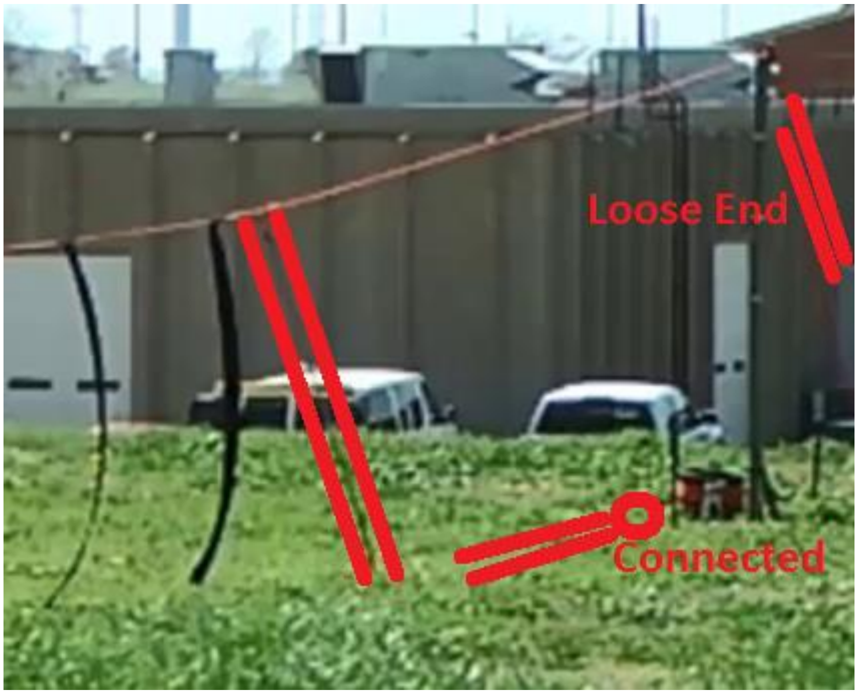


Figure 0-16 Net Orientation

(1) Bottom rope connected to dissipater rope

(2) Top rope loose end dangling from upper cleat

(3) Angle rope section angled as shown

ii. Height and Tension

Figure 0-17 Net Height and Tension

(1) Top rope should be very taunt

(2) Bottom rope should be taunt

(3) If the net still does not sit correctly, adjust height of upper cleats

8. Setup dissipaters

a. Wind up any slack onto the dissipater reels

b. WARNING do not leave rope below reel

Figure 0-18 Bottom of Dissipater Reel

i. Unwind and rewind rope until no rope is below the reel

c. Adjust both dissipater pressures to 125 psi.

NOTE

Do not pressurize over 700 psi

Figure 0-3 Adjusting Dissipater Pressure

1.2.2 After Landing

1. Disengage net from aircraft
2. Detach dissipater rope from net.
3. Set dissipaters pressure to zero psi

Figure 0-4 Adjusting Dissipater Pressure

4. Reel in dissipater rope.

Figure 0-5 Reeling In Dissipater Rope

5. Remove uprights.

1.2.3 Disassembly

1. Disengage net from aircraft.
2. Set dissipaters to zero psi.

Figure 0-6 Adjusting Dissipater Pressure

3. Disconnect net from dissipater rope.
4. Reel in dissipater rope.

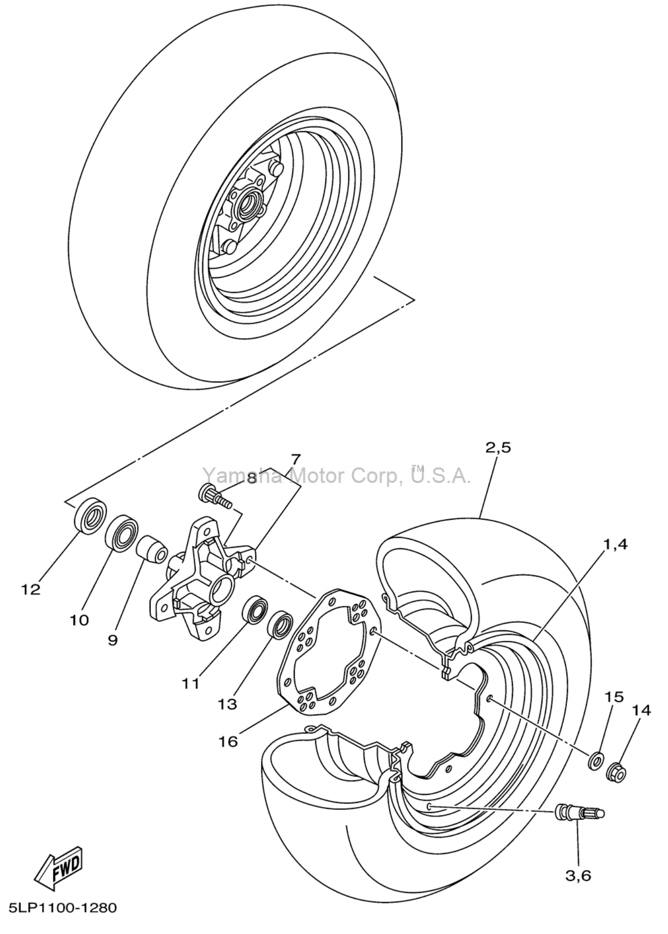
Figure 0-7 Reeling in Dissipater Rope

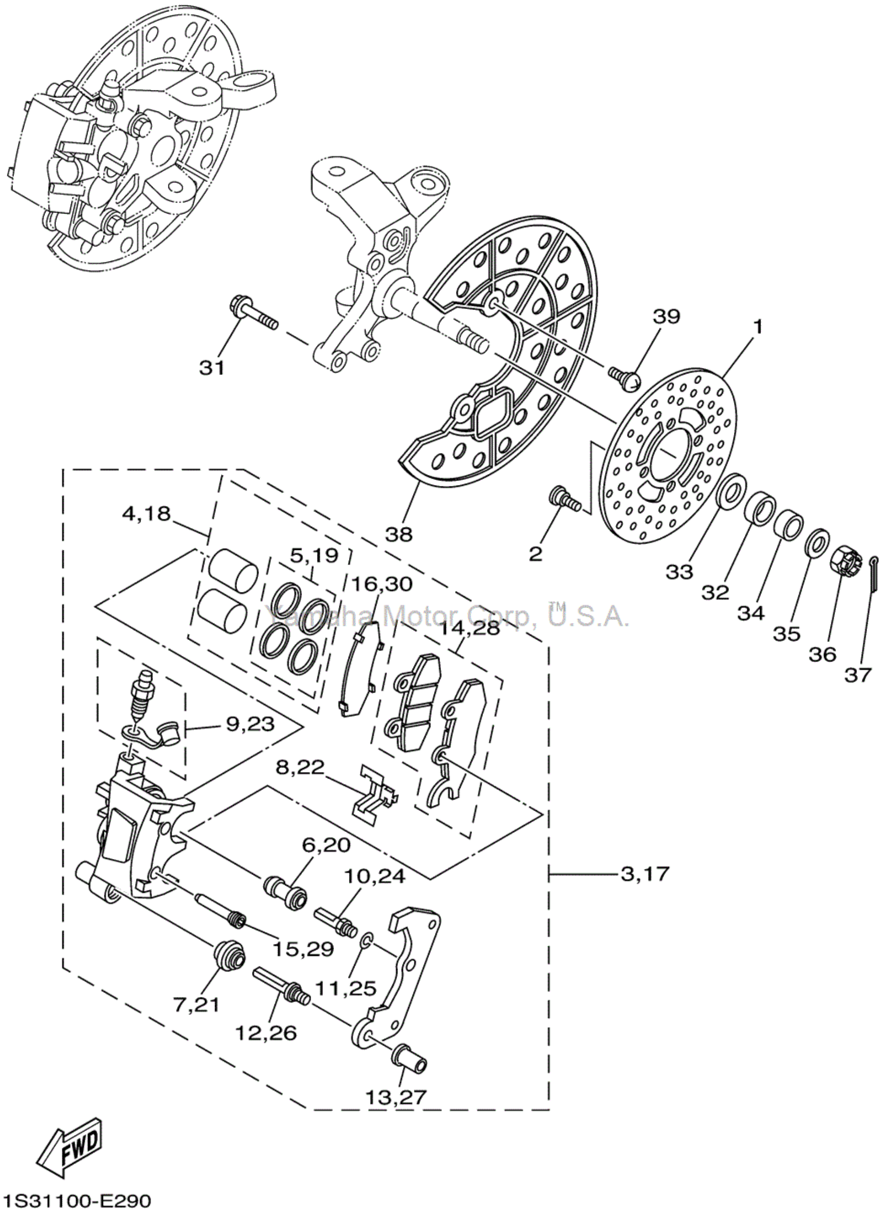
5. Remove Uprights.
6. Remove stakes from dissipaters.
7. If time permits, wind up the net onto the net spool

Figure 0-24 Net Stored on Spool

APPENDICES B

DISSIPATER BRAKING COMPONENTS

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FWD
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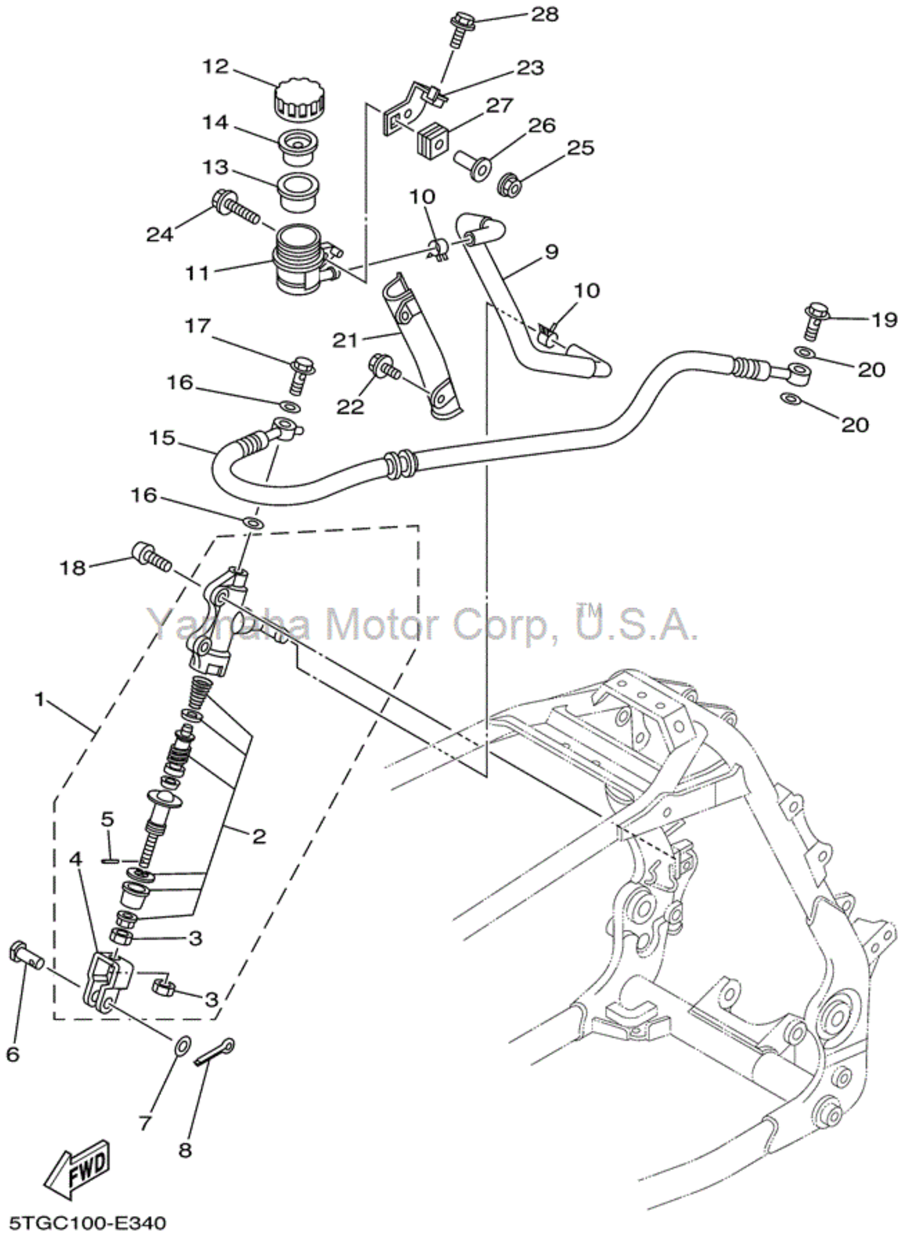
Yamaha Motor Corp, U.S.A. ™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Yamaha Motor Corp, U.S.A. ™
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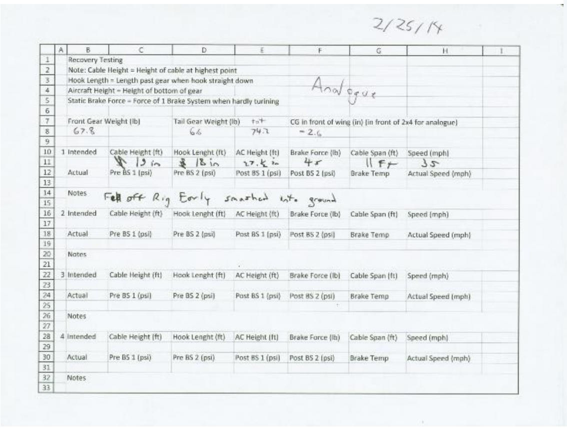
5TGC100-E340

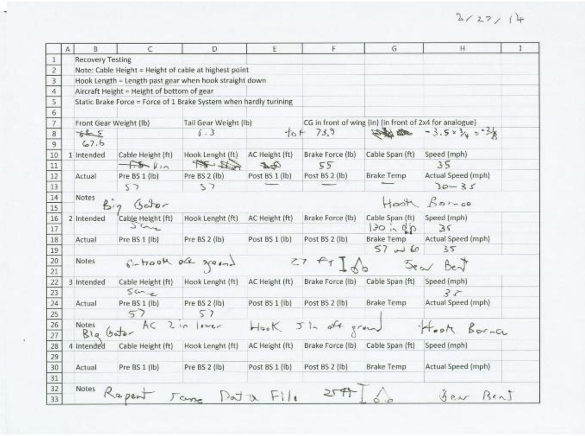
APPENDICES C

ARRESTING WIRE TEST CARDS



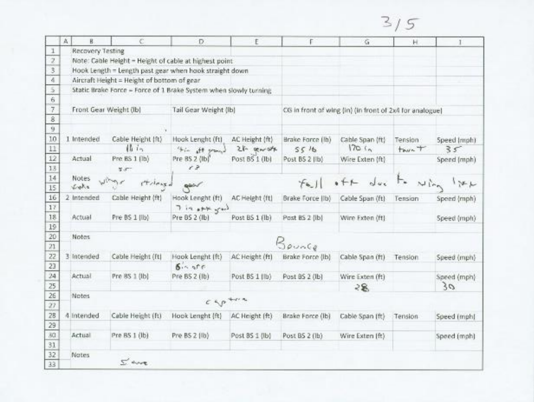
2/25/14

	A	B	C	D	E	F	G	H	I
1		Recovery Testing							
2		Note: Cable Height = Height of cable at highest point							
3		Hook Length = Length past gear when hook straight down				Analogue			
4		Aircraft Height = Height of bottom of gear							
5		Static Brake Force = Force of 1 Brake System when hardly turining							
6									
7		Front Gear Weight (lb)		Tail Gear Weight (lb)	tot	CG in front of wing (in) (in front of 2x4 for analogue)			
8		67.8		66	74.2	-2.6			
9									
10	1	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
11			13 in	18 in	27.5 in	45	11 ft	35	
12		Actual	Pre BS 1 (psi)	Pre BS 2 (psi)	Post BS 1 (psi)	Post BS 2 (psi)	Brake Temp	Actual Speed (mph)	
13									
14		Notes	Fell off Rig Early smashed into ground						
15									
16	2	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
17									
18		Actual	Pre BS 1 (psi)	Pre BS 2 (psi)	Post BS 1 (psi)	Post BS 2 (psi)	Brake Temp	Actual Speed (mph)	
19									
20		Notes							
21									
22	3	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
23									
24		Actual	Pre BS 1 (psi)	Pre BS 2 (psi)	Post BS 1 (psi)	Post BS 2 (psi)	Brake Temp	Actual Speed (mph)	
25									
26		Notes							
27									
28	4	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
29									
30		Actual	Pre BS 1 (psi)	Pre BS 2 (psi)	Post BS 1 (psi)	Post BS 2 (psi)	Brake Temp	Actual Speed (mph)	
31									
32		Notes							
33									



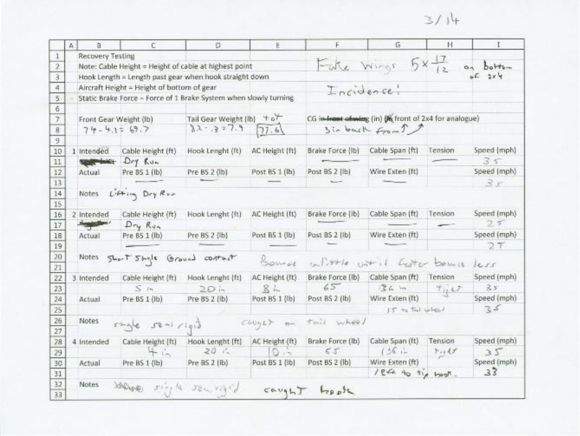
2/27/14

	A	B	C	D	E	F	G	H	I
1		Recovery Testing							
2		Note: Cable Height = Height of cable at highest point							
3		Hook Length = Length past gear when hook straight down							
4		Aircraft Height = Height of bottom of gear							
5		Static Brake Force = Force of 1 Brake System when hardly turining							
6									
7		Front Gear Weight (lb)		Tail Gear Weight (lb)		CG in front of wing (in) (in front of 2x4 for analogue)			
8		~~68.5~~		6.3	tot	73.9		-3.5 × 3/4 = -3 3/8	
9		67.6							
10	1	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
11			11 in			55		35	
12		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Brake Temp	Actual Speed (mph)	
13			57	57	—	—	—	30–35	
14		Notes							
15			Big Gator				Hook Bounce		
16	2	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
17			Same				130 in dip	35	
18		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Brake Temp	Actual Speed (mph)	
19							57 and 60	35	
20		Notes	6 in hook off ground			27 ft		Gear Bent	
21									
22	3	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
23			Same					35	
24		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Brake Temp	Actual Speed (mph)	
25			57	57					
26		Notes	AC 2 in lower		Hook 5 in off ground			Hook Bounce	
27		Big Gator							
28	4	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Speed (mph)	
29									
30		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Brake Temp	Actual Speed (mph)	
31									
32		Notes							
33			Repeat Same Data File			25 ft		Gear Bent	



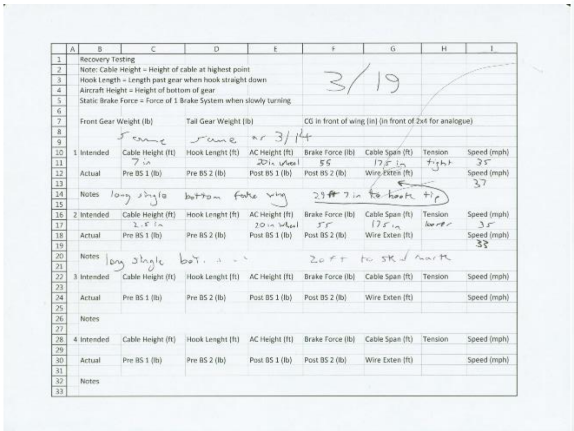
3/5

	A	B	C	D	E	F	G	H	I
1		Recovery Testing							
2		Note: Cable Height = Height of cable at highest point							
3		Hook Length = Length past gear when hook straight down							
4		Aircraft Height = Height of bottom of gear							
5		Static Brake Force = Force of 1 Brake System when slowly turning							
6									
7		Front Gear Weight (lb)		Tail Gear Weight (lb)		CG in front of wing (in) (in front of 2x4 for analogue)			
8									
9									
10	1	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
11			16 in	4 in off ground	2 in gear off	55 lb	170 in	taunt	35
12		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
13			55	53					
14		Notes							
15		Fake	wings changed	gear		fall off due to wing [illegible]			
16	2	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
17				7 in off ground					
18		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
19									
20		Notes							
21						Bounce			
22	3	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
23				6 in off					
24		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
25							28		30
26		Notes							
27				capture					
28	4	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
29									
30		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
31									
32		Notes							
33			Same						

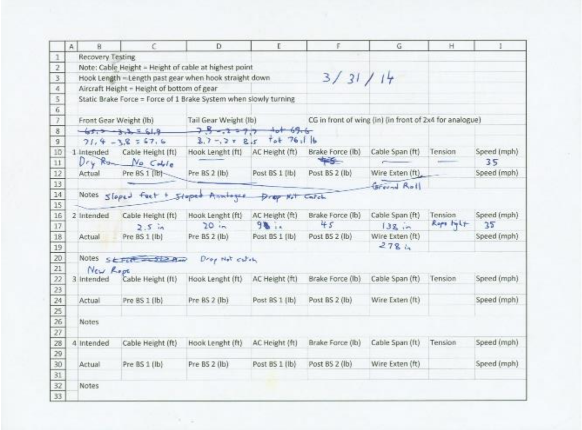


3/14

	A	B	C	D	E	F	G	H	I
1		Recovery Testing							
2		Note: Cable Height = Height of cable at highest point				Fake Wings 5 × 17/12			on bottom
3		Hook Length = Length past gear when hook straight down							of 2x4
4		Aircraft Height = Height of bottom of gear				Incidence!			
5		Static Brake Force = Force of 1 Brake System when slowly turning							
6									
7		Front Gear Weight (lb)		Tail Gear Weight (lb)	tot	CG ~~in front of wing~~ (in) ~~(in~~ front of 2x4 for analogue)			
8		74 - 4.3 = 69.7		8.2 - .3 = 7.9	77.6	3 in back from ↗			
9									
10	1	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
11			Dry Run			—	—	—	35
12		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
13			—	—	—	—	—		35
14		Notes	Lifting Dry Run						
15									
16	2	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
17			Dry Run			—	—	—	25
18		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
19			—	—	—	—	—		27
20		Notes	Short Single Ground contact						
21						Bounce a little until faster bounce less			
22	3	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
23			5 in	20 in	8 in	65	136 in	tight	35
24		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
25							15 to tail wheel		35
26		Notes	single semi rigid			caught on tail wheel			
27									
28	4	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
29			4 in	20 in	10 in	65	136 in	tight	35
30		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
31							184 to tip hook.		33
32		Notes	single semi rigid		caught hook				
33									



	A	B	C	D	E	F	G	H	I
1		Recovery Testing							
2		Note: Cable Height = Height of cable at highest point							
3		Hook Length = Length past gear when hook straight down				3/19			
4		Aircraft Height = Height of bottom of gear							
5		Static Brake Force = Force of 1 Brake System when slowly turning							
6									
7		Front Gear Weight (lb)		Tail Gear Weight (lb)		CG in front of wing (in) (in front of 2x4 for analogue)			
8									
9			Same	same as 3/14					
10	1	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
11			7 in		20 in wheel	55	175 in	tight	35
12		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
13									37
14		Notes	long single	bottom fake wing		29 ~~ft~~ 7 in ~~to~~ hook tip			
15									
16	2	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
17			2.5 in		20 in wheel	55	175 in	lower	35
18		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
19									33
20		Notes							
21			long single	bot. " "		20 ft to skid mark			
22	3	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
23									
24		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
25									
26		Notes							
27									
28	4	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
29									
30		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
31									
32		Notes							
33									



	A	B	C	D	E	F	G	H	I
1		Recovery Testing							
2		Note: Cable Height = Height of cable at highest point							
3		Hook Length = Length past gear when hook straight down				3/31/14			
4		Aircraft Height = Height of bottom of gear							
5		Static Brake Force = Force of 1 Brake System when slowly turning							
6									
7		Front Gear Weight (lb)		Tail Gear Weight (lb)		CG in front of wing (in) (in front of 2x4 for analogue)			
8		~~65.1 - 3.2 = 61.9~~		~~7.9 - .2 = 7.7~~	~~tot 69.6~~				
9		71.4 - 3.8 = 67.6		8.7 - .2 = 8.5	tot 76.1 lb				
10	1	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
11		Dry Run	No Cable	—		~~45~~	—	—	35
12		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
13							Ground Roll		
14		Notes	Sloped feet + ~~Sloped Analogue~~	~~Drop Not Catch~~					
15									
16	2	Intended	Cable Height (ft)	Hook Length (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
17			2.5 in	20 in	9 in	45	138 in	Rope tight	35
18		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
19							278 in		
20		Notes		Drop Not catch					
21		New Rope							
22	3	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
23									
24		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
25									
26		Notes							
27									
28	4	Intended	Cable Height (ft)	Hook Lenght (ft)	AC Height (ft)	Brake Force (lb)	Cable Span (ft)	Tension	Speed (mph)
29									
30		Actual	Pre BS 1 (lb)	Pre BS 2 (lb)	Post BS 1 (lb)	Post BS 2 (lb)	Wire Exten (ft)		Speed (mph)
31									
32		Notes							
33									

VITA

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Candidate for the Degree of

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