AHS 2010-Lift! More Lift!

T. win-Lift
H.elicopter
O.perations
R.esearch

Executive Summary
27th Annual AHS Student Design Competition
2010 – Graduate Category

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BOEING

Introduction

- Twin-lift represents a departure from standard sling load operations which require a completely different method of rigging, formation flight and load stabilization. To handle these changes, THOR focused on the following:
  - DAFCS/EGI Formation Flight System– Uses feedback from EGIs and feedforward from DAFCS to allow precision formation flight while one aircraft acts as a master and is flown by a pilot and the other aircraft acts as a slave being controlled by the DAFCS
  - Optical Load Stabilization System– Uses cameras mounted on each aircraft and control logic to direct the master/slave formation flight system in such a manner to minimize load oscillation while in the twin-lift configuration
  - Modular Spreader Bar– Allows the aircraft to lift the load vertically with 100% of the available lift; modular design allows the bar to be broken apart and transported in separate pieces in the back of a single aircraft

- Additional design features :
  - Emergency Load Release– Provides a fail-safe at the bar to separate the aircraft and the load in case of a catastrophic emergency
  - DAFCS Updates– Both the Formation Flight and Load Stabilization systems can be used independently of the twin-lift configuration to improve single aircraft load handling and standard formation flight
  - Low Life Cycle Cost– Alleviates the need for a heavy lift helicopter by nearly doubling the lifting capability of the Army's main lifting platform at a fraction of the cost of developing a new helicopter

Starting from a current, in-service design…

- Develop a twin-lift system such that two rotorcraft can be cooperatively operated to lift 75% more Payload than either aircraft alone could lift
- Carry enough fuel at takeoff for a 100 nm delivery distance, 10 minute mid-point hover, and return without the payload
- The baseline aircraft should have at least 5,000 lb useful load capability at Sea Level/ISA +20°C conditions
- Be able to accommodate 20' and 48' ISO containers, various wheeled or tracked vehicles, and large construction machinery

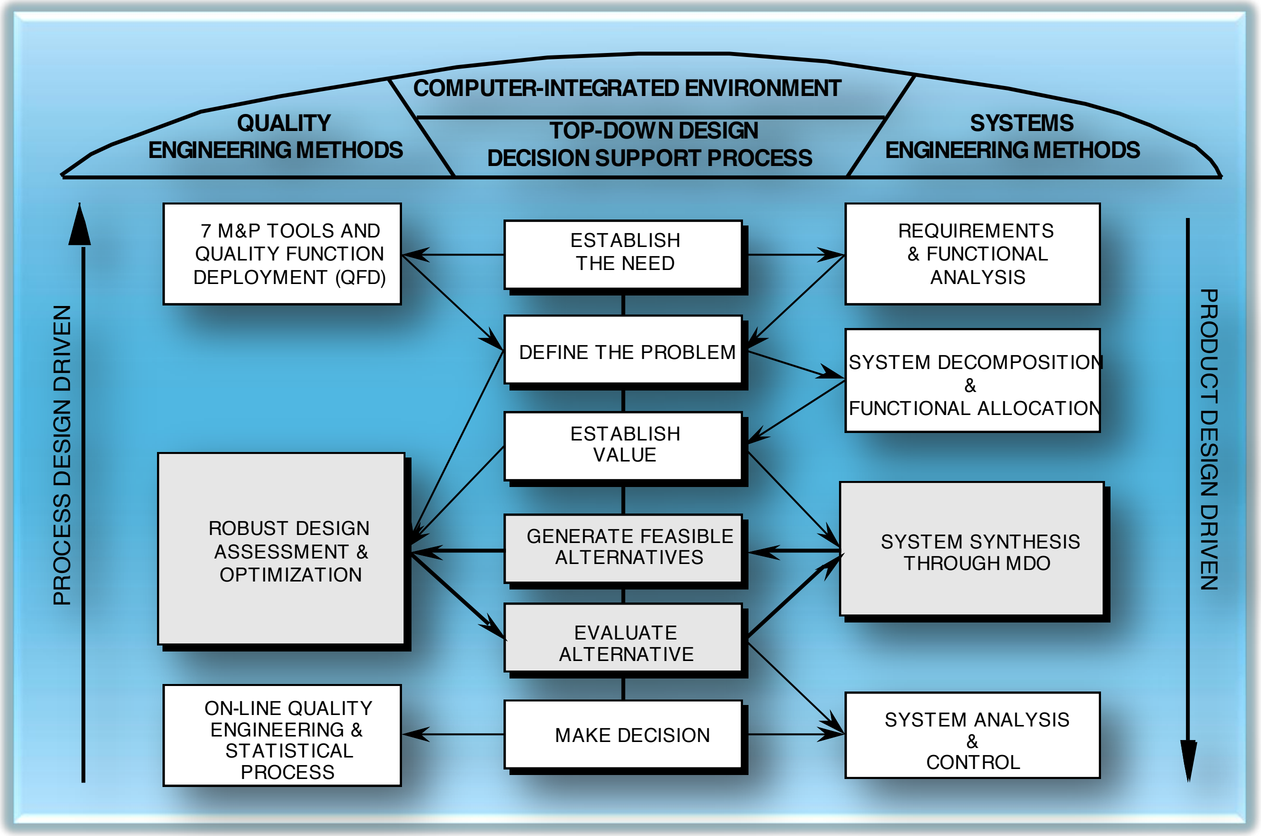
CH-47F chosen for the following capabilities:

•US Army's primary lifting platform

•Highly advanced DAFCS for superior controllability

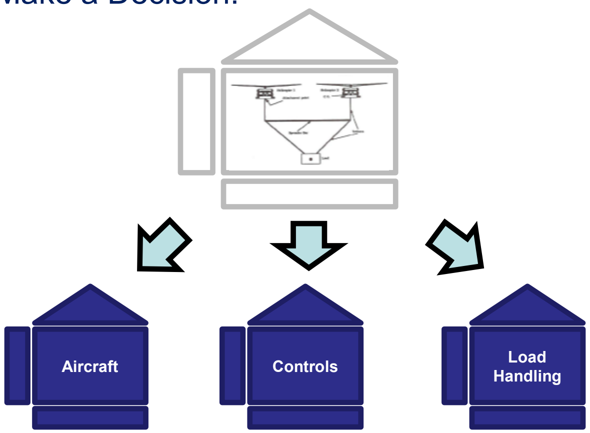
Preliminary Design

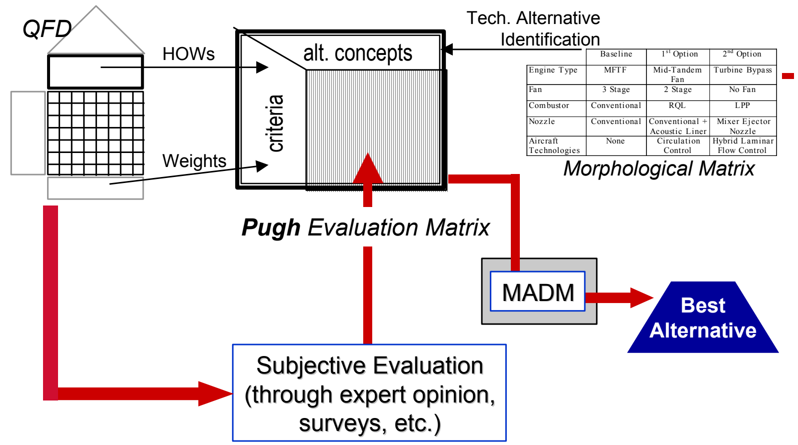
- Georgia Tech Integrated Product and Process Design (IPPD) Methodology
  - Three design loops: Conceptual Design, Preliminary Design, and Process Design
  - Integration through Product Lifecycle Management (PLM)



Conceptual Design

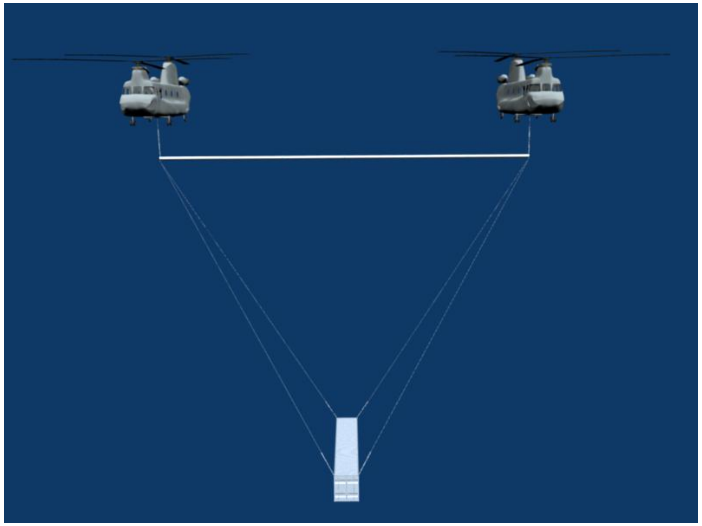
Make a Decision:

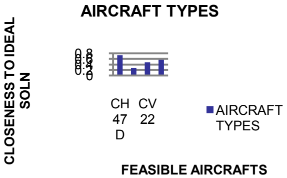


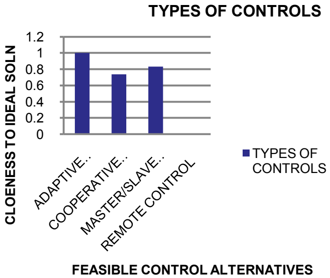


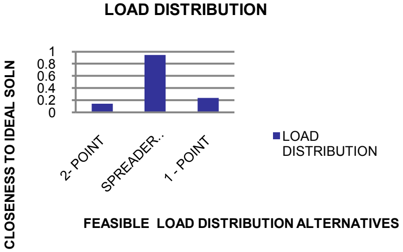
	Baseline	1st Option	2nd Option
Engine Type	MFTF	Mid-Tandem Fan	Turbine Bypass
Fan	3 Stage	2 Stage	No Fan
Combustor	Conventional	RQL	LPP
Nozzle	Conventional	Conventional + Acoustic Liner	Mixer Ejector Nozzle
Aircraft Technologies	None	Circulation Control	Hybrid Laminar Flow Control

Morphological Matrix



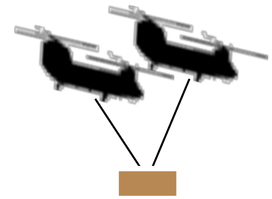






➢ **CH 47 F, ADAPTIVE CONTROL & SPREADER BAR LOAD DISTRIBUTION MOST FEASIBLE**

Mission Sizing



Taxi/Warm-up 10 min
Take-off Hover for 15 min
Climb to 1000 ft

Fly with Payload at 100 kts

Descent
Landing Hover for 10 min
Drop the payload

Origin — 100 nm — Destination

Decent
Landing Hover for 5 min
Cool down
20 min Fuel Reserve

Return without Payload at 130 kts

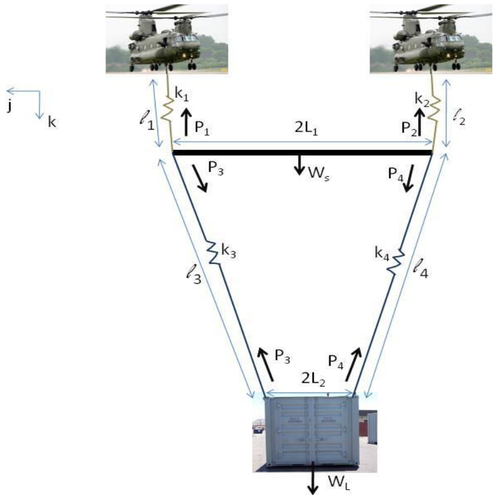
Climb to 1000 ft

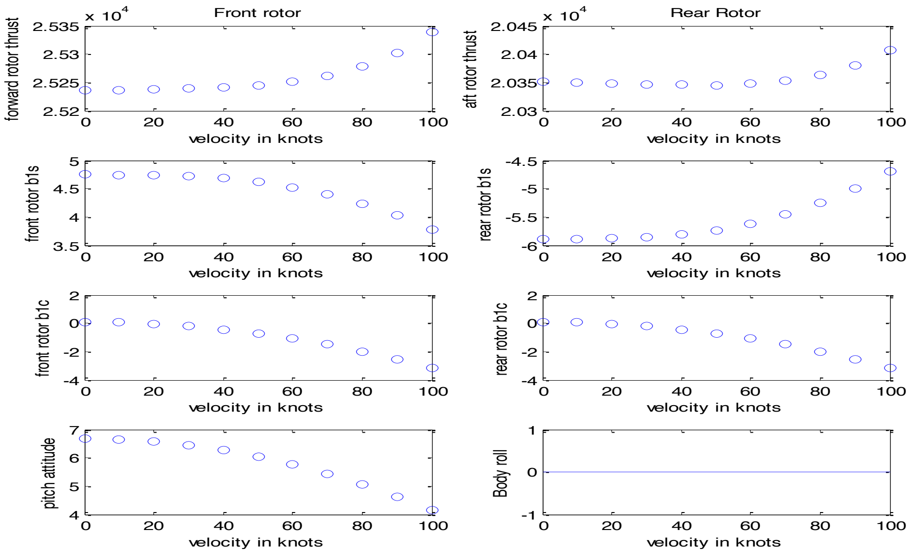
- Utilizing the stated mission profile, we used the FalconView/PFPS software from GTRI to find the maximum load weight that can be carried for the mission
  - This is the program used by the US Army to conduct mission planning for aircraft currently in service
- We also found the maximum distance the system can fly with the aircraft at maximum gross weight

	Meets Requirements	Max Weight
Load Weight	31,000 lbs	34,000 lbs
Mission Distance	100 NM	78 NM

FalconView

Twin-Lift System Dynamics



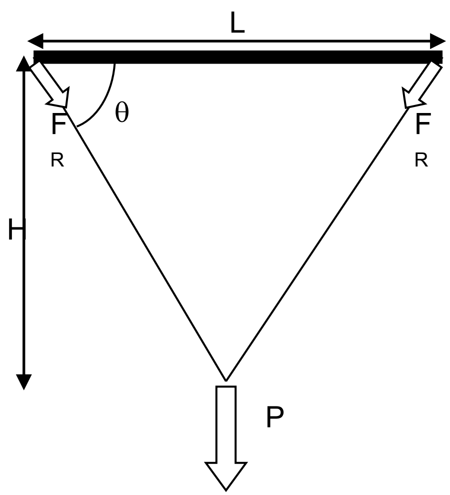


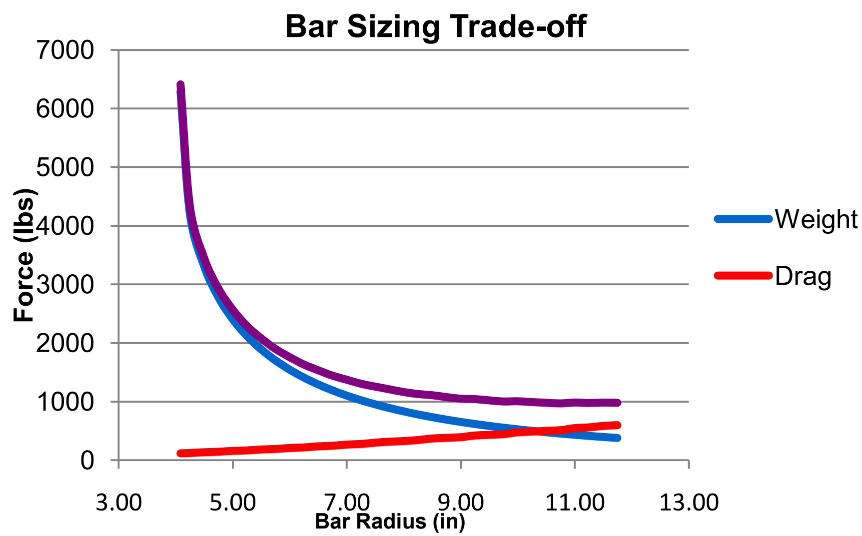
Creation of Trim model

- Uses a 4 body 3D dynamics model to calculate all forces and moments in the system, based on system state and controller inputs
- Changes system inputs in order to make all forces and moments zero for the system similar to as shown to the right.
- With all forces in the system calculated, Structural analysis of the cables and the spreader bar can be done for any system state.
- Trim states can be used in designing controls for the system .

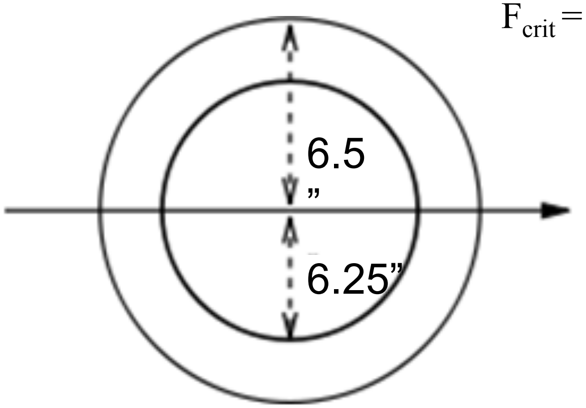
Spreader Bar Sizing

Inputs	
L, (ft)	100
H, (ft)	100
P, (lbs)	60,000
E, (psi)	1.00E+07
ρ_{bar}, (lbs/in³)	0.1
K	1
ν_{air}, (ft^2/s)	1.79E-04
ρ_{air}, (slug/ft^3)	2.18E-03
airspeed (knots)	100
Preliminary Calculations	
θ, (deg)	63
F_R, (lbs)	33541
$F_{R,x}$, (lbs)	15000
I, (in⁴)	219
airspeed (ft/s)	169
ρ_{air}, (lbs/in³)	4.06E-05



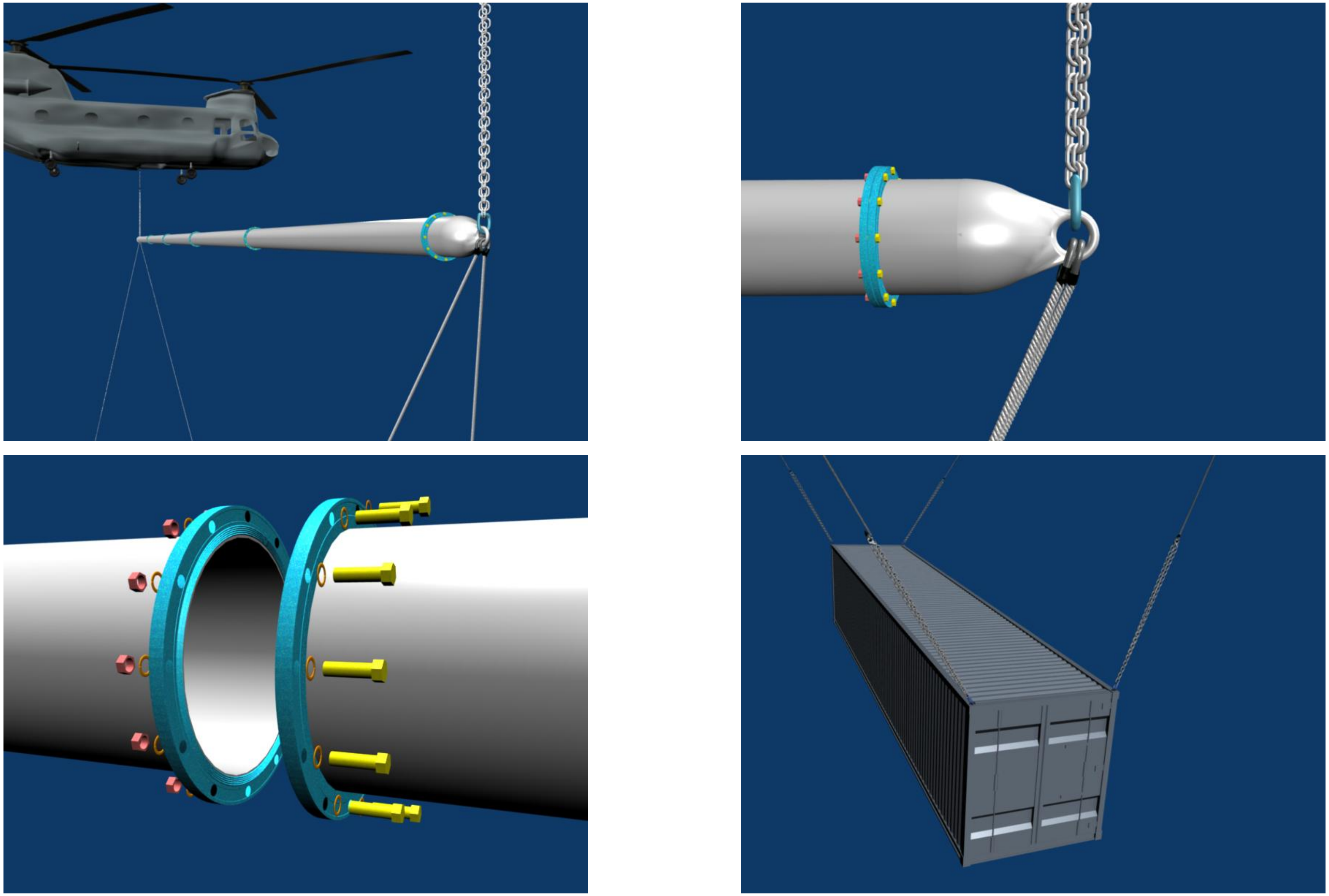


$$F_{crit} = \frac{\pi^2 EI}{(KL)^2}$$



- Assuming weight and drag are equally costly, the bar must be sized to minimize both, but the minimum wall thickness must be 0.25”
- Occurs when OR = 6.5”
- Size of Spreader Bar
  - L = 100’
  - OR = 6.5”
  - IR = 6.25”
  - Weight = 1106 lbs

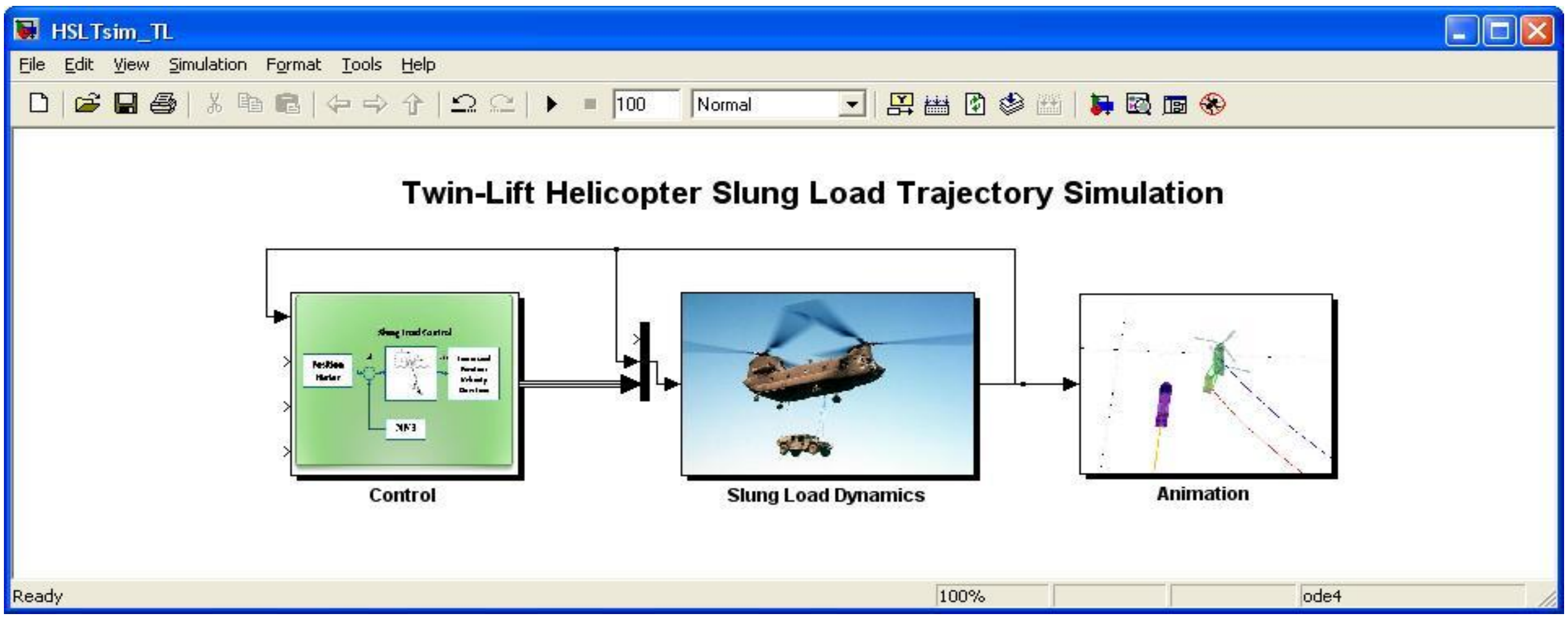
Twin-Lift System CAD Model



Modeling and Simulation

Model is made using Matlab® and utilizes equations from NASA Technical Paper 3280 for twin-lift operations

The main purpose of this simulation is to test swing motions and disturbances and find stable boundaries for various operations to be accomplished within the system. Several tests were done to determine the stable boundaries. These results will be used as a starting point for future control logic determination.

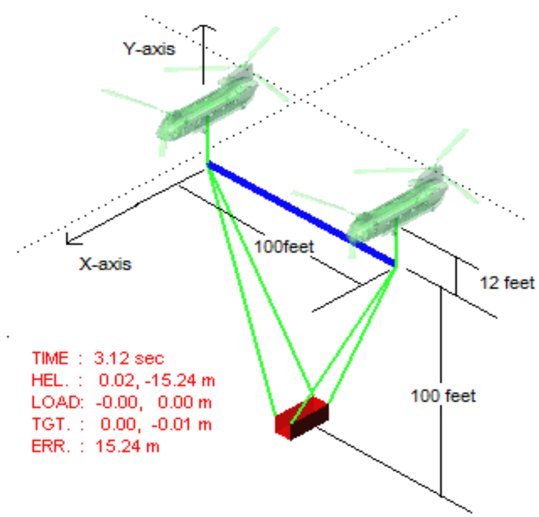


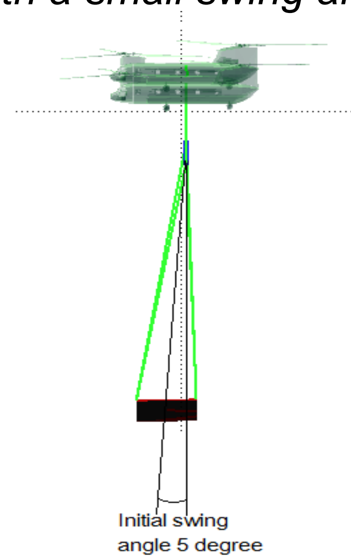
Initial Condition Setup

Initial condition assumption

-Length of spreader bar: 100ft
-Height from spreader bar to the load: 100ft
-Initial swing angle: 5 degree (in fore/aft motion)

Note that this initial swing degree is used to represent the "normal condition". As there is always an outside force such as the aerodynamic force acting on the load or a slight offset of the system when taking off to a hover, we can never make the load totally static. So we should consider the "normal stable condition" as one with a small swing angle.

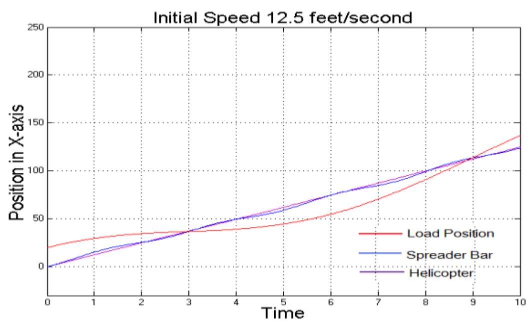


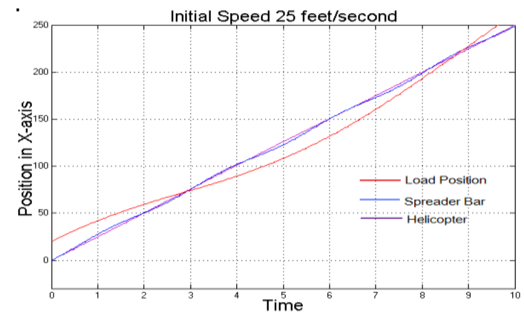


Testing and Analysis

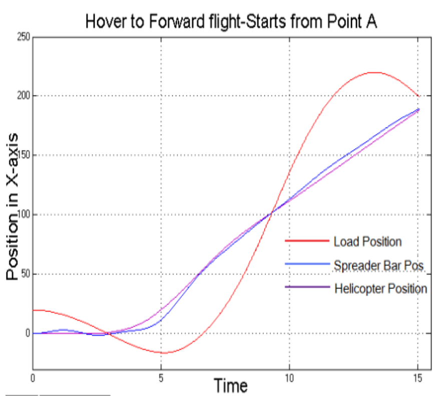
Conducted multiple tests to check system stability under different condtions:

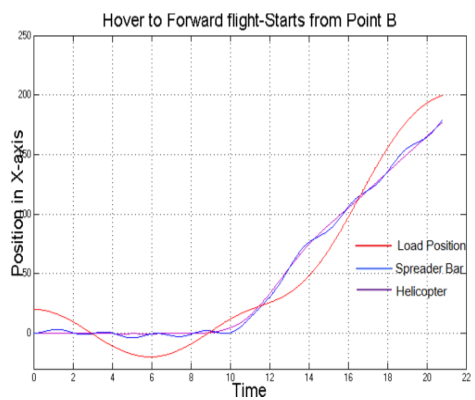
Test 1: Changing airspeeds





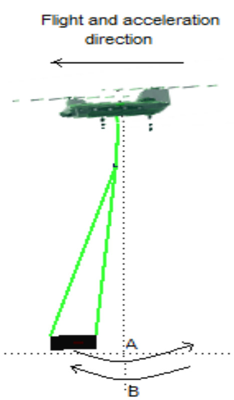
Test 2: Accelerate at different rates





If the aircraft accelerates at point A, the stability will be jeopardized (depending on the magnitude and rate of acceleration). On the contrary, if the a/c accelerates at point B (and the rate is not excessive), the system will remain be stable, and stability can even increase.

This information can be applied in control logic (which will be illustrated later).



Testing and Analysis

Test 3: Swing Angle

The swing angle was used to classify the stability/safety criterion.

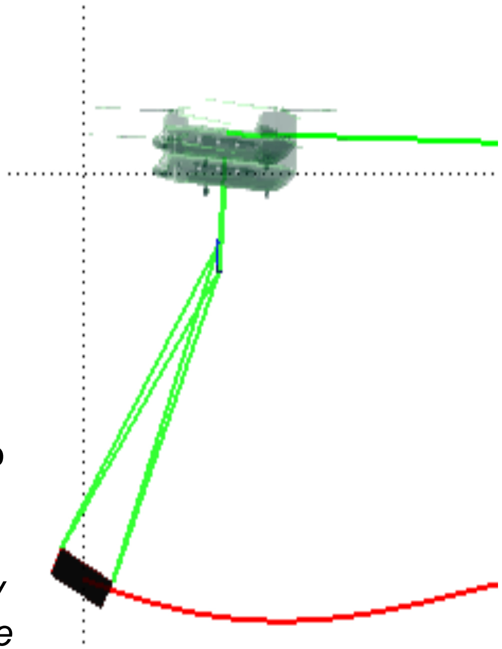
If swing angle exceed 30 degree: dangerous

If swing angle exceed 20 degree but less than 30: caution

If swing angle less than 20: safe though control is still needed

Throughout this test, acceleration happens at point A. This is done in order to simulate a worst-case scenario.

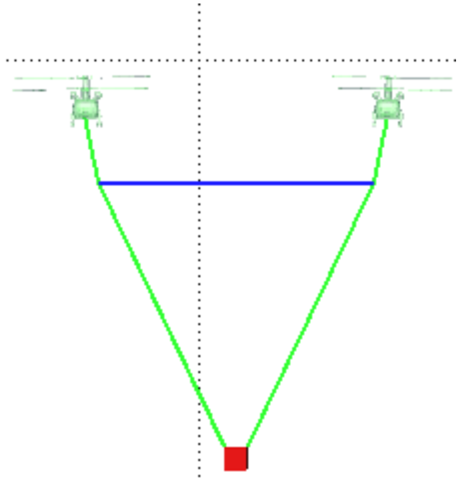
Because as the initial swing angle is small and the pilot cannot always exactly check the location of load or judge the right time point to start acceleration, the worst case rather the best case is used.

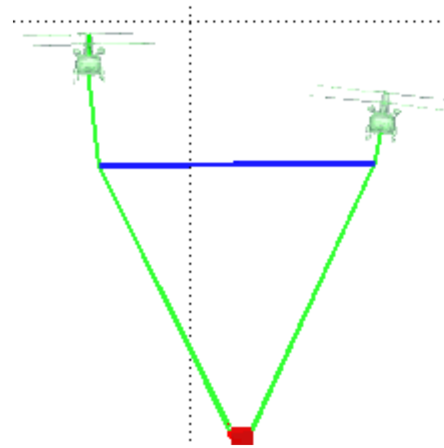


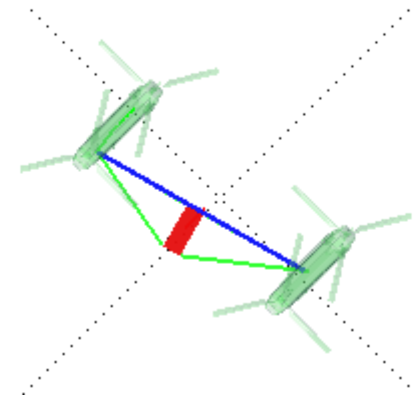
Dangerous

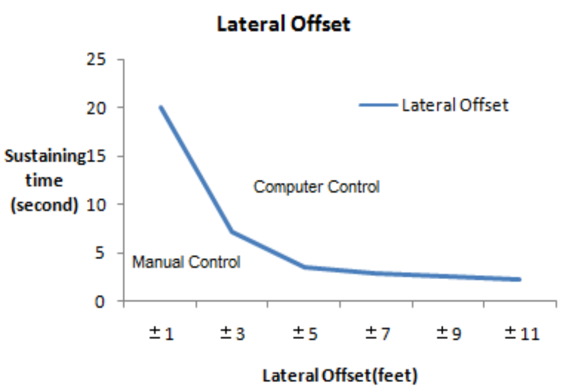
Testing and Analysis

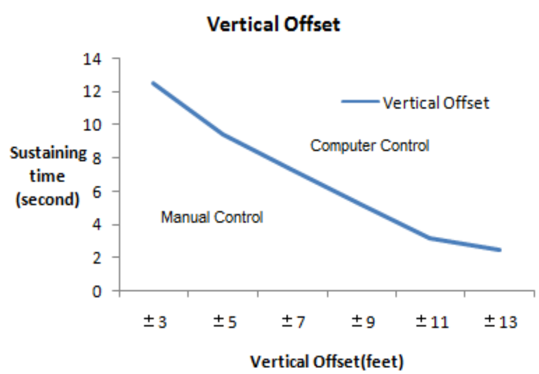
Test 4: Different Aircraft offsets

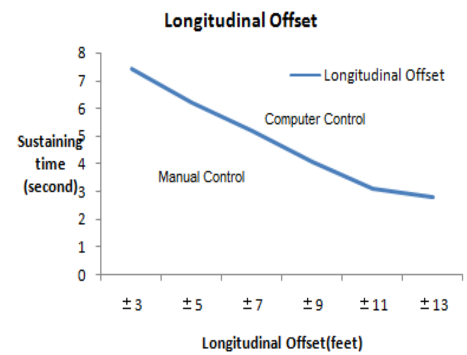








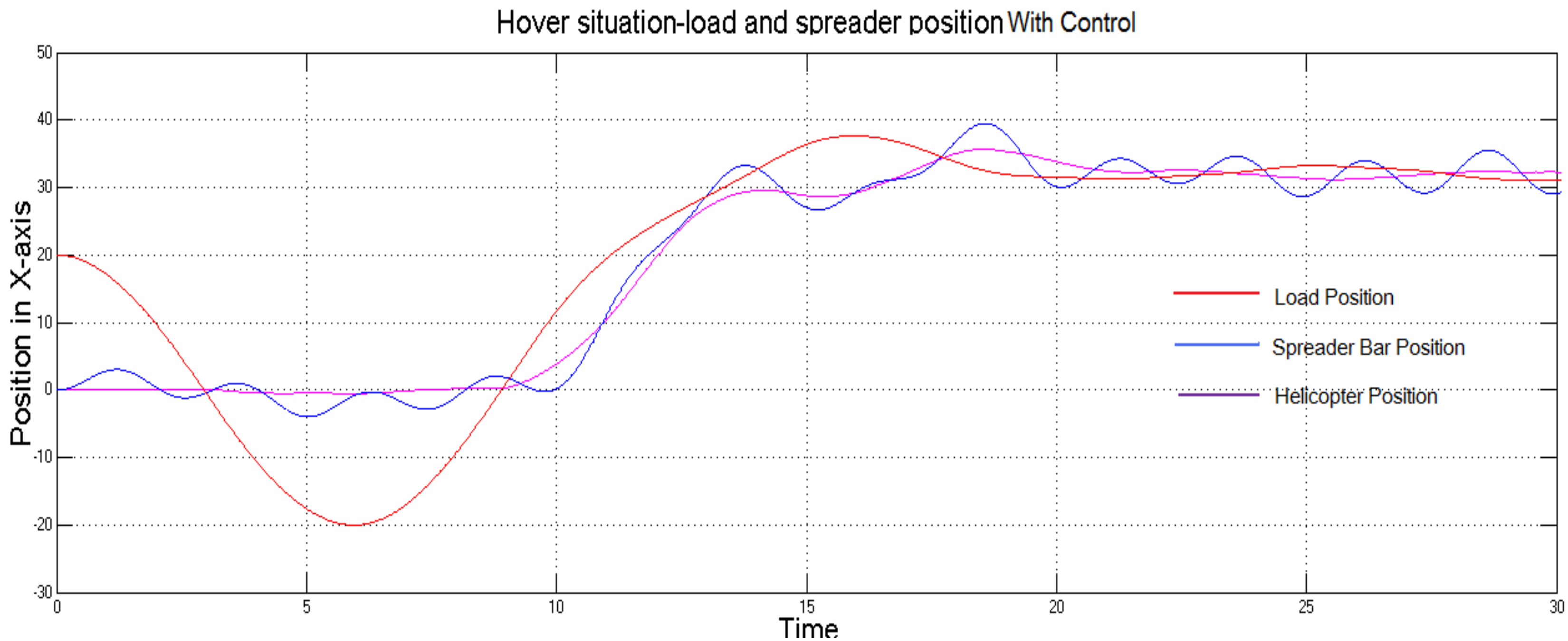




Other tests were also conducted for less-frequent situations.

Control Logic

Next our simulation model implemented simple control logic. For these tests, larger initial swing angles were used to make the effect of control more obvious.

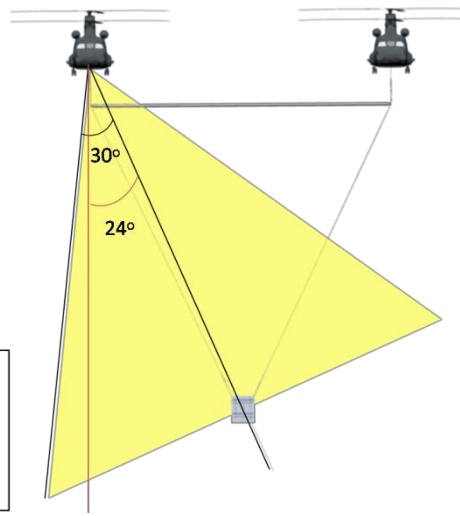


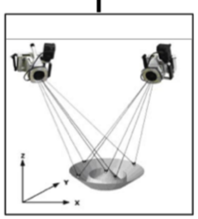
Control Systems

- Simulations show a need for two type of control:
  - Load Stabilization
    - Improper acceleration can lead to unstable load oscillations,
    - System assists pilot in keeping load oscillations stable while the system accelerates
  - Formation Flight
    - Close formation flight very intensive maneuver
    - Bar misalignments in any axis can lead to catastrophic failure
    - Desire for coordinated flight and single pilot operations
- Different control options
  - Helicopter Independent Systems
    - Cable Reeling Stabilization System: Unfeasible
    - Smart-Load Stabilization System : Unfeasible
    - Adjustable Spring-Damper System : Unfeasible
  - Helicopter Dependent Systems
    - Optical Load Stabilization Control System : Selected

Load Stabilization System

- Optical Components
  - Wide Angle cameras below each helicopter
  - With 60° FOV and tilted 24°, at 132’ this provides 150’x150’ of coverage, More than enough for full overlap
- Targets
  - Targets coded to be differentiable
  - Targets will be IR reflective providing low visibility utility
  - Circular targets placed on each chain from the bar to the load, placed very near the load
- Helicopter
  - On-board EGIs used to provide position information about the helicopters
- Inter-ship control link
  - Similar to standard WLAN
  - Encrypted for signal protection





Load Position

1/s

Load Velocity

1/s

Load Acceleration

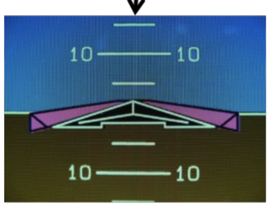
Δ of Load Oscillation relative to A/C

Control Logic

Acceleration needed for A/C to match load oscillation

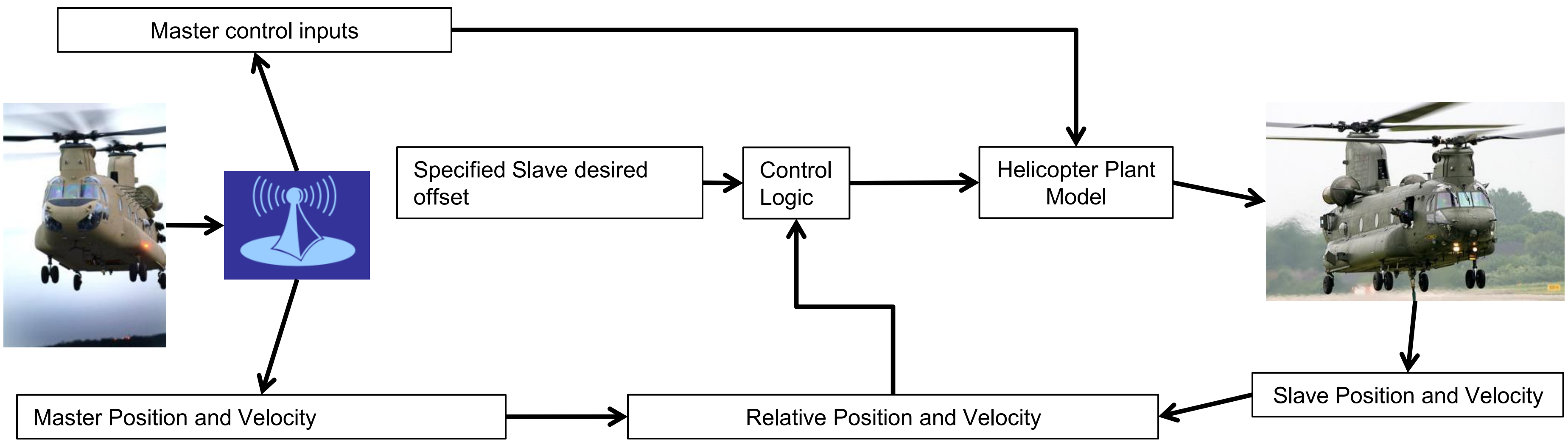
DAFCS computes Pitch to command accelerations

A/C Position Velocity & Acceleration



Formation Control System

- Senor Information
  - EGI Position and velocity data, sensors already natively on the helicopters
  - Stick Position and DAFCS control input information
    - This information is already measured by the DAFCS and is easy to access
- Inter-Ship Control Link
  - Necessary to transmit EGI and control inputs between aircraft
  - Uses same link for load stabilization system
    - Similar to WLAN
    - Encrypted to protect signals



Costs of Twin-Lift System

Direct Operating Cost

- Utilized Cost Trade-Off tool to determine the additional DOC incurred by adding the twin-lift system
- Calculated the additions to the DOC by both the spreader bar as well as the flight control and load stabilization systems
- Concluded the DOC would be increased by approximately $900 per flight hour due to reserves and maintenance for upkeep of the twin-lift system

$$DOC\ Spreader\ Bar = DOC\ Reserves + DOC\ Maintenance = \$516.91/FH$$

$$DOC\ Flight\ Controls = DOC\ Reserves + DOC\ Maintenance = \$349.95/FH$$

Spreader Bar Production Cost

- Utilized Cost H production tool to determine the cost of the spreader bar after calculating the weight of the system

	Aluminum-Li
R_2, (in)	6.50
R_1, (in)	6.25
W, (lbs)	1106
a	0.853
b	438
c	20000

Material Cost	$172,900.89
Tooling Cost	$1,106,000.00
Total Cost	$1,278,900.89

Development Cost

- Used Bell PC Based Cost Model to calculate the development of a modification to the CH-47F; most of the costs come in the Engineering Phase

Engineering	
Design	$2,847,000
Flight Test	$5,730,000
Component Test	$0
Systems Engineering/Project Management	$1,171,000
Total Engineering	**$9,748,000**
Manufacturing Engineering	
Planning, Loft, Other	$1,034,000
Project Management	$268,000
Total Manufacturing Engineering	**$1,302,000**
Tooling	
Tool Make	$575,000
Outside Tooling	$213,000
Total Tooling	**$788,000**
Manufacturing	
Prototype (1)	$193,000
GTV (1) STA (1) FTA (1)	$435,000
Flight Test	$3,699,000
Component Test	$0
Total Manufacturing	**$4,327,000**
Logistics	**$912,000**
Other	
Travel and Per Diem	$338,000
Direct Expense	$1,242,000
Total Other	**$1,580,000**
Grand Total	**$25,284,000**

Conclusions

THOR has developed a twin-lift system which allows two CH-47F aircraft to cooperatively lift in excess of 90% more Payload than either aircraft alone could lift at its design gross weight. In order to accomplish this, the system uses the following:

- A spreader bar made of five identical 20' sections to maintain portability as well as strength, modularity, increase maintainability and allow the aircraft to use 100% of its lifting capability
- An innovative EGI/DAFCS formation flight system which allows safe, close proximity flight while operating in a master/slave configuration
- An optical load stabilization system which implements control logic allowing the twin-lift system to operate safely across the entire flight envelope

In addition to showing the feasibility of the system, THOR has done it in a manner which is significantly cheaper than developing a new heavy-lift helicopter to accomplish this seldom occurring mission. It was also accomplished with redundant safety measures that will allow it to pass certification and be fielded within the next 4 years.

All of this adds up to a superior lifting system, capable of accomplishing its required mission safely, quickly and in a cost effective manner.