Final Challenge Report 2017-2018

Sikorsky STEM Challenge

Joel Barlow High School

Team Members:

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Advisor: Dr. Katherine Nuzzo, Ph.D.

Mentors: Mr. Frank Krzyzanski & Mr. Jeff Parkhurst

Submitted on April 25, 2018

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Executive Summary:

The objective was to design an automatic flight control system (AFCS) for the F4U-4 Corsair. The purpose of creating this AFCS system was to promote safety and meet Federal Aviation Regulations for a future flight from Texas to Connecticut. This included developing code for a stability augmentation system to be used on the Corsair via arduino technology and changing the Corsair's aileron and elevator systems from mechanical to fly-by-wire (FBW).

The final solution represents the changes in the aircraft industry since the Corsair was introduced. Most notably, the final solution is fly-by-wire, as most modern aircraft are today. Implementing this technology into the Corsair, as we have done, will improve safety, reliability, and efficiency.

The solution significantly improves upon the Corsair's safety and reliability. This is because the aileron and elevator systems are supported by duplex servos, which add an extra level of protection. Also there is a mechanical back-up should the fly-by-wire system fail. The solution was designed to compensate for both mechanical and electrical failures. This redundancy makes the Corsair safer and more reliable.

In order to ensure safety and reliability further, tests have been devised for the final design. These tests primarily focus on the functionality of the servos and the mechanical backup, however they also test for coding errors in the arduino and the strength of the manufactured lever and bellcranks.

The nature of fly-by-wire technology also makes the final solution more efficient. This is because the aircraft will correct changes in its orientation due to disturbances, such as gusts, on its own, leaving less work for the pilot to do.

Statement of Work:

In order to develop the final solution, ample organization and planning was necessary. First, research was conducted on current FAA regulations to ensure that the final solution would adhere to modern standards. Then SAS functionality and the advantages of the different types of SAS were researched to better understand how to implement SAS into the Corsair as part of the final solution.

Next, conceptual designs were drafted for the Corsair aileron and elevator systems. Kinematic sketches were made for each design to illustrate how they worked. These designs stood as the basis for further development of what would become the final solution.

A trade study matrix with seven criteria was created to assess each design. Each criteria was assigned a weighting based on a pairwise comparison of the criteria. Afterwards, the trade study matrix was used to score each design, providing us with our solution.

After reconsideration of the complexity of the chosen solution, another design was drafted and traded. It scored higher on the trade study and it became the final solution. To better visualize this solution a computer aided design (CAD) model was created. Accompanying arduino programs were also developed to calculate airspeed, atmospheric pressure, orientation, altitude, and flight path for the Corsair.

In order to complete the free body diagrams, lift calculations were made to find the force of lift at different speeds. This information was used along with information supplied by Sikorsky as well as certain assumptions to solve for all the forces and moments on the Corsair.

Description of Research:

Research was an essential component of the engineering challenge to further understand the necessary information of the F4U-4 Corsair and the mechanics and the role of autopilot systems in the aircraft industry. Through *Corsair Surface Controls Stress Analysis Report 5480* as well as schematics, blueprints, and diagrams found online, it was found that the Corsair was a carrier-based fighter bomber used primarily in World War II for combat. The aircraft utilized a mechanical system of pulleys, levers, rods, and pulleys for movement and control, but the aircraft industry moved towards computerization with the invention of FBW, or Fly-By-Wire technology in 1972 by NASA.

It was discovered through reputable sources and discussion with Sikorsky engineers that this innovation relies on an electrical system between the cockpit computers and servos within the airplane to make precise movements. With the convenience of precision with FBW systems, it became more of a standard to use FBW to the point in modern aviation history where it is a standard to use these computerized systems for efficiency. To add, the use of AFCS or an Automated Flight Control System became another critical topic within the industry to promote efficiency and safety. In an AFCS, Electronic SAS, or Stability Augmentation Systems, are intended to minimize pilot input by using information gathered from sensors around the aircraft to make adjustments to the aircraft's preplanned path and orientation (pitch, roll, yaw) as turbulence occurs during the flight. The Corsair actually had some original SAS through the use of an inverse gullwing design and trim or balance tabs, but it became necessary to implement Electronic SAS to comply with AFCS. Finally, in order to understand the regulations of FBW systems and AFCS, FAA regulations were analyzed so this information could be used in the design process. FAA requirements state that the SAS must not hinder the pilot in any way and if necessary, the pilot must have the ability to deactivate the AFCS and control the aircraft.

Team Organization Chart:

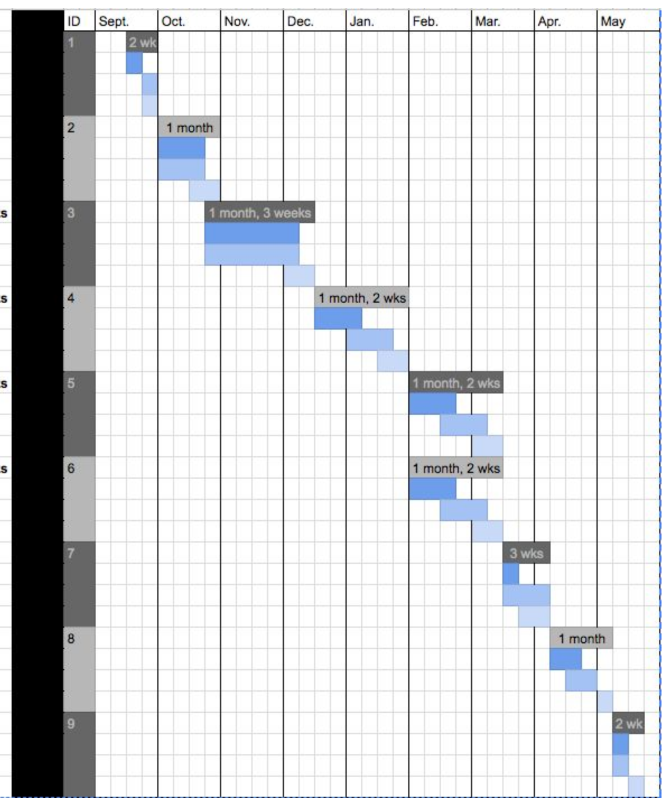
Member	Role	Responsibilities
Adam Boczar	Sub-Captain	Assessing Risks and exploring mitigation techniques
Andrew Yu	Member	Developing the final design and writing the bill of materials
Alex Palvinski	Sub-Captain	Designing qualifications tests for the final design
Christine Tong	Sub-Captain	Sketching free-body-diagrams and calculating forces and moments
Emily Larkin	Member	Coding arduino and designing the arduino test bed
Foster Rowberry	Member	Compiling research gathered throughout the challenge
Gus Sanderson	Member	Assessing performance to schedule and handling big picture scheduling
Rahul Kiefer	Sub-Captain	Assessing Risks and exploring mitigation techniques
Jacob Lenes	Sub-Captain	Checking arduino code and troubleshooting
Keegan Kolf	Member	Developing the final design
Liam Prevelige	Member	Developing the final design and writing the bill of materials
Luca Cerbin	Captain	Delegating tasks within the arduino activities, scheduling arduino specific meetings, and checking arduino code
Meghan Ogrinz	Member	Coding arduino and designing the arduino test bed
Michael Klein Wassink	Captain	Scheduling meetings, setting deadlines, and advising on the final

		design and free-body-diagrams
Tate Tower	Member	Writing arduino wiring diagram, designing circuitry for the arduino activities and designing the arduino test bed
Zac Shortt	Member	Working on the trade study and defensive conclusions

A hierarchy of roles was created in order to make the team more efficient. The Grinders are at the lowest tier. Their job is to grind out or complete the majority of the work with assistance from the Minders and Finders. The tier above Grinders is the Minders. They are in charge of overseeing and assisting the Grinders in their work. They help complete work if necessary and make comments and edits to the Grinders work. The top role of a Finder is like a CEO. Finders have the role of assigning tasks and reviewing work created by the Grinders and the Minders. The Finder does not do specific work, but instead in knowledgeable about all topics and gives assistance.

Project Schedule:

ID	Task Name	START DATE	END DATE	DURATION
1	**Research**	**September 13, 2017**	**September 27, 2017**	**2 weeks**
	Task Research	September 13	September 20	
	Proofreading	September 20	September 27	
	Presentation practicing	September 20	September 27	
2	**Requirements**	**September 27, 2017**	**October 26, 2017**	**1 month**
	Practice arduino, learn programming	September 27	October 19	
	Research SAS; SAS Functionality; AFCS SAS Requirements	September 27	October 19	
	Proofreading	October 12	October 26	
3	**Conceptual Design**	**October 26, 2017**	**December 14, 2017**	**1 month, 3 weeks**
	Begin work on an arduino program-operates the servo	October 26	December 7	
	Hand-drawn sketches	October 26	December 7	
	Proofreading	December 1	December 14	
4	**Preliminary Design**	**December 14, 2017**	**February 1, 2018**	**1 month, 2 weeks**
	Arduino Activities	December 14	January 7	
	CAD of kinematic sketch	January 1	January 21	
	Proofreading	January 14	February 1	
5	**Free Body Diagram**	**February 1, 2018**	**March 15, 2018**	**1 month, 2 weeks**
	Calculations at 175mph	February 1	February 21	
	Calculations at 340mph	February 14	March 7	
	Proofread and create final diagram	March 1	March 14	
6	**Final Design**	**February 1, 2018**	**March 15, 2018**	**1 month, 2 weeks**
	Arduino Activities	February 1	February 21	
	CAD and 3D printed version of finalized kinematic sketch	February 14	March 7	
	Proofreading	March 1	March 14	
7	**Final Report**	**March 15, 2018**	**April 6, 2018**	**3 weeks**
	Arduino Activities	March 15	March 23	
	Ensure quality of report and final creation	March 15	April 6	
	Proofreading	March 23	April 6	
8	**Competition**	**April 6, 2018**	**May 4, 2018**	**1 month**
	Create Presentation	April 6	April 13	
	Practice	April 13	May 1	
	Memorize Presentation	May 1	May 4	
9	**CT Student Innovation Exposition**	**May 4, 2018**	**May 19, 2018**	**2 weeks**
	Practice	May 4	May 11	
	Presentation	May 4	May 11	
	Exposition	May 19	May 19	



In general, the project has been successful in terms of planning and scheduling. Although team meetings have been lost and work days due to inclement weather, these days have been made up through new days scheduled and group discussions through video chat technology. Team members have spent hours after school each day to meet module deadlines, spending extra time to make up for the recent increase in canceled school days. Rescheduling efforts includes moving the 3D model design to the Final Design instead of Preliminary Design. This was decided to ensure quality control, focus, and group understanding.

Risks and Mitigation Approaches:

Risk Cube:

	Marginal	Minor	Moderate	Major	Severe
Almost Certain	1. SAS makes unwanted adjustments to control surfaces.		4. Strong gust of wind.		
Likely					
Possible			2. One servo fails.		
Unlikely					
Rare				3. Lightning strikes the plane and damages the FBW system.	

Risk Assessment Process:

Each risk was assessed based on their likelihood and severity. Then they were placed accordingly in the risk cube. During solution development, these risks were taken into account and were mitigated by making certain design choices.

Mitigation Approaches:

1. Since the pilot will be new to the Corsair’s SAS system, he or she must be informed as to the use of its automatic correction system. These corrections will occur relatively often; it must be made clear that the pilot should expect and allow such corrections to be made. To make clear when the arduino is performing these adjustments, a small LED will be installed into the aircraft that turns on when the arduino is active. Doing so will provide a heads up for the pilot and reduce the

chances of the SAS corrections taking him or her by surprise. Although this risk was already marginal, the LED should reduce this further.

2. In the event of a mechanical failure in one of the servo's, there are multiple backups in place to mitigate risk. Duplex servos will be installed; if the main half of a servo has an internal failure, then the second half will automatically be engaged, thus allowing the aircraft to remain functional. Although this is a possible risk, the malfunction would only pose a moderate risk to the aircraft. In the event that both halves of a servo malfunctions, a mechanical linkage breaks, or power is cut off to the aircraft, a set of mechanical springs attached to both ailerons and the elevator should allow the aircraft enough stability to land. However, this level of failure is very unlikely to occur.
3. In the case of a lightning strike both hitting the Corsair and rendering the FBW system broken, a set of Cessna springs attached to both ailerons and the elevator will allow the aircraft to maintain a consistent downward descent for the pilot to land. Such an extreme failure would be rare, however the springs in the aircraft should serve as a legitimate backup system.
4. Strong gusts of wind are expected when using the SAS system, hence the use of an automatically correcting arduino system. In the case of a strong gust of wind, sensors read by the on-board computer (arduino) will makes changes in orientation without the need for pilot interference. This will result in a more stabilized aircraft.

Trade Study:

Criteria Matrix:

Criteria	Weight and Inertia	Travel of the Servo	Load on the Servo	Cost	Manufacturability	Ease of Assembly	Safety
Points							
4	Solution is well under the weight of a fully armed Corsair and it marginally	Servo travel is low enough to allow very high fidelity, very high resolution servos	Load on the servo is low enough to allow for a wide range of servo options	Solution is extremely cheap	All parts can be easily manufactured	Solution is very easy to assemble	Solution has no unmitigated safety concerns

	changes the inertia						
3	Solution is under the weight of a fully armed Corsair and it moderately changes the inertia	Servo travel is low enough to allow high fidelity high resolution servos	Load on the servo is moderate and rules out the weakest of servos	Solution is somewhat cheap	Most parts can be easily manufactured	Solution will be somewhat easy to assemble	Solution has one or more unmitigated minor safety concerns
2	Solution does not exceed the weight of a fully armed Corsair and it greatly changes the inertia	Servo travel is low enough to allow moderate fidelity moderate resolution servos	Load on the servo is substantial and requires high power servos	Solution has considerable costs	Parts take substantial effort to manufacture	Solution will take substantial time to assemble	Solution has one or more unmitigated moderate safety concerns
1	Solution exceeds the weight of a fully armed Corsair and drastically changes the inertia	Servo travel is so high that it lowers the resolution of the servos	Load on the servo is too high for any servo to bear reasonably	Solution is very expensive	Manufacturing parts will be extremely complex	Solution's assembly is overly complex	Solution has one or more unmitigated major safety concerns

Weighting:

The criteria in the trade study matrix above were weighted according to the pairwise comparison below. The team voted to decide which criteria were most important in the context of the pairwise comparison. Weighting information is included to the right of the pairwise comparison.

Pairwise Comparison:

	Safety	Manufacturability	Cost	Load on the Servo	Servo Travel	Ease of Assembly	Weight and CG
Safety (S)		S	S	S	S	S	S
Manufacturability (M)			C	M	M	EA	WCG
Cost (C)				C & LS	C	C & EA	WCG
Load on the Servo (LS)					LS	LS	WCG
Servo Travel (ST)						ST	WCG
Ease of Assembly (EA)							WCG
Weight and CG (WCG)							

Criteria	Points	Weighting
Safety	6	26.09%
Manufacturability	2	8.70%
Cost	4	17.39%
Load on the Servo	3	13.04%
Servo Travel	1	4.35%
Ease of Assembly	2	8.70%
Weight	5	21.74%
Sum	23	

Applied Trade Study Matrix:

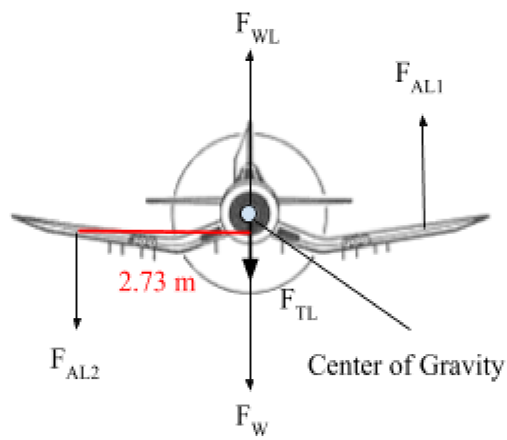
Criteria	Weighting		PDR Solution	Solution2	Solution 3	Solution 4	Solution 5	Final Design
Safety	0.2609		4	3	3	2	2	4
Weight and Inertia	0.2174		4	3	2	2	3	4
Cost	0.1739		3	2	2	3	3	4

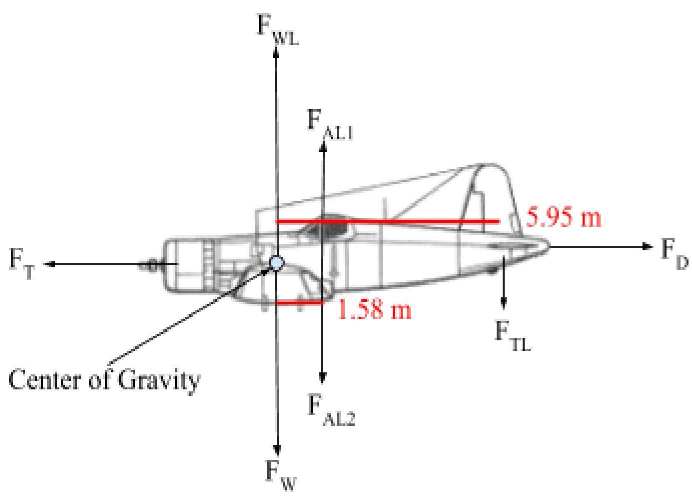
Load on Servo	0.1304		4	2	2	2	3	4
Manufacturability	0.0870		3	2	2	3	3	3
Ease of Assembly	0.0870		3	4	4	1	3	3
Servo Travel	0.0435		4	2	2	2	2	4
	Total:		3.6525	2.6525	2.6960	2.1741	2.6959	3.8264

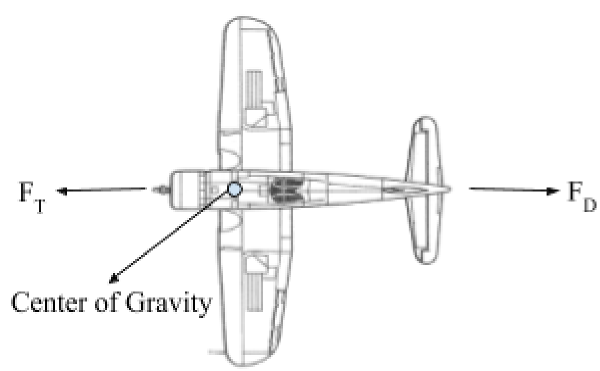
Out of the 5 solutions the final solution scored higher than all of the other solutions in the trade study. This solution was designed to preserve the Corsairs Inertia and have the greatest mechanical advantage. The other solutions were designed for: ease of assemble and access, simplicity, and maintaining inertia while keeping a mechanical advantage. The final solution scored a four in the category weight and inertia due the servos being placed as close to the center of gravity as possible, granting the pilot greater control of the aircraft. Also the mechanical connections between the yoke and the servos are removed for this solution, thus reducing the overall weight. The solution scored a four in safety because of the duplex servos that are used in the design as well as the mechanical fail safe that is included. The final solution also scored fours in the load on the servo and servo travel categories because the positions of the servos provide a mechanical advantage, reducing the load, and because the angles through which the servos must rotate are large enough not to require servos of extremely high fidelity and or resolution. The cost for the solution was rated at four as well. This is because the final solution requires few manufactured parts. The only two categories that scored threes were manufacturability and ease of assembly. These were rated as such because there is one bellcrank and one lever that must be manufactured and subsequently tested; also in order to implement the solution, panels must be temporarily removed from the Corsair's wings.

Free-Body-Diagrams:

Calculations were made for the free-body-diagrams below both at 175 mph and 340 mph. In both cases all forces summed to zero, resulting in no linear acceleration. All but one moment summed to zero. The moment about the roll axis did not, resulting in an angular acceleration of 0.23 rad/s in the counterclockwise direction at 175 mph and an angular acceleration of 0.91 rad/s in the same direction at 340 mph. These calculations can be found in the appendices.





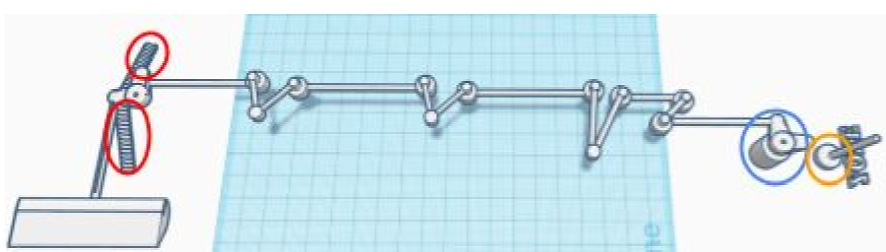


Final Design:

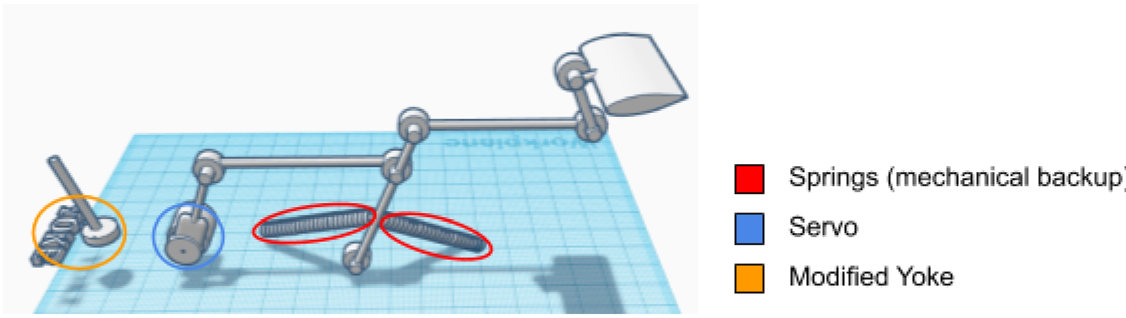
Description of the final design:

In the final design for both the elevator and aileron systems, the linkage system between the yoke and the bellcrank closest to the hull of the Corsair is removed. The bell crank is modified so that a duplex servo can control its rotation. This was put into effect so if one half of the servo malfunctions, the other half half can still control the aircraft. The yoke is also modified to act as a joystick for the servos. When the yoke is moved it sends a signal to the Arduino which then interprets this signal; a new signal is sent to the duplex servos to move in accordance with the yoke. As the servos rotate the bellcranks or lever, the mechanical system is engaged and deflects the ailerons or elevators. Since the default system is electrical, a mechanical backup is also utilized; sets of springs are placed in both systems. In the elevator system, the springs are attached to an internal linkage halfway down the mechanical system. In the aileron system, the springs are attached to the bell cranks closest to the ailerons. The springs create a mechanical failsafe if the electrical system fails. The springs will return the ailerons and elevator to a neutral position. Both locations of the springs allow for easy access if repair is necessary. Visual aids are shown below. The springs hold the elevator and aileron systems in neutral positions should electrical failures occur.

Aileron System:



Elevator System:



This locations of the servos were determined by debate and discussion relating to the trade study and weighting. Once these positions were determined, other improvements were discussed. Many ideas were created and discussed until the final design was reached with the ideas discussed above.

Description of Arduino system:

The arduino system consists of an arduino uno, three servo motors and a display screen. The arduino system will be active when the plane is in flight. During flight, the arduino continuously receives data from sensors that monitor elevation and air speed. When the pilot moves the yoke the arduino will translate that motion into servo motion that will deflect the ailerons and or elevators. Also if the aircraft experiences any disturbances such as wind, the arduino will interpret those disturbances and correct for them by actuating the servos. This will help achieve greater stability. A LED will go on everytime the arduino automatically corrects the plane. The purpose of this is to inform the pilot of flight corrections without distracting him from flying the plane.

Total Price: $8591.66

Part	Quantity	Estimated Price (USD)
Three servo motors	3	3 x $2,500.00
Two bellcrank-servo connectors	2	2 x $25.00
One lever-servo connector	1	1 x $25.00
Two wing servo mounts	2	2 x $7.50
One tail servo mount	1	1 x $8.16

One Electrical modification for the yoke	1	1 x $1,000.00
Wiring (yoke to servos)	1	1 x $18.50
Electric Drill	1	$29.99
Tig Welder	1	$1,559.00
Bolts	25	25 x $1.00
Nuts	25	25 x $1.22
Lock Loop Spring Mount	12	12 x $11.59
Cessna 1414116-1 Spring	6	6 x $34.90
		Total Price: $10,609.63

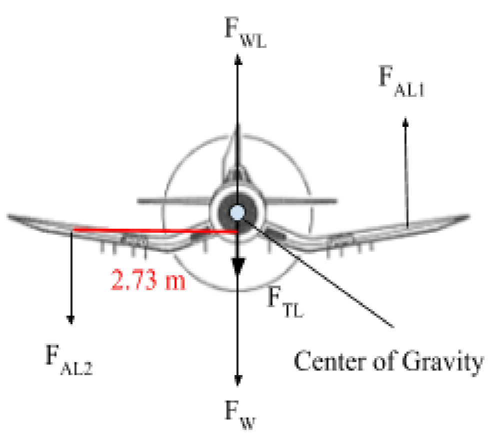
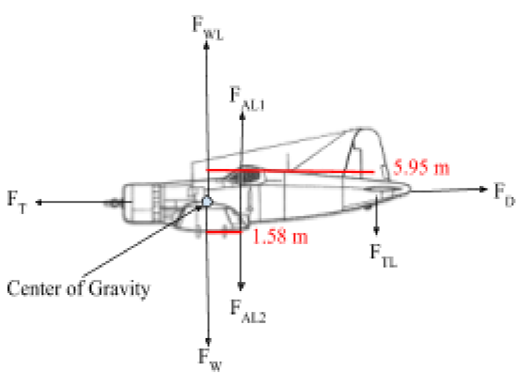
Qualification Testing:

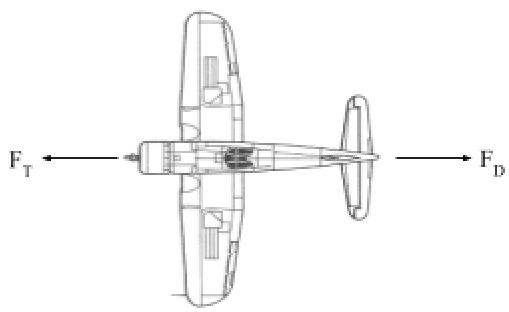
For the qualification testing, eight wind tunnel simulation tests will be conducted. Four of these tests will examine the aileron system. The system will be tested at full positive deflection at the velocities of 215 mph and 450 mph, and at full negative deflection at the same velocities. Once the full positive deflections and negative deflections are reached, the electrical system will be shut off. These tests will occur for all 4 of the positions. The purpose of this additional tests is to make sure the spring mechanical backup works and the aileron will return to a neutral state from all positions and speeds. The other four wind tunnel simulation tests will be conducted on the elevator system, and the tests will be identical to those on the aileron system including tests on the spring mechanical backup. These tests are being conducted to ensure that the elevator and aileron systems are capable of deflecting the elevators and ailerons at cruising speed (215 mph) and maximum speed (450). Although it is unlikely that the Corsair would fly at maximum speed back to CT, it is important that the solution does not limit the aircraft. The arduino will also be tested for coding errors to prevent the AFCS from malfunctioning and lastly the bell cranks and levers will undergo simulated strength and fatigue testing to ensure that they are strong enough to withstand the pressures in the elevator and aileron systems during flight.

Appendix:

Free-body-diagrams at 175 mph

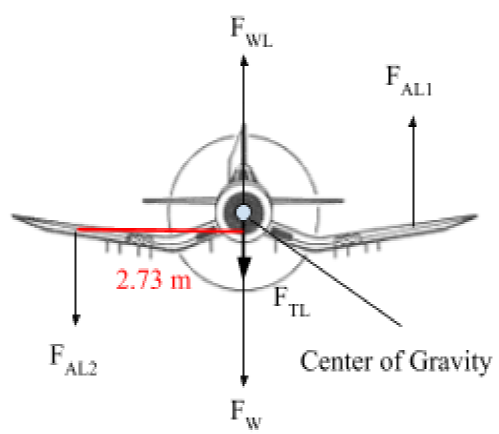
Force	Abbreviation	Magnitude (N)
Wing Lift	F_{WL}	59,142
Weight	F_W	60,051
Tail Lift	F_{TL}	328
Aileron Lift 1	F_{AL1}	3,281
Aileron Lift 2	F_{AL2}	2,044
Thrust	F_T	Unknown
Drag	F_D	Unknown

FBDs	Forces	Moments
	$\Sigma F_X = F_{WL} - F_W + F_{AL1} - F_{AL2} - F_{TL}$ $\Sigma F = 59{,}142\text{N} - 60{,}051\text{N} + 3{,}281\text{N} - 2{,}044\text{N} - 328\text{N} = 0\text{N}$ The forces sum to zero, therefore there is no linear acceleration with respect to the x-axis.	$\Sigma M_X = (F_{AL1} \times 2.73\text{m}) - (F_{AL2} \times 2.73\text{m}) + (F_{WL} \times 0\text{m}) - (F_W \times 0\text{m}) - (F_{TL} \times 0\text{m})$ $\Sigma M_X = (3{,}281\text{N} \times 2.73\text{m}) - (2{,}044\text{N} \times 2.73\text{m}) + (56{,}416 \times 0\text{m}) - (60{,}051 \times 0\text{m}) - (1{,}314 \times 0\text{m}) = 3{,}377\ \text{Nm}$ $\tau = I_{xx} \times \alpha$ $3{,}377\text{Nm} =$ $14{,}930\ \text{kg} \cdot \text{m}^2 \times \alpha$ $\alpha = 0.23\ \text{rad/s}^2$ The sum of the moments creates an angular acceleration of 0.226 rad/s in the counterclockwise direction about the x-axis.
	$\Sigma F_Y = F_{WL} - F_W + F_{AL1} - F_{AL2} - F_{TL}$ $\Sigma F = 59{,}142\text{N} - 60{,}051\text{N} + 3{,}281\text{N} - 2{,}044\text{N} - 328\text{N} = 0\text{N}$ The forces sum to zero, therefore there is no linear acceleration with respect to the y-axis.	$\Sigma M_Y = (F_{AL1} - F_{AL2}) \times (1.58\text{m}) + (F_{TL} \times 5.95\text{m}) + (F_{WL} \times 0\text{m}) + (F_W \times 0\text{m})$ $\Sigma M_Y = (3{,}281 - 2{,}044) \times (1.58\text{m}) - (328 \times 5.95\text{m}) + (59{,}142 \times 0\text{m}) + (60{,}051 \times 0\text{m}) = 0\text{Nm}$ The moments sum to zero, therefore there is no angular acceleration about the y-axis.

	$\Sigma F_Z = F_T - F_D$ ΣF_Z = 0N The aircraft is at constant velocity, therefore F_T and F_D must be equal and there is no linear acceleration with respect to the z-axis.	ΣM_Z = 0Nm There are no moments, therefore there is no angular acceleration about the z-axis.

Free-body-diagrams at 175 mph

Force	**Abbreviation**	**Magnitude (N)**
Wing Lift	F_{WL}	56,416
Weight	F_W	60,051
Tail Lift	F_{TL}	1,314
Aileron Lift 1	F_{AL1}	13,126
Aileron Lift 2	F_{AL2}	8,177
Thrust	F_T	Unknown
Drag	F_D	Unknown

FBDs	**Forces**	**Moments**
	$\Sigma F_X = F_{WL} - F_W + F_{AL1} - F_{AL2} - F_{TL}$ ΣF = 56,416N - 60,051N + 13,126N - 8,177N - 1,314N = 0N The forces sum to zero, therefore there is no linear acceleration with respect to the x-axis.	$\Sigma M_X = (F_{AL1} \times 2.73\text{m}) - (F_{AL2} \times 2.73\text{m}) + (F_{WL} \times 0\text{m}) - (F_W \times 0\text{m}) - (F_{TL} \times 0\text{m})$ $\Sigma M_X = (13{,}126\text{N} \times 2.73\text{m}) - (8{,}177\text{N} \times 2.73\text{m}) + (56{,}416 \times 0\text{m}) - (60{,}051 \times 0\text{m}) - (1{,}314 \times 0\text{m}) = 13{,}510\text{Nm}$ $\tau = I_{xx} \times \alpha$ 13,510Nm = $14{,}930\ \text{kg} \cdot \text{m}^2 \times \alpha$ $\alpha = 0.91\ \text{rad/s}^2$ The sum of the moments creates an angular acceleration of 0.905 rad/s in the counterclockwise direction about the x-axis.

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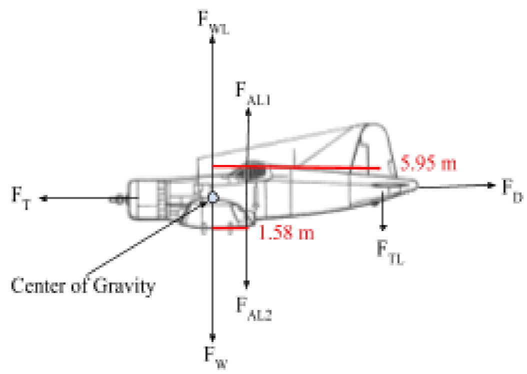
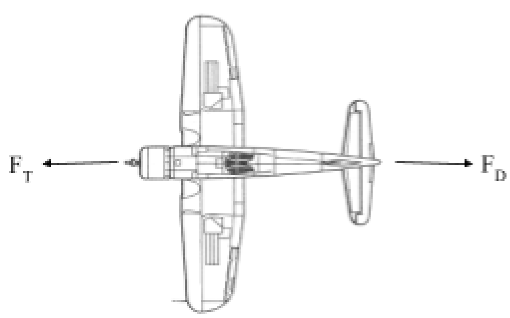
<td>
</td>
<td>$\Sigma F_X = F_{WL} - F_W + F_{AL1} - F_{AL2} - F_{TL}$

$\Sigma F =$ 56,416N - 60,051N + 13,126N - 8,177N - 1,314N = 0N

The forces sum to zero, therefore there is no linear acceleration with respect to the y-axis.</td>
<td>$\Sigma M_Y = (F_{AL1} - F_{AL2}) \times (1.58m) + (F_{TL} \times 5.95m) + (F_{WL} \times 0m) + (F_W \times 0m)$

ΣM_Y = (13,126N - 8,177N) × (1.58m) + (1,314N × 5.95m) + (56,416 × 0m) + (60,051 × 0m) = 0Nm

The moments sum to zero, therefore there is no angular acceleration about the y-axis.</td>
</tr>
<tr>
<td>
</td>
<td>$\Sigma F_Z = F_T - F_D$

ΣF_Z = 0N

The aircraft is at constant velocity, therefore F_T and F_D must be equal and there is no linear acceleration with respect to the z-axis.</td>
<td>ΣM_Z = 0Nm

There are no moments, therefore there is no angular acceleration about the z-axis.</td>
</tr>
</table>

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