Autoflight Aileron Control System Integration and Testing

Jerry Lu

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1. Assumptions

Based on the given problem statement in Appendix A, and the additional Cessna 172 context in Appendix B, the following assumptions are made for the solution:

1. The problem statement mentions that the aileron actuator is "internally mounted in the uncontrolled environment of the wing". Assume from this statement that there are two aileron actuators, one mounted in each wing's internal structure to directly actuate that wing's aileron.
2. Assume that each actuator needs its own line replaceable unit (LRU) to interface with the flight computer (FC).
3. Assume that the design details for the actuator, LRU, and FC are outside the scope of this solution (the focus of this solution is on their inputs, outputs, and integration into the aircraft).
4. Assume the bigger picture of this project is to achieve full autonomous flight of the Cessna 172 aircraft (not just to have an autonomous aileron control system that compliments manual flight).
    - Given this assumption, actuators and LRUs for the other control surfaces of the aircraft also need to be integrated. While the focus of this solution is meant to be on the integration of the aileron control system, the integration of all flight surface control systems will be considered to yield a more realistic and better integration solution.
5. The most recent and comprehensive Pilot's Operating Manual I've managed to locate so far is the 1998 Cessna 172S POH [1]. This handbook will be the primary reference for the subsequent integration discussions. The relevant dimensions of the aircraft for this solution are identical across all Cessna 172 POHs I've seen.

These assumptions only serve to clarify my interpretation of the given problem statement. Some of them will be challenged in Section 3 for what may be a potentially more reliable and simpler design than the assumed design above.

2. System Integration Requirements

2.1 FC Requirements

1. The FC must have both autonomous and manual flight settings and can easily switch between both as instructed by an operator.
    - In autonomous flight, the FC has full control over the aircraft.
    - In manual flight, the FC receives and executes tele-operations from a remote operator, or is override by manual controls from an onboard pilot.
2. When active (autonomous or tele-operated), the FC must incorporate flight envelop protection in its controls software: It must ensure that the position commands sent to all control surface LRUs (aileron, rudder, elevator, elevator trim) do not drive the aircraft outside of its flight envelope, shown in Appendix C (ex. does not cause stalls).

2.2 LRU Requirements

1. The LRU must be easily accessible and replaceable.
2. The LRU must check the validity of position commands from the FC to ensure they are executable given the LRU's power supply and that the position command is within the operating range of the actuator.
3. The LRU should send system status signals to the FC at regular (sub-second) intervals during nominal operation. Its failure to do so would indicate an LRU malfunction, and the FC should take corresponding action to ensure continued safe flight of the aircraft (ex. switch to backup aileron control system, look for emergency landing, alert remote-control personnel).

2.3 Actuator Requirements

1. The aileron actuator should send position feedback signals to the LRU at regular intervals, and its failure to do so would indicate an actuator malfunction. The LRU should then alert the FC with the appropriate system status signal and the FC should take similar actions as above.

2.2 Control System Operating Envelope

1. Maximum voltage and current draw
2. Maximum actuation cycle before failure and before maintenance
3. Vibration tolerance
4. Temperature range

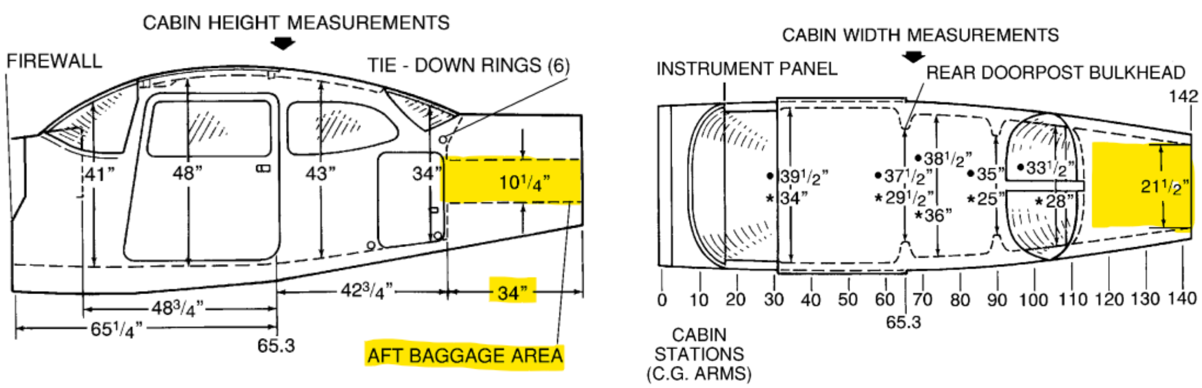
For further details on LRU design and interfacing standards, such as specific values for the operating envelope above, one possible resource to reference is the ARINC 700 series standards [2].

3. Physical Integration Plan

3.1 First Order Sizing

The figure in the given problem statement depicts the aileron LRU in the wing of the aircraft, understandably just for illustration purposes. In the actual aircraft, such a position would be difficult to access and would impose severe limitations on the size and mass of the LRU for integration.

Instead, the aileron control LRU should be integrated in the fuselage of the aircraft, along with the FC, where it would be much easier to access and have more options for mounting. Figure 1 shows detailed dimensions of the Cessna 172 fuselage, around the cockpit and baggage areas.



DOOR OPENING DIMENSIONS

	WIDTH (TOP)	WIDTH (BOTTOM)	HEIGHT (FRONT)	HEIGHT (REAR)
CABIN DOORS	32 1/2”	37”	40 1/2”	39”
BAGGAGE DOOR	15 1/4”	15 1/4”	22”	21”

Figure 1: Detailed Fuselage Dimensions [1].

One potential location to place the aileron control system (along with other control systems and electronics, further discussed in Section 3.2) is in the aft baggage area, highlighted in yellow above. Not only would it be easily accessible via the baggage doors and easily secured to custom racks that can be installed in the area, the cockpit would also be free for potential passengers, cargo, or larger flight instruments if necessary. As shown in Figure 1, the aft baggage area is 10.25" in height, 21.5" in width, and 34" in length. However, the assembly should be able to easily fit through the baggage door, which is 15.25" wide. So a first order sizing of **the assembly should be at most 10" high by 21" wide by 14" long.**

Another factor to consider is the mass limits of the assembly and the load moment it would cause about the aircraft's center of gravity. The POH includes useful charts for estimating the load moment of components placed in various locations of the aircraft, and the aircraft's loading envelope.

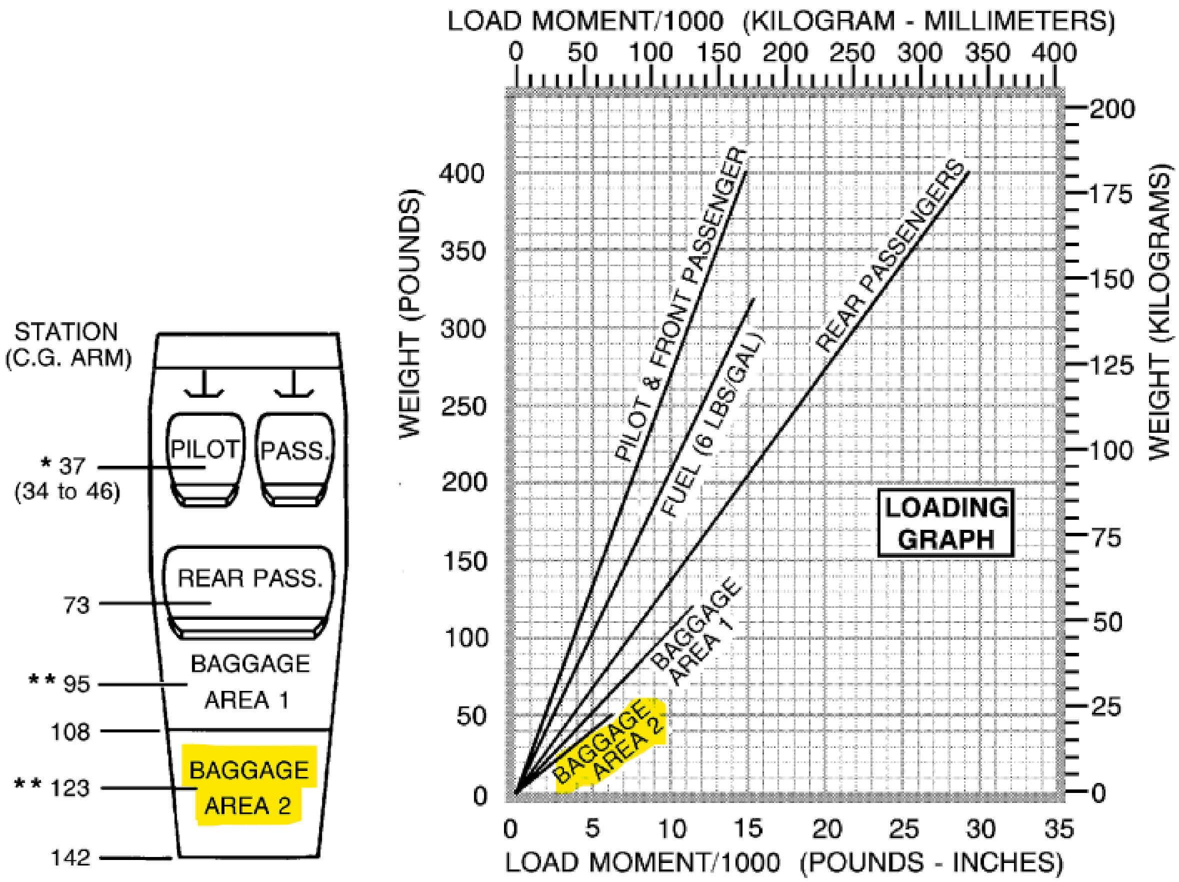


Figure 2: Cessna 172S Loading Graph – Mapping component weights to load moment [1].

Figure 2 shows one disadvantage of placing control systems in the aft baggage area (Baggage Area 2) – it is the farthest storage location from the aircraft's center of gravity, so components installed there would contribute the most load moment per unit weight. However, when considering the overall aircraft, it is likely that control electronics such as the FC and LRUs are among the lightest components and thus most suitable to be placed in Baggage Area 2, leaving the other spaces for heavier components.

As per Figure 2 and warnings in the Handbook, Baggage Area 2 can support a maximum weight of 50 pounds. This corresponds to a load moment (in units of 1000 pounds-inches) of about 6.2. Figure 3 below shows the loading envelope within which the Cessna 172S is safe to fly (any *(weight, moment/1000)* point within the solid lines), with total load moment/1000 on the horizontal axis.

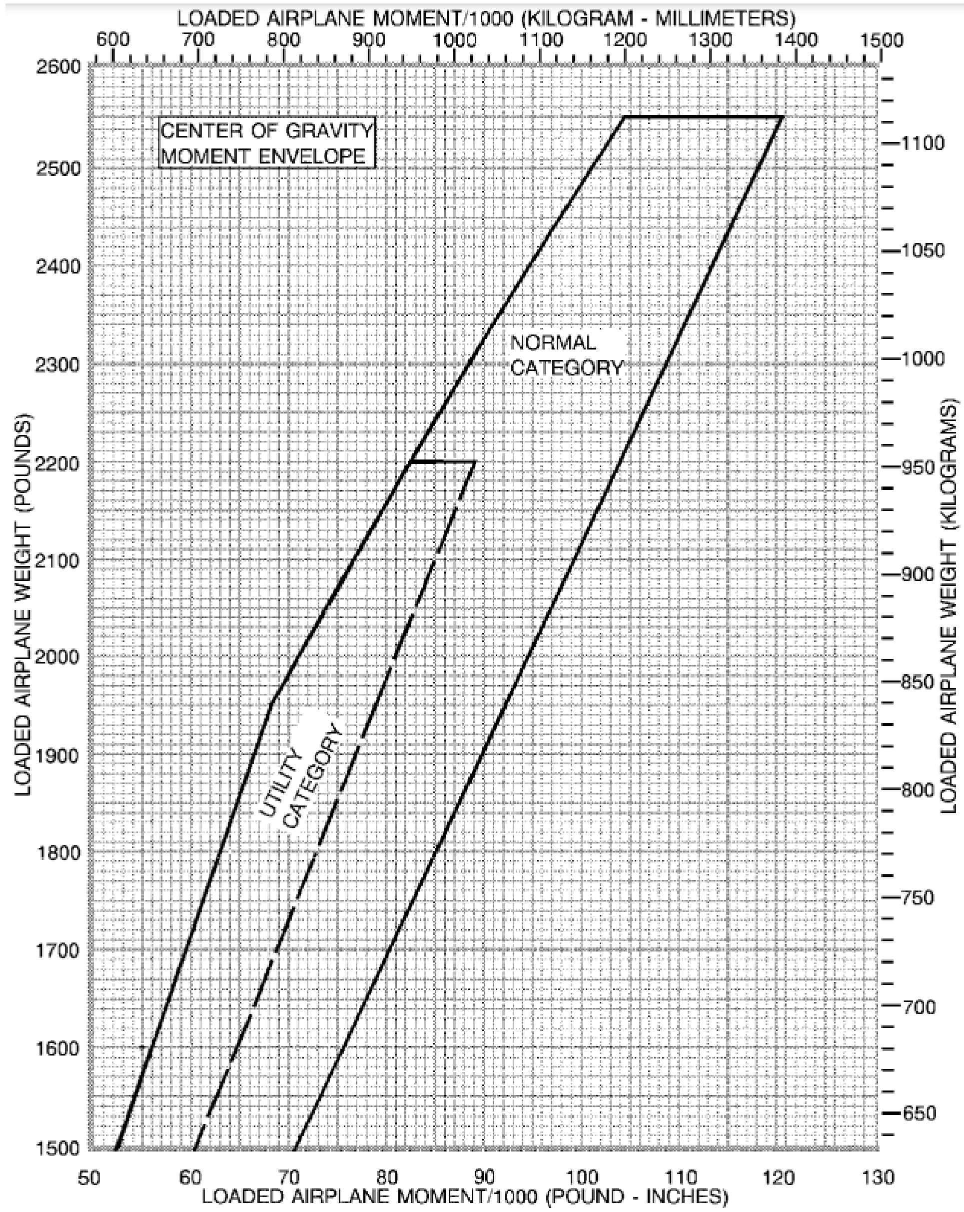


Figure 3: Cessna 172S Center of Gravity Moment Envelope [1].

The acceptable total load moment (in units of 1000 pounds-inches) on the aircraft ranges from about 52 to 120. At the **maximum weight of 50 pounds**, the control electronics assembly would contribute about 6.2/120 = 5.2% to 6.2/52 = 11.9% of the total load moment on the aircraft. This conservative weight budget should be acceptable, and there is room in the fuselage for the assembly to move forward if not.

3.2 Further Physical Integration Details

Besides the aileron control system, additional systems will be required to actuate the remaining control surfaces of the aircraft (rudder, elevator, elevator trim) to achieve full autonomous flight. Each such system would then require its own actuator and LRU to interface with the FC. While the current objective is to integrate the aileron control system, considering the entire flight controls system would yield a more realistic and better solution.

All actuator LRUs should have identical inputs (power, position commands, position feedback) and outputs (actuator power and system status), so they can be modular units grouped together in an LRU rack placed in Baggage Area 2, along with the FC and other flight electronics. Given the space in the baggage area, there can be two electronic racks installed side-by-side, each measuring at most 10” high by 10” wide by 14” long.

One rack can house all the control LRUs, one for each of the four control surfaces. Then each LRU can be as big as 10” high by 10” wide by 3.5” long – likely more than enough room to accommodate the necessary electronics. Extra room can be used for heatsinks and/or cooling fans if thermal management is determined to be necessary. The second rack can house the FC and other flight electronics such as navigation and communication systems. With electronic modules housed in racks, each rack can be secured in the baggage area via straps as if they are normal baggage, requiring no modifications to the baggage area. Within a rack, each module slides into their allocated slot via guide spacers, and the rack is enclosed with a cover via latch clamps (example [3]) to ensure electronics are secured against vibrations. Furthermore, no tools are necessary for assembly or disassembly, allowing for efficient and simple maintenance.

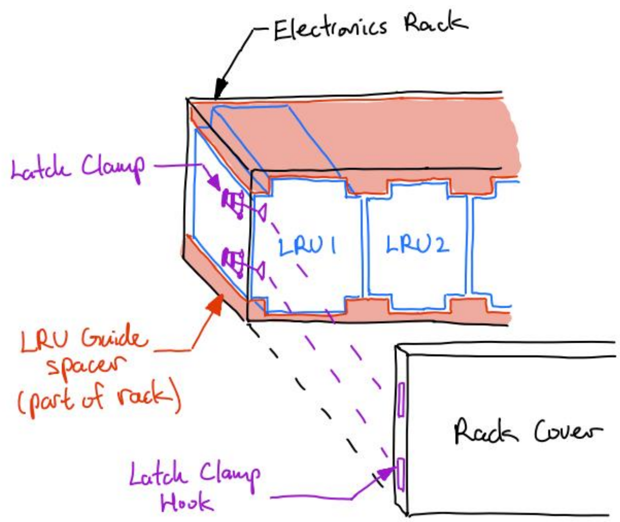


Figure 4: Integration sketch of LRU modules in a rack.

For clean wire management, each rack should have one cable bundle carrying power wires and one bundle carrying signal wires that directly plugs into the rack. All the wiring can be routed within the rack to the corresponding module slots. The guide spacers and modules in each rack can also be keyed to ensure each module is installed into the correct slot.

Figure 5 summarizes the proposed integration. The two aileron actuators are in the wings as per assumptions from Section 1. The other control surface actuators are not shown.

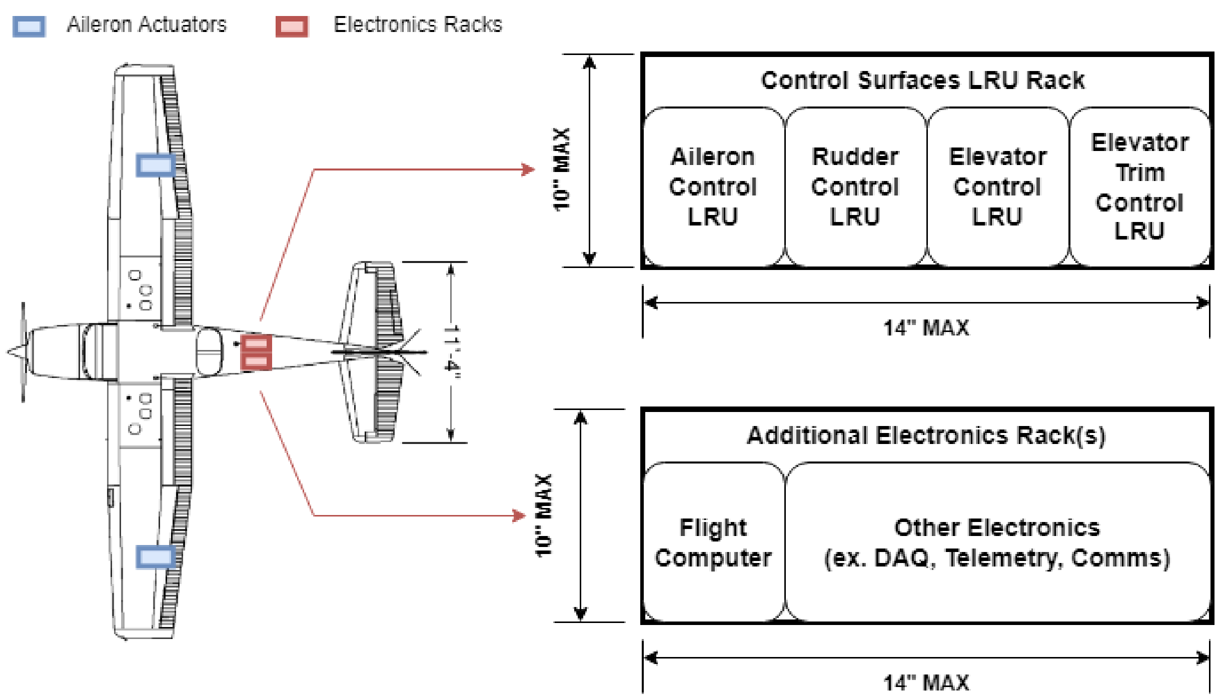


Figure 5: FC, LRU, and actuator integration following assumptions in Section 1.

Circling back to Assumption 1 made in Section 1, it doesn't really make sense to install one actuator in each wing to control one aileron. In a normal workplace setting where I'm handed this project, this would be amongst the first things I would communicate to my team to reach a common understanding. Given this being in the context of a take home assignment, I have done the above integration work with the assumption following the given problem statement, and now present an alternative that I think is much better and intuitive.

The integration proposed in Figure 5 above can be further improved if one actuator is used to control both ailerons – which is the case with a typical Cessna 172 where one yoke controls both ailerons. The actuator, like the yoke, would turn cables that attach to each aileron via pulleys and bell cranks. This actuator can then be installed somewhere in the fuselage where it is easily accessible for maintenance (ex. cockpit ceiling where it can access both aileron control lines).

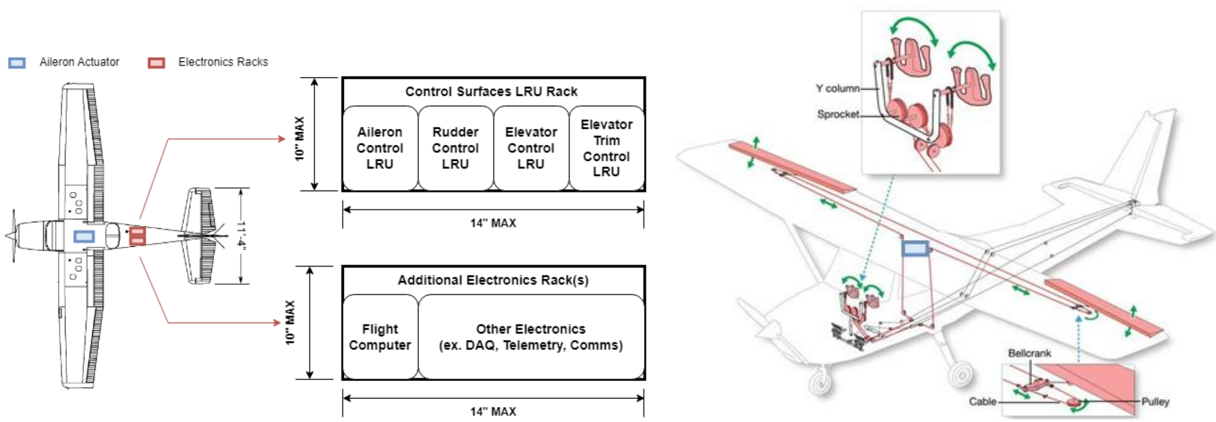


Figure 6: Improved FC, LRU, and actuator integration.

The same idea can also be extended to the other control surface actuators – placing them in suitable places in the fuselage and connecting them to the corresponding control surface via cables and pulleys. Such a layout would allow all actuators to be accessible (especially important for an experimental aircraft), be closer to the aircraft's center of gravity, and have more structural mounting options compared to other sections of the aircraft.

4. System Failure Prevention and Mitigation

Risk: aileron control system failure during autonomous flight

Prevention:

- Rigorous fatigue and environmental testing of the system before flight, outlined in Section 5.
- Preflight system inspection and full-range actuation.
- Scheduled system inspection and actuation after every specified number of actuation cycles or specified number of flight hours.
- Strict flight envelope protection in flight controls – ensure no command is sent to actuators that would drive the aircraft outside of its nominal operating envelope.

Mitigation:

- Backup aileron control system (redundant aileron actuator and control LRU) that activates if:
    - Original LRU does not receive position feedback signals from the actuator at regular intervals.
    - Original LRU does not receive correct position feedback after supplying actuator power multiple times.
    - FC does not receive system status from the LRU at regular intervals.
    - FC does not receive correct system status after sending position commands multiple times.
- Manual override of autonomous system if backup system experiences similar issues as above.

5. Test Campaign

5.1 Ground Test Campaign

1. Unit tests of FC, LRU, and actuator.
    - Ensure each component meets their component requirements. (Section 2)
2. System assembly and actuation tests in the aircraft.
    - Ensure no integration issues with other aircraft systems.
3. Simulated autonomous tests of individual control system and of the entire aircraft.
    - Ensure the system correctly responds to all potential flight scenarios, by itself and integrated with all other systems in the aircraft.
4. Fatigue, vibration, and thermal tests of assembled system on a test jig.
    - Ensure system meets its specified operating envelope.
    - Ensure proposed electronics mounting in Section 3.2 satisfies vibration and thermal requirements.

5.2 Flight Test Campaign

1. Segmented tests of autonomous aileron controls during manned flight in various flight conditions.
    - Isolated test of aileron control system from other experimental systems.
2. Fully autonomous flight tests.
    - Take-off, low altitude cruise, and land tests.
    - Higher altitude tests.
    - Various weather conditions.

References

[1] 1998 Cessna 172S POH. https://www.befa.org/wp-content/uploads/2019/12/POH-Cessna-172S.pdf

[2] ARINC 700 series standards. https://aviation-ia.sae-itc.com/product-categories/arinc-standards/700-series

[3] Latch Clamp Example. https://www.amazon.ca/chfine-Adjustable-Holding-Capacity-Release/dp/B0BX6PKP9L/ref=asc_df_B0BX6PKP9L/?tag=googleshopc0c-20&linkCode=df0&hvadid=578924164988&hvpos=&hvnetw=g&hvrand=12293397679088244883&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9000797&hvtargid=pla-2199382257026&mcid=cea33986050434ba92d70ce449f95c72&th=1

[4] Cessna 172 YouTube Video. https://www.youtube.com/watch?v=DvCv2SuKCE8&t=40s

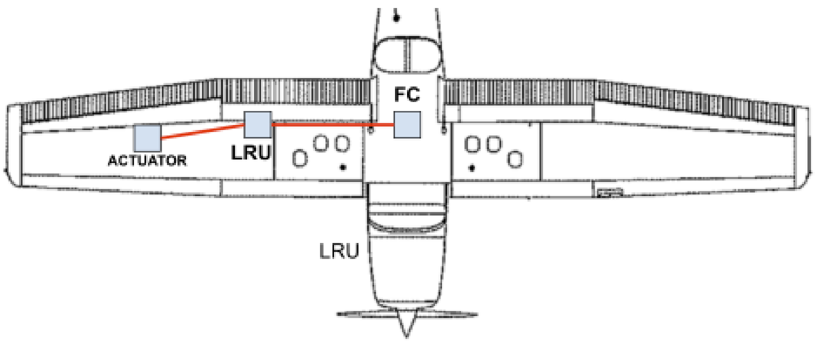
[5] Ailerons Article. https://www.aopa.org/news-and-media/all-news/2019/september/flight-training-magazine/how-it-works-ailerons

Appendix A. Take Home Problem Statement

Vehicle Integration/Test Take Home Problem

Instructions: Feel free to make reasonable assumptions and justify them along the way.

For this task, you will describe how to integrate an autoflight aileron control system into an experimental Cessna 172. A sample system architecture is shown below.



A line replaceable unit (LRU) receives aileron position commands (CMD) from a flight computer (FC) and relays them to an actuator, internally mounted in the uncontrolled environment of the wing. In addition, the LRU provides aileron actuator voltage and receives control surface position feedback (FDBK) from the actuator. Finally, the LRU can provide basic system health (SYS STATUS) monitoring to the flight computer.

Please write up the details on how you would safely integrate and test these components. (Hint: Use online resources or the Pilot Operating Handbook to learn more about the aircraft) CAD drawings are not necessary. However, sketches, system block diagrams, and references/standards are recommended to support your approach. When able, use actual numbers to describe the performance or limits of the system.
Consider the following:

- What are your first-order sizing considerations for the system? (form/fit/function)
- How will you set the operating envelope of the system?
- How will you package and mount the LRU assembly?
- How will you ensure that everything functions as intended and survives in operation?
- If the continued function of this system is critical to safety, how would you detect or prevent an in-flight failure from impairing the ability to continue flying safely?
- Outline the ground and/or flight test campaign for this system.

Appendix B. Background Research for Cessna 172

Figures referenced to gain some background context for this integration project:

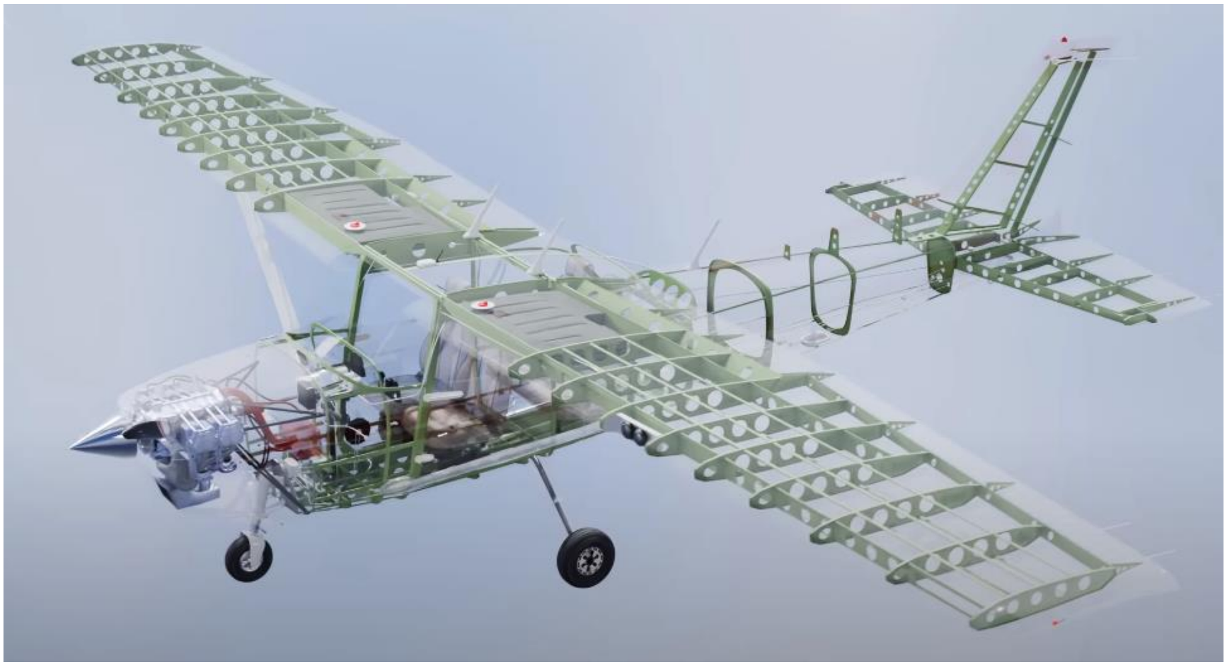


Figure 7: Cessna 172 Structure [4].

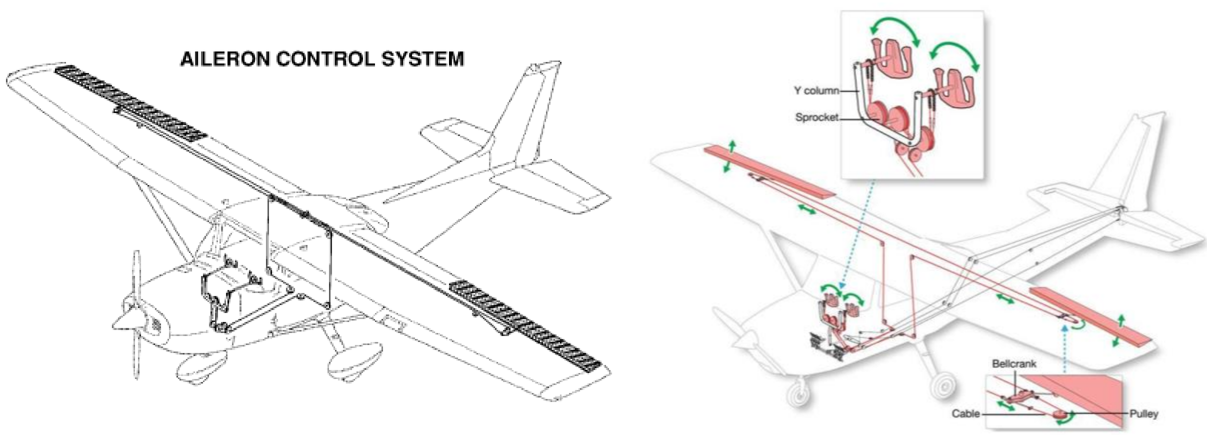


Figure 8: Cessna 172 Manual Aileron Control System [1] [5].

Appendix C. Cessna 172 Flight Envelope

SYMBOL	SPEED	KCAS	KIAS	REMARKS
V_{NE}	Never Exceed Speed	160	163	Do not exceed this speed in any operation.
V_{NO}	Maximum Structural Cruising Speed	126	129	Do not exceed this speed except in smooth air, and then only with caution.
V_A	Maneuvering Speed: 2550 Pounds 2200 Pounds 1900 Pounds	 102 95 88	 105 98 90	Do not make full or abrupt control movements above this speed.
V_{FE}	Maximum Flap Extended Speed: 10° Flaps 10° to 30° Flaps	 107 85	 110 85	Do not exceed this speed with flaps down.
-----	Maximum Window Open Speed	160	163	Do not exceed this speed with windows open.

Figure 9: Airspeed Limitations [1].

NORMAL CATEGORY MANEUVERS AND RECOMMENDED ENTRY SPEED*

Chandelles . . . . 105 Knots
Lazy Eights . . . . 105 Knots
Steep Turns . . . . 95 Knots
Stalls (Except Whip Stalls) . . . . Slow Deceleration

*** Abrupt use of the controls is prohibited above 105 KIAS.**

Figure 10: Maneuvering Limitations [1].