A Digital Controller
For Coolant & Oil Door Actuators
Of the North American P-51 Mustang

Design Overview

Michael Malcolm

August 24, 2017

Introduction

The North American P-51 Mustang has two thermostatic actuators that open and close the air outlet flaps (also called, “doors”)[1] of the coolant and oil radiators. These electrically driven devices control the operating temperature of the engine.

The coolant flap actuator has a reversible 24-volt D.C. motor rated at 1/10 horsepower. The motor operates a jackscrew capable of retracting the flap 10.5 inches against a load of 1600 pounds. The load is generated by the flow and thermal expansion of air passing through the radiator. The jackscrew turns at the rate of 120 RPM, and the full 10.5-inch retraction or extension requires 31-3/8 revolutions.

The oil flap actuator has a reversible 24 volt D.C. motor rated at 1/30 horsepower. The motor operates a similar jackscrew capable of extending the oil flap 4.5 inches against a load of 500 pounds. The jackscrew turns at the rate of 80 RPM, and the full 4.5-inch retraction or extension require 23-1/8 revolutions.

Each actuator motor incorporates a magnetic brake that instantly stops the motor when the energizing circuit is broken. Each jackscrew assembly includes two cams. One cam operates the interrupter switch which breaks the energizing circuit after each complete revolution of the jackscrew. The other cam operates limit switches that break the circuit when the flap is fully extended or fully retracted.

The actuator incorporates an ingenious electro-mechanical control system comprising a relay and switch assembly activated by a diastat which senses the temperature of the coolant or oil with a bulb filled with a liquid (mercury?) and connected by a capillary tube to a small circular diaphragm connected to the actuator assembly. The diaphragm moves a total of 30 thousandths of an inch as the temperature of the coolant or oil change throughout its range.

These actuators were designed over 75 years ago. Most were manufactured over 70 years ago. The jackscrews, cams, and gearing have proven to be very reliable. The diastat and thermostatic switch assembly have been less reliable. For the past 60 years of private Mustang ownership, faulty actuators have been replaced with new old-stock (NOS) actuators. Nobody has manufactured new actuators since the Mustang went out of production. As NOS actuators have aged in their boxes, the grease has deteriorated, and the bearings and electrical contacts have rusted. This led to overhaul procedures that included lubricating gears, replacing rusted bearings, and inspecting and cleaning electrical contacts. The stock of serviceable actuators has dwindled, and most of the remaining NOS actuators cannot be made to work properly because very few diastats can pass a bench test today. Apparently, enough liquid has escaped from most diastats over the past 70 years to render them dysfunctional. The diastats that still function properly are likely to fail within a small number of years.

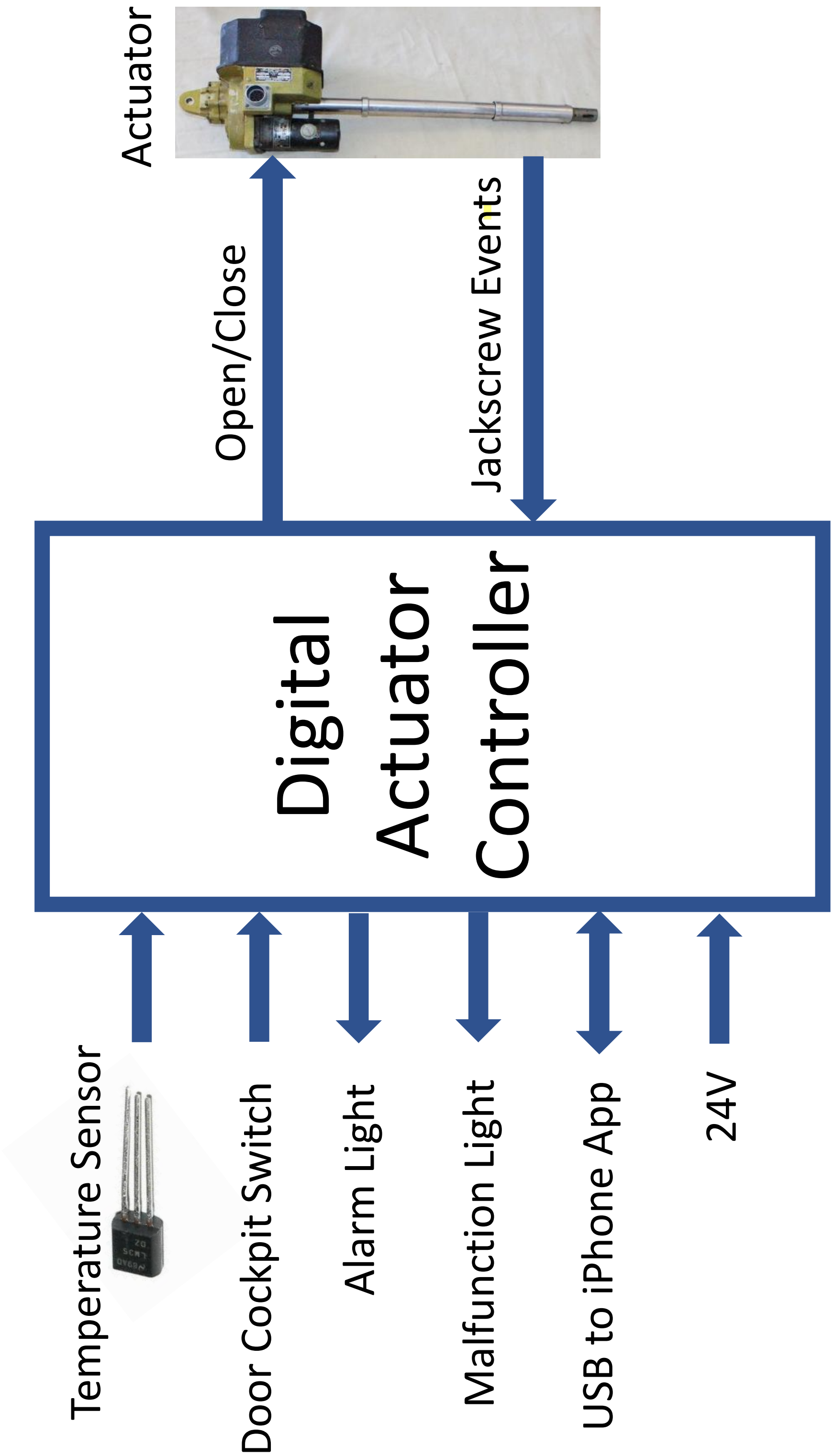
The lack of functional diastats, and our inability to repair them, threatens our ability to keep P-51 Mustangs flying for very many more years. Also, the actuators that are still working are less reliable than in the past, reducing the safety of Mustangs that continue to fly.

The digital controller described below will solve the worst of these problems by replacing the actuator’s electro-mechanical control system with a digital control system that uses a transistor temperature

[1] The terms, “outlet flap” and “outlet door” will be used interchangeably in this document.

sensor and modern computer control. It will give the pilot greater visibility into the operation of the actuator, the position of the outlet flap, and the temperature of the coolant/oil. It will provide a cockpit warning in the event that the temperature becomes unsafe, and it will maintain a complete record of operating temperatures and outlet flap movements.

Digital Actuator Controller



The digital actuator controller will be built in a small aluminum box that can be mounted on a bulkhead near the actuator it controls, where it can be reached by the existing cable from the cockpit door switch.

The Controller will have a 5-pin Cannon connector, of the same type used on the original actuator, which will provide the controller with the cockpit switch inputs. Only four of the pins are used: Open, Close, Auto, and ground.

The Controller will have a 3-pin Cannon connector for transistor temperature sensor input.

The 2-conductor Alarm Light output, the two-conductor Malfunction Light output, and the USB connection, and the 24V power can all be combined into one Cannon connector. The USB cable will be terminated somewhere in the cockpit with a Bluetooth transmitter/receiver that will communicate with the pilot's iPhone or iPad. This will require the USB connector to supply power to the Bluetooth receiver/transmitter dongle.

The 5-pin Cannon connector on the actuator will be replaced with a different Cannon connector with more pins – at least eight. All of the open/close commands and jackscrew event information will be communicated through this new connector:

1. Close door
2. Open door
3. The fully extended limit switch is closed
4. The fully retracted limit switch is closed
5. The cam-driven interrupter switch is closed
6. Ground
7. +5V (?)
8. Grounded if coolant actuator; not grounded if oil actuator

Only one of (8) and (9) will be asserted, depending on what type of actuator is being controlled. The same Digital Actuator Controller box will be used to control either type of actuator.

An advantage of changing the Cannon connector on the actuator is that nobody will accidently connect a Controller to a legacy actuator, and nobody will accidentally install a modified actuator in an airplane without a Controller.

The "24V" ship's power can fluctuate considerably. In flight, the generator supplies approximately 28.5V. Before engine start and at low RPM, the battery supplies around 25V, but it could fall to 16V or lower.

A transistor temperature sensor will be used instead of a bulb of mercury. Transistor temperature sensors are readily available for ranges of -50C to +150C. This matches the range on the analog temperature gauges for both coolant and oil. Operating temperature for the coolant will range from -20C to +130C. For oil, it will range from -20C to +110C. Normal in-flight temperatures for the coolant is 100C to 110C[2], and for oil it is 70C to 80C. The transistor temperature sensor will be placed inside a probe, and the probe will be filled with a potting compound that is a good heat conductor.

[2] However, some operators prefer to set the coolant operating temperature to something in the range of 90C to 100C.

All connectors on the controller must be Cannon connectors. The USB connection will go to a normal USB socket in the cockpit, where it will be connected to a Bluetooth dongle so it can communicate to an iThing. An iOS app will be developed specifically for monitoring, configuring, updating, and downloading event logs from the controller. It will display the temperature of the coolant and/or oil, the position of each door, and other information. It will also be used for adjusting the set point temperatures. The default set point temperature will be 105C for the coolant, and 75C for the oil.

The controller will notify the pilot with an alarm light on the instrument panel if the temperature is outside the acceptable operating range. In addition, the controller will send an alert message to the iPhone/iPad if the temperature exceeds the maximum acceptable operating range.

The aft fuselage can get warm, especially on hot days. In addition, the controller will be mounted near the radiators. It will be necessary for the controller to work reliably and continuously in hot environments. I plan to do some test flights to measure the temperatures of possible mounting locations so we can quantify the hottest operating temperature to be expected for the controller

The controller can have one or more cooling fans if necessary. It may be a good idea for it to have two cooling fans, each of them powerful enough to cool the electronics if the other fan fails. The fans can make all the noise in the world. (Nobody will notice!) It would be nice if the controller could detect and report the failure of a fan.

The controller will have a modern, relatively powerful, microcomputer. It will run Linux. It will have a considerable amount of flash memory – enough to load software upgrades and new control parameters from the iPad app, and enough to store the entire event log for the lifetime of the engine. That would include temperature readings every 5 seconds or less, and every event that occurs: cockpit switch change, assertion of Open or Close to the actuator, (de-bounced) change in limit switch or cam-interrupter switch state, software upgrade, change in temperature set point, temperature exceedance, etc. Note that Merlin engines have a TBO of 600 hours. If we allow for 1,000 hours of engine time, this isn't a great deal of data. E.g., there would only be 720,000 temperature measurements (using 5-second intervals) during 1,000 hours of engine lifetime. It should be possible to clear the event log when the engine is overhauled or replaced.

The software will likely be written in Python, and the control algorithm will likely be an off-the-shelf PID control method. (PID stands for proportional, integral, and differential.) The iPad app may implement tuning of the control parameters based on the history log.

The controller's MTBF must be at least 15 years and 2,000 operating hours. Longer would be even better because some of these airplanes may fly for another 75 years!

Failure Modes

The Controller's control algorithm will operate whenever the corresponding cockpit switch is in AUTO. When the cockpit switch is not in AUTO, the pilot can control the door using the switch's spring-loaded OPEN and CLOSE positions. The OPEN and CLOSE switch positions must always work, even if the controller has failed. I.e., those switch positions must be hard-wired to the actuator's OPEN and CLOSE pins.

The Controller must be powered through a circuit breaker. In the event of a run-away Controller, the pilot can pull the circuit breaker and operate the doors in manual (OPEN and CLOSE) mode.