Multi-actuator Integrated Control Design FOR Freighter Cargo Door

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Abstract. An integrated airborne Actuator Control Electronics (ACE) based on Field Programmable Gate Arrays (FPGAs) has been designed to control the main cargo door motion of ARJ21-700 converted freighter. This paper illustrates the designing method of the ACE, and analyses the relationship between control timing and door slippage. In the experimental part, a prototype Main Cargo Door Actuation System (MCDAS) is constructed and tested. The results show that multiple actuators of the system move sequentially under the control of only one ACE, and the switching process is smooth. The cargo door can be parked at any position with small slippage, just by adjusting the reverse braking time parameters in the FPGA.

Keywords: Main Cargo Door Actuation System · Actuator Control Electronics · FPGA platform · Relays layer · Timing optimization · Door slippage

1 Introduction

China is expected to need 750 new or converted freighters in the next 20 years, and 90% of the world's converted freighters come from China [1, 2]. However, domestic Chinese enterprises are still at the bottom in the industrial chain of engineering design, airworthiness certification, modification, and maintenance. One of the difficulties is the lack of cargo door actuators that meet the airworthiness standards of civil aircraft, have intellectual property rights and complete supply chains [3, 4].

MCDAS is composed of lock actuator, latch actuator and lift actuator, which controls lock mechanism, latch mechanism and lift mechanism in turn to try the opening and closing of the door, considering that the ARJ21-700 main cargo door has huge normal scale and large structural weight. The location diagram of the actuators is shown in Fig. 1.

Each actuator is an electro-mechanical type composed of an electrical motor, reduction gear trains, an output shaft, and a manual drive mechanism. When electrical power is supplied to the motor, the output torque of the motor is transmitted to the output shaft through the reduction spur gears and planetary gears [5]. The lock actuator is linear actuator driven by a low-power permanent magnet synchronous motor, while latch and lift ones are rotary actuators driven by Alternating Current (AC) electrical motors. The part of ACE about the lock actuator refers to the literature [6].

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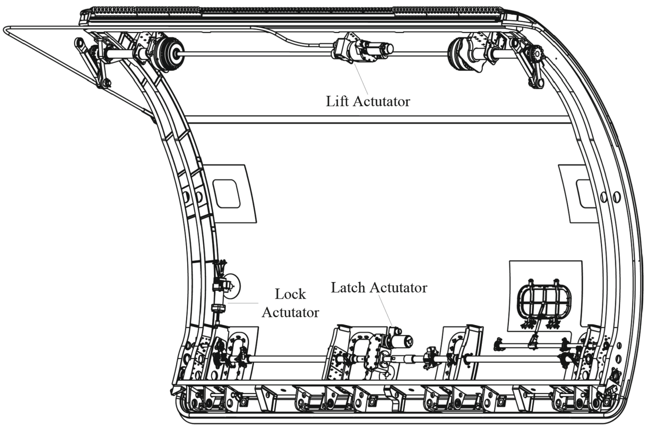

Fig. 1. Location of the actuators

Traditional AC motor control schemes use different types of relays, such as delay relays and overcurrent protection relays, through a large number of "wire-and" and/or "wire or" connections, which construct complex control logic [7]. First, different types of relays are more likely to cause supply chain problems, and parameter selection is difficult. Furthermore, cumbersome cable connections are very space-consuming, difficult to maintain, and low reliability.

To solve the above problems, an integrated control design based on FPGA has been shared in this paper, and has very significant advantages:

- Reduced supply chain pressure, and more reliable system.
- More flexible due to adjustable parameters.
- Wider connectivity to different interfaces.
- Intuitive design process, in accordance with DO-254 airworthiness certification requirements [8].

2 Hardware Design

2.1 System Structure

The ACE of MCDAS physically is a compact box mounted on 9G-wall, including function keys (see Table 1), indication lights, and connectors to three actuators, airborne signals, or power supply, as shown in Fig. 2.

The interior of ACE is divided into four areas, called relays layer, Built-In self-Test (BIT), I/O Interface layer, and FPGA. Among them, the relays layer contains a contactor and three simple relays, which are held in place by nuts to the case. The remaining three parts are all on the printed circuit board, on which rectangular connectors with accessories connect circuit interface, relays layer, and circular connectors on the case. The conceptual schematic of the ACE is shown in Fig. 3. Each of these parts is described in detail Fig. 3.

Table 1. Definition of Keys

Key	Function	Type
ARM/OFF	Power Supply (+115 V/400 Hz)	SPST (locking lever toggle switch)
UNLOCK/LOCK	Lock Actuator	SPDT
OPEN/CLOSE	Latch and Lift Actuators	SPDT
CARGO LIGHT	Light a Lamp	SPST

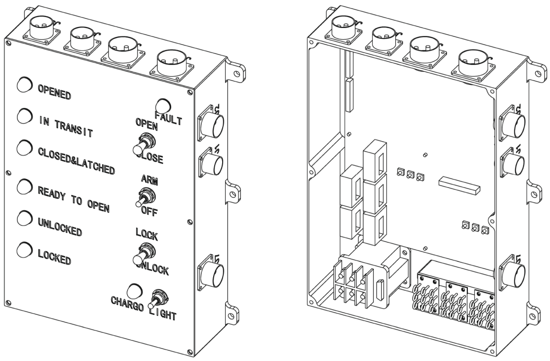

Fig. 2. Exterior and interior of the ACE

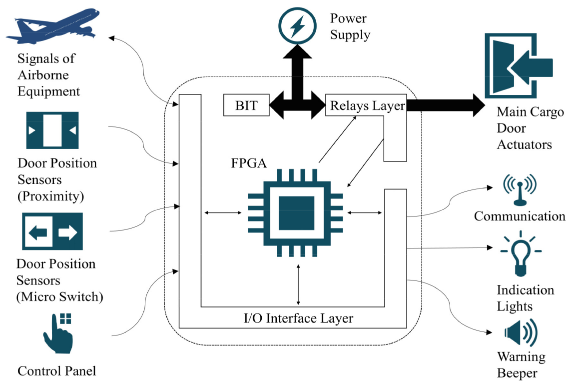

Fig. 3. Schematic of the ACE

2.2 Relays Layer

As stated in CCAR-25-R4 chapter 783, all power supply which can move any door's latch or lock mechanism must be power off before flight or on flight [9]. A locking lever toggle switch, which prevents accidental touch, is applied to shut off the AC power supply through a contactor whose status is continually monitored by the ACE.

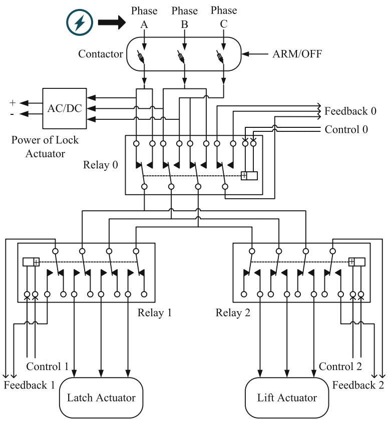

Fig. 4. Wiring diagram of Relays Layer

Next, the same type 4PDT high-grade relay for commercial aircraft is used in this ACE. Relay 0 selects a phase sequence output from the two input phase sequences, A/B/C or A/C/B, to realize the forward and reverse rotation of the AC motor. The functional characteristics of the relay guarantee no short-circuit. Additionally, input currents are continually monitored by the ACE. If the current amplitude exceeds a certain threshold, ACE must shut off the AC power supply through the contactor. Last, Relay 1 starts or stops the latch actuator, and Relay 2 starts or stops the lift actuator.

The fourth pole of the relay is used to detect the working condition of the relay. The FPGA sends out control signals and accepts feedback signals according to the MCDAS workflow. Ultimately, the relays layer is shown in Fig. 4.

2.3 I/O Interface Layer

The number of proximity or micro-switch sensors arranged on each door of a civil aircraft varies from dozens to hundreds [10]. The cargo door states sensed by these sensors can be roughly divided into: door open status, door closed status, door latched status, door locked status, preposition status, and differential pressure status. As a regional freighter, due to cost considerations, the sensors distributed in the cargo door are directly connected to MCDAS, instead of the Proximity Switch Electronic Unit (PSEU) in Boeing's counterpart. The received signals of other airborne equipment and status information of the sensors are processed and synthesized by FPGA, then are output to the cockpit display through indication lights, warning beeper, or the avionics system, and finally can be used by the aircrew to check the status of the cargo door.

Most of the input and output signals are GND/OPEN discrete signals, and these can be isolated using optocouplers, see b) in Fig. 5. The feedback signals of the contactor and relays can also be classified into this category.

When connecting ACE to manage high voltages of 115 V or higher, it is critical to physically and electrically isolate low digital voltages from high voltage equipment [11]. If a power unit fails or is physically damaged, it can quickly cause hundreds of volts to be injected into the digital logic. In addition to destroying the control device,

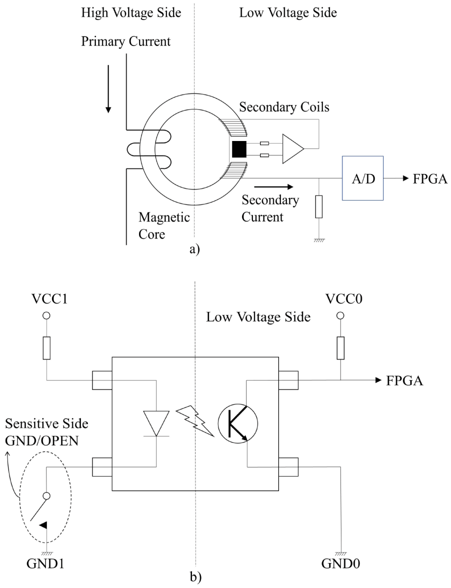

Fig. 5. Circuit Diagrams of I/O Interface Layer

this puts the aircrew at risk. Therefore, the current transformer is used to measure the input current and motor current, and the collected data enters the FPGA for subsequent protection, control and monitoring, see a) in Fig. 5.

2.4 BIT

The BIT circuit is designed for fault detection and isolation [12, 13]. Since FPGA has the ability of parallel processing, BIT is put into it, and it is carried out at the same time as normal work. Fault types include:

- Input current amplitude exceeds the threshold
- Motor phase current amplitude exceeds the threshold
- Relays Layer's feedback signals have a logical conflict
- Door position sensors have a logical conflict
- State of the door does not correspond to the operation
- Function keys behave incorrectly
- Signals of airborne equipment are obviously wrong
- Relay switching actions exceed the service life

After the fault is detected, the FPGA lights up the fault indicator and sounds the beeper to warn the crew to deal with it. Simultaneously, it quickly cuts off the power supply, locks the motor, and waits for troubleshooting or maintenance.

3 FPGA Logic Design

The three actuators of MCDAS run in sequence, which can realize fully electric automatic operation of the cargo door. FPGA uses decision rules based on a priority model to process redundant door status sensor information to ensure operational safety. The switching delay between the actuators is adjusted by parameters, thus ensuring a smooth transition of the relative movement between the mechanisms. By not relying on the use of delay relays, these important parameters can be flexibly optimized at the assembly line.

3.1 Door Opening Process

The state machine of the FPGA responds to the door opening operation of the ground crew according to the process shown in Fig. 6:

1) ACE receives the Weight on Wheels signal and braking signal from the landing gear system, and determines that the ground crew can only press "ARM ON" key and operate the cargo door after the aircraft has landed, otherwise the Fault light will be on, and the actuators will not move.
2) After the ACE judges that the cargo door is in the locked and latched state, if the "UNLOCK" key is pressed, the lock actuator will retract to release the lock mechanism.
3) After the ACE judges that the cargo door is in the unlocked and latched state, if the "OPEN" key is pressed, the latch actuator will rotate to release the latch mechanism.
4) After the ACE judges that the cargo door is unlatched and not fully opened, if the "OPEN" key is continuously pressed, the lift actuator will rotate and open the cargo door through the four-bar mechanism.
5) After the cargo door is in place, the ground crew can choose "ARM OFF" key.

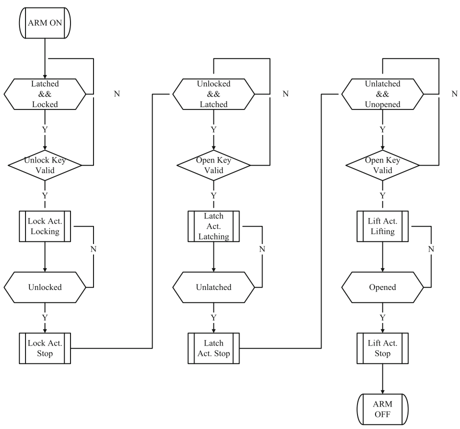

Fig. 6. Flow chart of opening door

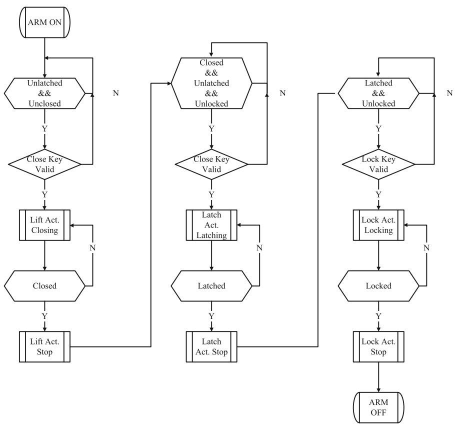

Fig. 7. Flow chart of closing door

3.2 Door Closing Process

The state machine of the FPGA responds to the door closing operation of the ground crew according to the process shown in Fig. 7.

The process of closing the door is generally the inverse process of opening the door, which will not be repeated here. It should be pointed out that if the ground crew didn't press "ARM OFF" key or the door hadn't been closed properly after the door closing operation, and if the ACE judges that the aircraft is ready to take off or is in flight, the "FAULT" light will flash, and the buzzer in the cockpit will sound and the warning light will be on.

4 Experimental Results

The designed prototype ACE of the MCDAS is shown in the Fig. 8.

Mount the three actuators (Act.) on the test fixture, then connect the MCDAS to simulate airplane signal box and AC power supply. Follow the cargo door operation manual, the measured data are shown in Table 2. Test results conform to system design specifications.

The characteristic of the AC asynchronous motor is that the speed variation range is very small when it works within the rated output torque range. When the cargo door is closed, there is a huge motion inertia under the action of gravity load [14]. It hits the door frame at a high speed and produces extrusion deformation, causing damage to the body structure. Figure 9 shows this phenomenon in the test.

One method is to adjust the installation position of the position sensor and cut off the power supply to the motor in advance; the other method is to use the reverse connection brake. Reverse braking is to change the phase sequence of the three-phase power supply of the stator winding when controlling the motor to stop, so that the rotating magnetic field of the stator winding is reversed, and the rotor is quickly stopped by the braking torque opposite to the rotation direction. This design uses two methods comprehensively.

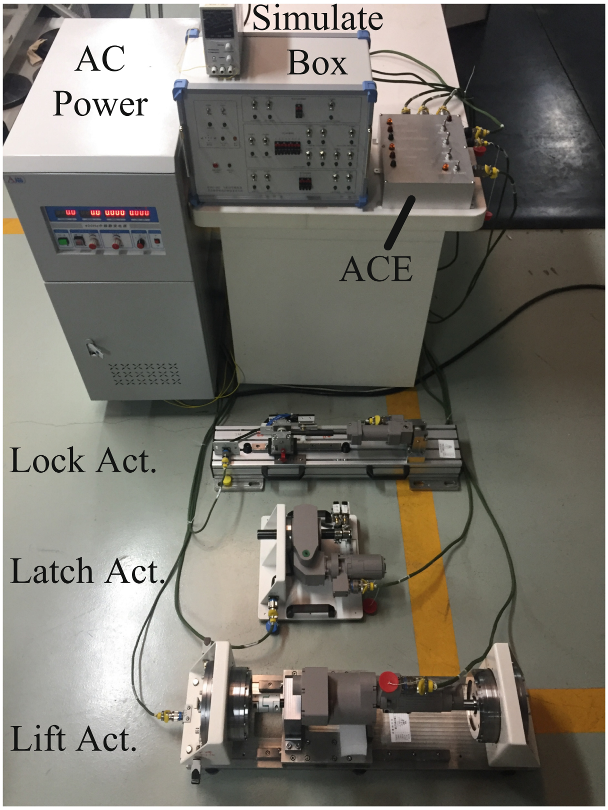

Fig. 8. Image of ACE based on FPGA

Table 2. Measured Performance Data

Item	Range/Time	Rated current
Lock Act.	0–38 mm/2 s	2 A
Latch Act.	0–110°*/4 s	7.5 A
Lift Act.	0–160°*/52 s	18 A

* rotate angle of the actuator's output shaft

By optimizing the control timing of relay 0, not only when the door is closed, but also when the door is started and stopped at any position in the whole process of opening and closing, the AC motor can be quickly braked, and the electromagnetic brake can hold the motor shaft after the speed is relatively slow, and can also reduce the adverse effect of high-speed friction on the life of the electromagnetic brake friction disc. The oscilloscope screenshot of the timing implemented by FPGA and the motor phase current during the motor stopping process is shown in Fig. 10.

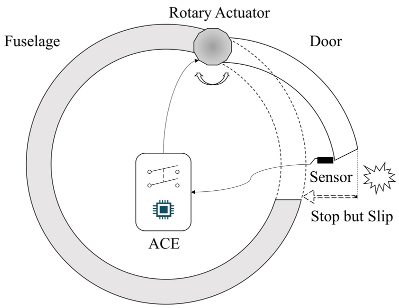

Fig. 9. Abridged general view of door flipping

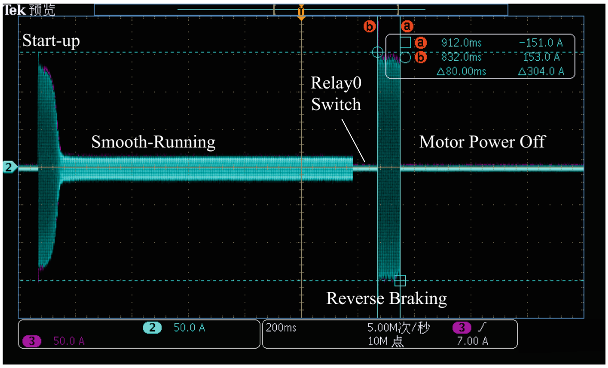

Fig. 10. Screenshot of the oscilloscope

5 Conclusion

This design innovatively abstracts the relays layer, etc., and uses only one type of relay to relieve supply chain pressure. Compared with the traditional solution, the function of each area is very clear and concise, and the connection relationship between the areas is also greatly simplified. All the connections for realizing the logic function are put into the modern FPGA chip, thus improving the integration of the system.

The test results show that the logic design conforms to the opening and closing process of the cargo door, and the optimized relay reversing sequence timing parameters can effectively shorten the braking time of the cargo door at any position, thus improving the safety and reliability of the system. The current consumed is less than 20 A, and the amount of slip can be adjusted by the amount of reverse braking time (see Fig. 10). The proposal provides important guidance and reference for the design of the actuator ACE of a freighter.

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