Preliminary design of redundancy management for LSA -02 automatic flight control system

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Abstract. The final objective of this paper is to make preliminary design concept of redundancy management, which applied for the automatic flight control system in LAPAN Surveillance Aircraft - 02 (LSA-02). The LSA-02 concept use a certified class I aircraft, which has a MTOW ≤ 6000 pounds and use single reciprocating engine. Then, an automatic flight control system (AFCS) is installed in the aircraft, hence added the aircraft capability to fly autonomously. Although the pilot still onboard and act as safety pilot when the AFCS is going wrong, the design of AFCS shall be safe. The AFCS consist of components where some of them are critical and need redundancy. The identifications of component criticality are come from functional hazard analysis (FHA) where the result are list of critical and non-critical component in AFCS during the automated flight. The FHA is a systematic, comprehensive examination of basic aircraft system to identify potential minor, major, hazardous, and catastrophic conditions that may occur due to a malfunction or a function failure of AFCS. The FHA result shows the critical components of AFCS that may lead to the catastrophic conditions in case of failure are the actuator that connected to the elevator, flaperon, rudder and throttle stick, also the flight control computer. Therefore, they need redundancy and the design of redundancy explained in the redundancy management. The redundancy management suggest eight actuators needed for the critical control surface and the throttle stick. This critical actuator is configured as cold standby redundancy. For non-critical control surface (flap and air break), two actuators are needed and configured with no redundancy. The flight control computer is also a critical component and built in dual modular redundancy (DMR) configuration and one independent communication channel for each flight control computer.

1. Introduction
1.1. Project background

National Institute of Aeronautics and Space of Indonesia is an Aeronautics research institute; begin to develop an UAV technology demonstrator. The UAV technology demonstrator is called as LSA-02. The aircraft platform used in LSA-02 is a typical conventional aircraft and has a mechanical flight control system to move the flight control surface. The LSA-02 design has a safety pilot onboard while flying autonomously. The LSA-02 is an UAV technology demonstrator that has a specific mission, which is performing the automatic flight control functions and technologies. To complete that mission, the mechanical flight control system is supplemented with an automatic flight control system (AFCS); therefore, the AFCS is an important parts of the LSA 02 demonstration activities. It shall be ensure that the UAV technology demonstrator is flying safely when AFCS is active. To achieve that condition the AFCS is designed carefully and correctly.

The FHA is a first step in design sequence of automatic flight control system. With the application of FHA, which function and underlying system is really critical in certain flight phase can be
identified; therefore a correct redundancies decision that must be applied to that critical function and underlying system can be made. Various system redundancies are designed in the LSA-02 aircraft to enhance the probability of safety in the event of AFCS failures during flight. In LSA-02 aircraft, each flight control surfaces are connected to the actuator as a principal force motivator to deflect the flight control surface. Depart from these conditions; the redundancy management system, for AFCS shall be developed for LSA-02 aircraft to ensure performed flight safely when AFCS system is active. In this paper, the preliminary design process of redundancy management system for LSA-02 aircraft will clearly described.

1.2. Concept of operation
The concept of operation LSA-02 technology demonstrator is same as conventional aircraft concept of operation. The pilot will give command to the aircraft flight control surface via mechanical flight control system to excite the aircraft maneuver. When the LSA-02 performing UAV technology demonstrator mission, such as aerial photography, disaster response, SAR and so on, the LSA-02 must flying autonomously. In this condition, pilot activates the AFCS and commands the AFCS through HMI device. The AFCS responses the pilot command and calculate the necessary control surface deflection by using flight control law that already installed inside the AFCS.

In case of failure on AFCS during the LSA-02 mission, a FADEC mechanism shall be installed onboard the aircraft and safety pilot onboard the aircraft shall activated the FADEC mechanism. When the FADEC mechanism active, it will disengage the AFCS and simultaneously decoupling the actuator from the control surface shaft. This condition will lead the pilot to take control the aircraft back to manual mode using mechanical flight control system.

1.3. Aircraft requirement
To support the LSA-02 mission, a high endurance and high performance aircraft is needed. The aircraft specification must comply with Class I Aircraft, stated in [10]. The class I aircraft is a SRE aircraft which have MTOW ≤ 6000 lbs. The aircraft must have conventional design, which means as follows:

1. The aircraft is equipped with vertical and horizontal stabilizer and located behind the aircraft main wing
2. The aircraft flight control surface consist of following component :
   a. Elevator
   b. Rudder
   c. Aileron / flaperon
   d. Airbrake
   e. Flap

The aircraft certification must meet the certification for Normal, Utility and Aerobatic Aeroplanes, FAR 23, Amendment 7, and certified category of airworthiness is “normal”. The noise certification is based on ICAO Annex 16 – Chapter X for Propeller Driven Aircraft.

To fulfill the requirement, there are some important aircraft specification values. This value is only approximation, but the aircraft used for LSA-02 must meet this specification value.

1. Glide Ratio : 28 – 40
2. Engine fuel consumption : 10 – 20 l/h
3. Span : 16 – 20 m
4. Wing area : 14 – 20 m²
5. Endurance level : 5 – 10 h
6. Aircraft type : motorized glider, utility aircraft

1.4. The methodology
Figure 1 shows the methodology that implemented for this paper.
2. Preliminary AFCS concept

The AFCS concept for LSA-02 UAV technology demonstrator is inspired by [4] for fixed wing and [5] for rotary wing design. The hardware configuration for the UAV helicopter system consists of following element [5]:

1. Flight control CPU
2. Sensors, consist of INS/GPS, RPM Sensors for Engine, and Sonar
3. Servo controller to control 5 servo
4. Wireless module for communication with Ground Control Station

While the hardware configuration for fixed wing UAV consist of following elements [4]. The hardware use NI Single-Board RIO as a mainboard.

1. The flight control computer which divided into two parts, the field programmable gate array (FPGA) and the real time (RT)
2. Sensors, consist of IMU, GPS, RPM Sensors for Engine
3. RC receiver for auto/manual mode selection
4. Servo controller to control 5 servo
5. Wireless module for communication with Ground Control Station

For the LSA-02 AFCS, the design is slightly different compared to [4] and [5]. The differences are the location of pilot when controlling the UAV. In [4] and [5], the pilot is stay in the ground and controlled the UAV via radio-controlled device; meanwhile in LSA-02 pilot is stay onboard in aircraft.
and controlled the aircraft directly. Figure 2 show the preliminary concept of AFCS which will be used in LSA-02.

![Diagram of AFCS design concept](image)

**Figure 2.** Preliminary AFCS design concept.

The input command in LSA-02 AFCS design concept come from pilot. The pilot will insert the parameter via HMI device. Pilot also gets some important flight information from the HMI. The HMI and the FCC will communicate in two-way communication. The HMI will give input to the FCC and vice versa. The FCC will get important flight parameter in real time from onboard sensors installed in aircraft. The onboard sensors will be consisting of following element [11]:

1. Attitude and Heading Reference System (AHRS)
2. Inertial Navigation System
3. Angle of Attack sensors
4. Laser Altimeter sensors

The FCC shall able to communicate with ground control station, using data link module that plan to be equipped later. The FCC calculate necessary flight control surface deflection and throttle setting to fly autonomously in specific mission will process all the information. The deflection command sent to the actuator to generate sufficient force to deflect the control surface and throttle setting. As seen in figure 2 above, there are six elements of flight control surface and throttle, which connected to the actuator.

The communication between the LSA-02 and the ground control station via data link shall consider the civil domains communication. The communication shall not put considerable stress on air traffic control. Experimental results using the heterogeneous unmanned aircraft system are presented to show that meshed airborne communication is feasible, that it extends the operational envelope of small-unmanned aircraft at the expense of increased communication variability, and that net-centric operation of multiple cooperating aircraft is possible [9].

**3. FHA for AFCS**

The FHA main objective is to identify the functional hazard that might be happen due to failure. The failures that become concerned are the failure effect and severity level due to failure in system level or component level. The main concern of the FHA is to identify what is critical component inside the AFCS. The definition of critical components is working components that handle the specific and critical function. If these components failing, will make the AFCS unable to performs its function and can lead to catastrophic event. The probability of occurrence of catastrophic event while the AFCS active is shown in reference [10]. The FHA analysis based on reference [12] and [13].
3.1. FHA for actuator component
The actuator primary function is to generate sufficient force for flight control surface deflection. The actuator will response input command given by FCC and produce required force amount. Just like other mechanical or electrical component, the actuator could fail. Some of failure condition of actuator like unlimited runway, transient runway, and oscillating (see [14] for detailed explanation) can cause catastrophic event. As seen in figure 1, the actuator will connected to flight control surface and the throttle setting of the aircraft. Table 1 shows the result of FHA analysis for the actuator.

| Location | Critical | Redundancy Requirement | Failure Effect                        |
|----------|----------|-------------------------|---------------------------------------|
| Elevator | Yes      | Yes                     | Aircraft crash due to pitching moment |
| Rudder   | Yes      | Yes                     | Aircraft crash due to yawing moment   |
| Flap     | Yes      | Yes                     | Aircraft crash due to rolling moment  |
| Flap     | Yes      | Yes                     | No critical failure effect, longer landing distance |
| Flap     | No       | No                      | No critical failure effect, longer takeoff distance |
| Throttle | Yes      | Yes                     | Uncontrolled airspeed, critical for some flight phase |

As seen in table 1 above, four actuator locations are critical and need redundancy. Three actuators connect with the control surface and one connects with the throttle control.

3.2. FHA for FCC component
The FCC primary function is processing all information to calculate necessary deflection angle of flight control surface. Inside the FCC will be installed flight control law that contains set of algorithm to perform automatic flight control. The FCC is a computer, and when operational must consider availability margin, processor utilization, expansion capabilities and data loss. In reference [15], three failure condition categories may occur such as omission failure, commission failure and Byzantium failures. All three failures are very likely to occur in LSA-02 FCC. Table 2 below contains FHA result for FCC.

| Failure condition | Failure effect                                                                 |
|-------------------|--------------------------------------------------------------------------------|
| Omission failures | FCC can’t execute complete step of flight control law, the aircraft AFCS will be not responding, therefore the actuator will be stop working due to unavailability of inputs |
| Commission failures | FCC generates false calculation output but still execute correct order of algorithm. This condition will cause wrong control surface deflection direction |
| Byzantine fault   | FCC will act unpredictable; therefore the aircraft control surface will be deflected unpredictable due to unpredictable input |

The identification of failure condition and failure effect of the FCC component indicates that the FCC component is a critical component and need redundancy. From table 2 above it can be seen that if one or combination of failure occur in FCC will make the AFCS become malfunctioned and can caused catastrophic event due to failure.

4. Redundancy management
4.1. Redundancy management – a definition
Redundancy is a term to describe duplication of critical component inside a system, with purpose to increases the reliability and availability of the system, in case of failure or system performance
degradation [3]. In the X-33 unmanned advanced technology demonstrator, the redundant system is the vehicle and mission computer that controls the X-33 and manages the avionics subsystems. Historically, redundancy management and applications such as flight control and vehicle management tended to be highly coupled [1]. In the F-15 STOL (short takeoff and landing) and maneuver technology demonstrator (S/MTD), the redundancy management system is implemented on the integrated flight and propulsion control (IFPC) system [6].

The reliability is a probability that a component inside the system will continue to perform its intended function without failure for a specified period under stated conditions. There are two ways to increasing the reliability of the system, first by increasing the reliability of single system to meet the failure rates by increasing the reliability of system component and deploying more than one system in redundant working mode, so if the failures happen in single system, does not impact the reliability of the whole system. The reliability of the whole system must meet the mean time between failures requirements.

The availability defined as the probability of system will work properly when requested for usage. In other words, availability is the probability that a system is not fail or undergoing a repair action when it needed. In the redundant system, the availability and reliability of the system shall be high, therefore when the failure occurs; the system can still operate, even in degraded performance level. The architecture of arranging the system components, in such a specific order to fulfill the MTBF requirements is called redundancy management of the system. Another consideration in redundancy management is fault handling and redundancy managing. Adding hardware as well as software in order to tolerate faults requires a redundancy strategy to attain and prove the expected as well as the required fault tolerance [2].

Another example of redundancy management system is scalable integrated flight control computers that initiates the development of a redundancy management system operating in tandem with the host platform. The concept of such a device is realized in the hardware design of a frame based redundancy management system that incorporates a high speed cross channel data link. The device utilizes a programmable clock to synchronize the processes in lanes of the host redundant system [8].

4.2. Redundancy management criteria

The redundancy management target is to achieve highest MTBF requirements. To achieve redundancy management in LSA-02 project, some limitations shall be considered when designing the AFCS.

The first limitation factor is the cost for building AFCS. The LSA-02 shall use cost effective components while developing the AFCS. The AFCS is designed not to immune against failure. It can be fail; therefore, there is safety pilot onboard the LSA-02 aircraft and the FADEC mechanism, which responsible to maintain aircraft operated safely.

The second limitation factor is the weight of AFCS components. If the AFCS is developed with very high redundancy, the total weight of AFCS is increased. Later, the weight of AFCS component will be constrained by LSA-02 payload capability. Therefore, a lightweight redundant AFCS is preferable.

The last limitation factor is AFCS power requirement. A more redundant AFCS will need more components, and it need more power to operate. The power requirement of AFCS component will be constrained by LSA-02 onboard available power, provided by alternator. This limitation will lead to design a power efficient redundant AFCS.

For the LSA-02, the design criteria of AFCS are cost effective, lightweight and power efficient. The redundancy design of LSA-02 AFCS is made by duplicating some critical component inside the AFCS. As seen in chapter 3, the actuator that connected to the elevator, flaperon, rudder, and throttle need redundancy. The FCC also need redundancy to make sure the system still operate safely in case of failure occur.

4.3. Type of redundancy

The standby redundancy is the first type of redundancy. It is also known as backup redundancy, because in this configuration, the component will have an identical secondary (standby) component
that serves as back up the primary (master) component. Both of component, either standby or master, must have same function.

In standby redundancy, there are two type of operation. First is called as cold standby operation. In this operation, the standby unit is not powered on, therefore impossible to perform synchronization with primary unit. This condition will makes more challenging to reconcile synchronization issues, and will caused higher probability of data loss. The main advantage of this operation type is preserve reliability of standby unit because the secondary unit is powered off, also preventing the standby unit from damages occurring due to possible power surges. The disadvantage for this operation type is greater downtime to power up the standby unit and brings it online into known state. Also, the probability of data loss due to synchronization issues is higher. The second type of operation is called as hot standby operation. In contrast to cold standby redundancy, in hot standby redundancy both of components is powered on, therefore the standby component have Ability to continue the processing that was occurring previously when the Master system was interrupted or failed. In this configuration, the standby component will be in Synchronization with the Master with respect to events. Because of this mode of operation, the availability of the system is Increases, by shortening the downtime and since standby is synchronized with the Master events the data loss is zero or minimal. Unfortunately, this operation mode will not preserve the reliability of the standby component because both master and standby are running simultaneously.

The second type of redundancy called N modular redundancy and also known as parallel redundancy. This type of redundancy will have multiple component of same type running in parallel. All the components are highly synchronized each other and receive the same input of information at the same time. The advantage of this configuration, the system availability is very high as this model typically has faster switchover time. Since all components are fed with same inputs, simultaneously need for synchronization is reduced and therefore probability of data loss is minimal. The limitation for this configuration is vulnerable to common mode failure as all the components are powered up and engaged actively. The topology examples for this configuration are Dual Modular Redundancy (DMR), Triple Modular Redundancy (TMR), and Quadruple Redundancy. The average cost increase of a DMR system is about twice that of a non-redundant system, factoring in the cost of the additional hardware and the extra software development time, and this rule of thumb applies for TMR and Quadruple Redundancy [3].

The last type of redundancy called hybrid redundancy. This type of redundancy is combination between standby redundancy and N modular redundancy. The example of this type is configuration triple modular redundancy and standby replacement redundancy (usually in cold standby), consisting of a triple modular redundancy system with a set of spare units so that when one of the units (usually standby) in the triple modular redundancy system fails it is replaced by a spare unit [3].

4.4. Considered factor in redundancy management
Degeneracy is first factor to be considered when designing redundancy management. Degeneracy means varying multiple components with same function inside system to enhance the availability and reliability of the system. The variation of components can be started in architecture level up to brand selection level. In [7], the degeneracy process has been made by varying the controllers by chosen different microprocessors, INTEL, AMD and MOTOROLA. Same configurations are applied into controllers and monitors in the first and second channels. MOTOROLA and INTEL are used in the third channel, which can improve reliability of the system. This factor is needed to address the reliability problems arising out of common mode failure. The common mode failure is a failure that may occur in electrical or mechanical component with same type or architecture at the same time due to single cause.

Aging and longevity is also another factor that needs to be considered for design of redundancy management logic. When the components become ageing, the probability occurrence of Dorman mode failure is increasing. Although the preventive maintenance has been carried out regularly for that component, the Dorman mode failure still can occur. Therefore, a mechanism to address the Dorman mode failure is needed for critical component to ensure the system is safe and ready for operation. There are two mechanisms to address Dorman mode failure, first is intentional swapping. When the
swapping detects the Dorman mode failure, the immediate corrective action can be made. To increase the probability detection of Dorman mode failure, another concept of detection to bring out the dormant mode failure is made. The concept is called Continuous Built in Test (CBIT). In this concept, the component has capability to test itself, report the health condition to the central computer or central maintenance computer, and then give the pilot or crew warning if the health condition of component is poor or not ready for operation. The pilot or crew can take remedial action or recovery action to restore the un-occurred failure.

The other factor is validation. Validation is needed to address input signal error when performing switching between masters to standby component. Before the switching process is carried out, the input signal to standby component must be validated to ensure no signal error or signal failure has been detected. This process is similar to Double Switching, which is common practice employed in electrical circuits.

5. Redundancy management design for AFCS

5.1. Redundancy management design point for actuator

The redundancy type selected for redundant actuator component is cold standby redundancy. The reason of selection cold standby redundancy is lack of necessities for secondary actuator to be active all the time. The standby actuator component also not necessary to be synchronizes with master actuator, because the actuator is only work for responds to the inputs provided by FCC. The standby actuator only work when the master actuator is fail and powered up as soon as possible to bring it online into known state. For the actuator, the decision is to preserve the reliability of standby actuator. This configuration will make the system has greater downtime and switchover time. The greater downtime requirement must be define because the failure can be happen at critical phase. In this paper, the downtime must be much smaller than 0.5 s (The pilot can take over manual control at any time within duration of 0.5 seconds). Choosing cold standby configuration for the actuator will make the redundant actuator configuration is much simpler, compared to the N-Modular redundancy type. It will make the number of components required to build redundant configuration amounted to less. Therefore, with this configuration can support lightweight AFCS criteria.

The common mode failure shall be addressed by preserve reliability of standby actuator due to cold standby redundancy model (the actuator is sleep, not powered on when not in use). It’s assume that when the standby actuator is not active, the reliability of the standby actuator will be higher compared to the master actuator, therefore the probability occurrence of common mode failure is smaller compared to the master actuator. From this reason, selection of same type actuator for master and standby is safe and cost efficient.

The Dorman mode failure can be addressed by putting additional sensors to detect the operational parameters of actuator such as running time, number of switching / starts-stops, number of faults (torque & motor thermo-switch) etc. That parameter shall be easily retrieved from the actuator and can be used to addressed the dorman mode failure. For this requirement, an actuator, which has such capability, is needed for LSA-02 AFCS.

5.2. Redundancy management design point for FCC

The Dual Modular Redundancy configuration is needed for FCC. This configuration is selected because the FCC is a core of the AFCS and needed very high availability in case of one FCC is fail. The switchover time between both FCC shall as fast as possible. The most important think, the data loss probability when carrying out switching process is minimal or not happening. For all these point, the Dual Modular Redundancy is best suited for cost efficiency reason but retains the capability of the FCC to be synchronizing all the time and also work in parallel.

The common mode failure also shall be considered, although the implementation of degeneracy of FCC is not possible in Dual Modular Redundancy configuration. No degeneracy was used for FCC to protect the FCC from generic design errors [15]. The selection of same type FCC is motivated by needs for minimizing calculation error so that both FCC can produce same calculation output. The common mode failure shall be addressed by increasing the MTBF requirement for FCC. The Dorman mode failure could be addressed by selected the FCC, which has capability to perform Continuous
Built in Test (CBIT). The CBIT will report to the pilot or other crew if the FCC is failure, and the backup system also failure.

5.3. Redundancy management design
Based on all consideration that have been described in paragraph above, the preliminary design for redundancy management for LSA-02 UAV technology demonstrator is consist of following configuration.

1. The redundant actuator for elevator, flapperon, rudder, and throttle is configured as cold standby redundancy.
2. All of actuator used in LSA-02 AFCS shall equip with monitoring sensors, which has a capability to report self-health conditions.
3. The redundant FCC is configured as Dual Modular Redundancy, both FCC is always turning on, highly synchronize and get same input from onboard aircraft sensors, HMI, Data link, and also actuator monitoring sensors.
4. The FCC Dual Modular Redundancy configuration must ensure minimum data loss, very high system availability, and faster switchover time in case of one FCC failure.
5. Each FCC will connect into independent channel called IOM and connected to the same component each other.

Figure 3 below show the AFCS redundant design for LSA-02. As seen in picture below, both of FCC will produce same output signal. For normal condition (no failure happen), the output signal from FCC A is being used for master actuator. FCC A is act as master and FCC B is act as standby FCC. In case of FCC A failure, the FCC B will take control and give command to the master actuator, not to the stand by actuator. The FCC A or B will give command to the standby actuator if the master actuator is fail.

6. Conclusion
The preliminary design of redundant AFCS for LSA-02 has been done in this paper. Many factor and aspect have been investigated to fulfill the redundancy criteria. The final decision to put redundant FCC and actuator is based on investigation result. The FHA and redundancy management concept is utilized inside this paper to ensure the final decision is correct. The result shows actuator on elevator, rudder, flaperon, and throttle as well as FCC are critical component and need redundancy. The critical actuators are configured as cold standby redundancy and the FCC is configured as dual modular redundancy. The further investigation of redundancy management for sensors, HMI, and data link is investigated in another work. Until now, the project LSU-02 technology demonstrator is still running.
The preliminary design of redundant AFCS describe in this paper still may change in the future if there are better option for component selection and capability.

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