Smart Actuators for Mini Unmanned Aerial Vehicles

Ádám Bakos [*] **Gergely Regula** [*] **István Gőzse** [*] **Bálint Vanek** [*]
József Bokor [*]

[*] *Systems and Control Laboratory, Computer and Automation Research Institute, Hungarian Academy of Sciences (vanek@sztaki.hu).*

ABSTRACT

The present article details the development steps and experimental results obtained during the development of smart actuators used on mini unmanned aerial vehicles (UAV). The research effort is driven by the need of developing onboard health monitoring and diagnostics units for small size UAVs to improve their reliability. In the present all small UAVs use single string avionics systems with no built in redundancy, moreover the servo actuators onboard the airplane are often commercial of the shelf (COTS) hobby components with no reliability figures, limited performance guarantees and one directional communication using analog PWM signals. The development of new servo generation focused on solving the above issues. The proposed servo actuators use the existing mechanical gearboxes and housing of the COTS components, but their power electronics, motor control hardware and software components, sensors are custom designed to fit the needs of a higher demand. The actuators with their controlling microprocessors are capable of establishing two way communication via CAN and Flexray protocol, suitable for safety critical applications, and self diagnostics features are also hosted onboard the actuators. The development challenges and experimental results in a hardware in the loop (HIL) simulator are discussed in the paper.

KEYWORDS

Mini / Micro UAV, Smart Actuator, Electromechanical Actuator, Safety Critical Systems, Flexray communication.

1. UNMANNED AERIAL VEHICLES

The emerging role of Unmanned Aerial Systems (UAS) for both military and civil operations depends on the ability to gain unrestricted access to national airspace [Dempsey 2010]. One of the key issues that must be resolved to open up the skies for UAS is to be able to coexist safely and effectively with current manned operations in the national and international airspace . This includes the ability to follow pilot commands with high fidelity even in the case of component faults. Since current UAVs, with the exception of Predator, Global Hawk and a few other high cost systems, use single string avionics, there is no way of mitigating flight control system component faults during flight [Cox et al. 2004]. It is our aim to develop a redundant low-cost avionics system for UAVs, where hardware redundancy is combined with analytical redundancy to reduce the overall weight and cost, but take advantage of increased computational performance onboard the aircraft. The avionics system is based on the philosophy, that in most situations a carefully selected set of built-in-tests and

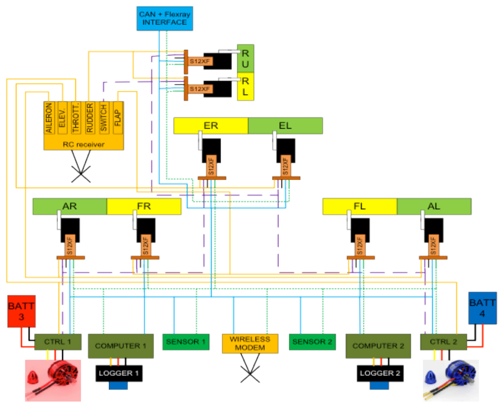

Fig. 1. Interconnection of the UAV avionics.

proper handing over protocols between parallel channels can provide the necessary reliability figures. In case two flight control computers are used and one fails the other will be able to clearly identify the event of a fault in almost all situations if we assume the failed node is transmitting random messages not intentionally trying to attack the rest of the system. The system architecture developed in SZTAKI (Computer and Automation Research Institute of the Hungarian Academy of Sciences) can be seen in figure 1. It consists of two independent flight control computers, two INS/GPS sensor units, the three major motion axes are controlled by pairs of independent flight control surfaces, the aircraft has two engines with their own dedicated batteries, two independent electrical power sources are fed to each avionics component and the avionics components are interconnected with a safety critical Flexray communication bus [Opel et al. 2010]. The overall architecture, in its simplest form consists of 12 smart units, each having its own computational capability, which allows to transmit two directional messages between Flight Control Computers (FCC) and actuators. In conventional small size UAV applications the FCC only sends analog commands to the actuators and might receive an analog feedback from a position sensor about the current status of the unit. In our approach the FCC sends commands over a digital channel to the actuators, where the smart unit takes care of the internal control tasks of servo control and Pulse Width Modulation (PWM) control of the DC motor inside the actuator. Besides the local control tasks the unit is also capable of providing fault detection capabilities [Vanek et al. 2011b], since position, back electromotive force, and drawn current are all measured and using the mathematical model of the actuator analytic parity relations can be used to identify anomalous behavior.

Flexray communication protocol is selected to provide interconnection between the nodes due to its low cost and the availability of development tools. A consortium including BMW, DaimlerChrysler, Motorola, and Philips, has developed FlexRay for powertrain and chassis control in cars. It differs from conventional buses like CAN or LIN, since its operation is divided between time-triggered and event- triggered activities. Published descriptions of the FlexRay protocols and implementation are described in [Opel et al. 2010]. In both cases, duplication of the interconnect is optional. Each FlexRay interface (it is called a communication controller) drives the lines to its interconnects through separate bus guardians located with the interface. (This means that with two buses, each node has three clocks: one for the controller and one for each of the two guardians; this differs from the bus configuration of TTA, an alternative time-triggered protocol [Kopetz and Bauer 2003], where there is one clock for the controller and both guardians share a second clock.) Like the bus configuration of TTA, the guardians of FlexRay are not fully independent of their controllers.

2. SERVO ACTUATOR

The UAV under development is based on a hobby RC aircraft frame, which is modified for the research purpose of autonomous flight and development of a vision based sense and avoid system [Vanek et al. 2011a]. Since the airframe is based on a hobby aircraft, the servo mounting positions and place for servos is based on commercially available units. Hence, it is practical to develop custom servos with the same form factor as the standard ones available, more over the gearbox, housing and DC motor can be re-used. On the other hand the onboard electronics of a COTS servo is a black box for the user, hence it cannot be modified for research purposes. Moreover, they do not satisfy the requirements of safety critical applications, they are built from a few standard components with minimum "intelligence" in their control logics:

- The control is done with a dedicated printed circuit board, in this form there is no way of modifying its behavior
- Servo shaft angle (motor shaft after the reduction gears) is measured with a potentiometer
- Induced voltage of the motor is measured
- Voltage regulation is done via a MOSFET bridge
- The reference signal is implemented with a $0 - 5V$ level, pulse with modulated input, this corresponds to a $50Hz$ frequency square wave signal with different pulse widths. Maximum displacement is commanded with $1ms$ long high and $1ms$ long low signal value, while negative sign maximum displacement is achieved with $2ms$ long high signal level.
- The difference between maximum and minimum displacement is less than 270 degrees, limited by the mechanical construction of the potentiometer
- Communication with the environment is one-way, via the analog PWM signal.

Due to the aforementioned limitations, COTS servos are not applicable for safety critical UAV applications, the custom made servo has to satisfy the following requirements:

- Independent, self-contained operation with multiple cascade control-loops, reference tracking with sufficient bandwidth and zero steady state error
- The control-loop parameters should be tunable, to achieve different desired responses
- To satisfy the model based control and fault detection requirements, the model parameters should be measured or identified
- All the measurable quantities should be available for diagnostic purposes, to provide the highest number of analytically redundant data
- Self-testing and self-diagnostics should be implemented
- High-level, two-way communication via the Flexray avionics bus should be implemented
- The lifespan of the servo due to customization should not be compromised

Fig. 2. Futaba S3305 COTS RC servo.

A smart actuator satisfying the performance requirements above can serve as a smart-unit onboard the safety critical UAV.

The first task is to select a suitable servo type for modification. The three main requirements were precision, maximum torque and lifespan. Since only the housing, gears and the motor is used in the modified servo, these requirements pointed towards a unit with metal gears, small backlash and with sufficient space in the housing. The motor should be coreless, since it is free from the reluctance type torque disturbances, which makes the characteristics of the motor magnetic field nonlinear around small torques, undesirable for control purposes. We used a commercial off the shelf (COTS) Futaba S3305 RC servo [Futaba Corp. 2012] as a baseline, which is modified during the development of the custom actuator unit 2. This has a non-coreless motor, which is replaced by a coreless one, but the gears are metal with minimal backlash. In the second stage of the development, the electronics modules of the unit are developed. According to the specification, the servo should be able to communicate via the Flexray bus. Since this communication protocol is not widespread in the industry, due to its maturity, only a limited set of microcontrollers have communication controllers built into them supporting the Flexray protocol. Our choice was to use the Freescale S12XF512 microcontroller, which has a development environment and available not only for automotive customers. This unit is a relatively large integrated circuit, with 112 legs, which is larger than the size of the servo housing, hence the complete electronics is done in two separate components. The board housing the sensors, power electronics and the control electronics is placed inside the servo unit, while the board containing the S12XF micro controller is outside the box, connected via a dedicated cable, see figure 5. The module containing the micro controller is designed to be able to control not only the servos but the large BLDC electrical engines of the aircraft via their dedicated power electronics.

The electronics inside the servo contains the following components:

Fig. 3. Disassembled Futaba S3305 COTS RC servo.

Fig. 4. Modified motor, electronics and angle sensor with the same form factor as the Futaba S3305 COTS RC servo.

- Sensor for the angle and angular rate measurement of the servo shaft
- Circuit, including signal conditioning and amplification, of the induced voltage measurement in the motor
- Circuit, including signal conditioning and amplification, of the current measurement inside the motor
- The MOSFET bridge, controlling the motor voltages, with its driving circuit

The magnetic sensor to measure shaft position is the Austria Micro Systems AS5045 unit which is a system on a chip solution for Hall-element sensing. The analog amplification and digital signal processing is done on the unit, measurement are sent via an SPI communication bus. It allows contactless angle measurement with $12bit$ resolution leading to 0.0875 degree maximum precision.

The signals sent to the microcontroller board, outside are the digital busses of measured current, voltage, and the position of the shaft, and the digital signals sent from the microcontroller are the sign of motor rotation and the voltage on the motor. The supply voltage for the motor and for the electronics are also sent via this cable. The control, fault diagnostics and communication algorithms are implemented on the micro controller, which has access to all internal and the necessary external signals. The circuit board is connected to the redundant electrical

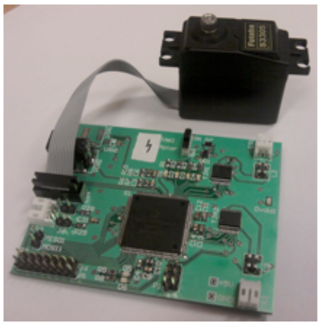

Fig. 5. Modified servo with the external S12XF micro controller in prototype form.

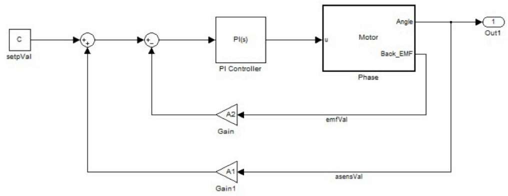

Fig. 6. PID control loop implementation of the actuator servo.

network onboard the aircraft, via a power switch, which is selecting always the healthier electrical bus with seamless transition.

It is worth to note, that each unit is also equipped with a CAN communication network, which serves as a direct backup communication link, in case manual flight is required by the safety pilot. In this case the RC receiver signals are captured from the receiver with a PIC24F micro controller and sent directly to the servos, bypassing the FCC and the Flexray communication network.

3. IMPLEMENTATION

The main goal of the custom servo development is precise position control. To close the position loop in the controller an additional inner loop on back EMF measurement is necessary. Back EMF is the voltage induced by the motor, when no current is drawn (no voltage is applied), from which RPM can also be measured at high rotation rate. It is interesting to note, that this signal can be measured only when there is no voltage applied to the motor (at the zero PWM level), after the transients. The designed control loop consist of a back EMF feedback, which is proportional to the angular speed, and an angle error feedback, both of them are modified by proportional gains $A1$ and $A2$ respectively. The resulting signal is than sent to a PI controller, which is controlling the voltage of the motor. A dedicated logic is determining the required PWM signal and based on the rotation speed the sequence of polarities applied to the motor to maintain the desired rotation direction, since only rate but not the direction is determined by the PWM signal. The logic behind the control is the following: position control is done with $250Hz$, with position measurement of $250Hz$. The frequency of the PWM signal is $1kHz$, while back EMF is measured also with $1kHz$ as shown in figure 7. It is also

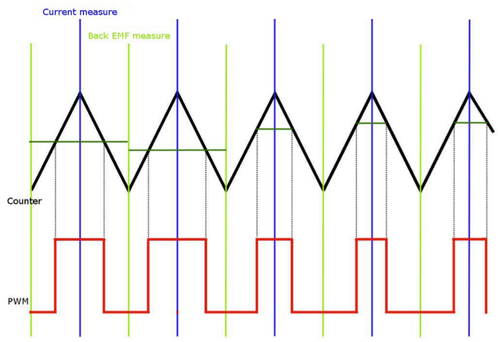

Fig. 7. PID control loop signals.

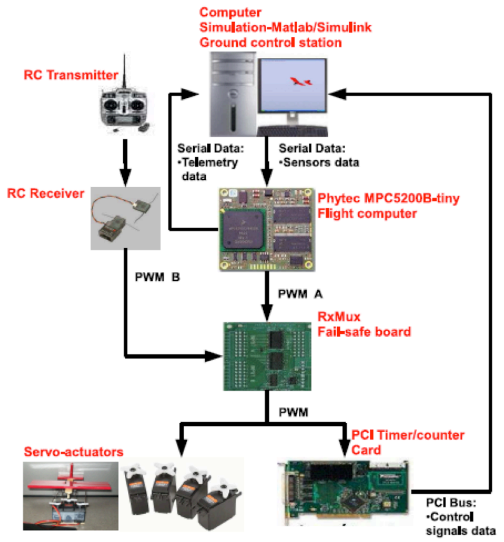

Fig. 8. Hardware-in-the-loop setup for UAV development.

important to note, that back EMF is always measured in the middle of the low PWM level, to reduce the transient effects.

The ultimate goal of the research is to use the actuator onboard the development UAV [Bauer et al. 2011], but before flight testing, the unit has to prove it performance and reliability. A hardware-in-the-loop test environment is used to test the FCC and the implemented control system (shown in figure 8). In its original form the PWM signals generated by the main FCC are sent back to the aircraft simulation via a PWM capture card and the actuator dynamics are omitted from the simulation. However, with the current simulation setup the real actual position of the actuator, along with other measurements useful for health monitoring, are sent back to drive the aircraft dynamics providing a more realistic simulation. As expected, the system responds slower to commands when the actuator model is in the loop, and creates significant lag in the closed loop, but since the actuator is present in the real world experiments, the control system has to be able to cope with the performance degradation introduced.

Experimental results are shown in figure 9, where a square wave signal is tracked with 12.5 deg amplitude. The steady state error of the control loop is non-zero, due to the lack of integrator inside the loop and the time constant of the actuator is also below the expectations, since the control loop update frequency of 250 Hz is not adequate for the task. Further experiments with 50 deg amplitude square wave signals show the ability of the system to

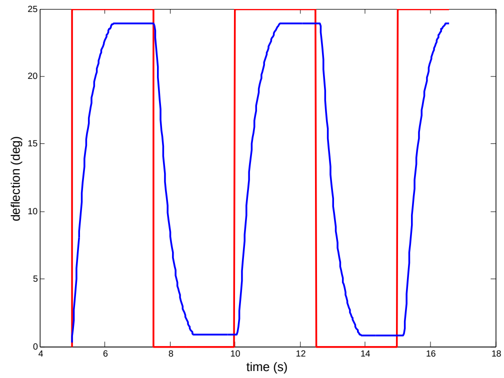

Fig. 9. Square wave reference tracking with 12.5 deg amplitude, experimental results.

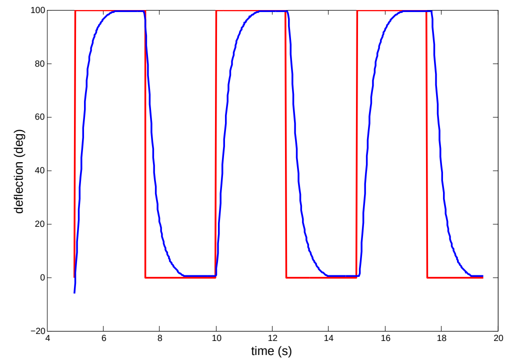

Fig. 10. Square wave reference tracking with 50 deg amplitude, experimental results.

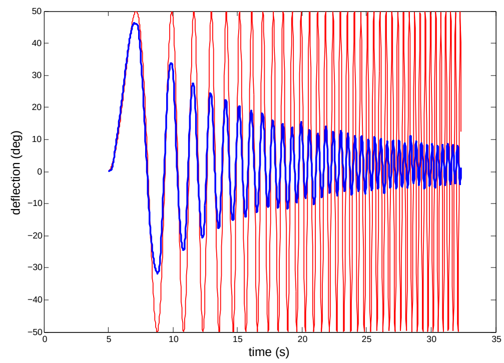

Fig. 11. Chirp signal reference tracking $(0.01 - 2Hz)$, 50 deg amplitude, experimental results.

track larger magnitude signals with similar steady state error (fig. 10), hence the offset might be due to sensor calibration error. Examining the time domain data of the experiments, suggest that for smaller commands faster response is achievable, since there is no sign of saturation in the experiments. To evaluate the frequency domain characteristics of the servo, an experiment with chirp reference signal is performed. The sequence is 20 seconds long and the frequency is changing from 0.01 to 2 Hz. It is clearly visible on figure 11, that for higher frequencies the gain of the system drops significantly below unity, hence in the current form the servo is not suited for implementation onboard the aircraft.

4. CONCLUSION

The present article discusses the development of a smart actuator used on a small scale UAV. The newly developed servo unit builds heavily on the mechanical components of a COTS RC servo unit, but its electronics an software are custom designed for the purpose of a fault-tolerant safety critical avionics system. The reasons behind design decisions are discussed and the development steps are detailed in the article, followed by experimental results done on a hardware-in-the-loop test facility. The future steps should include the characterization of dominant fault modes of the actuator, along with determining the reliability figures of the units including mean time between failures and evaluation of the performance of the onboard health monitoring unit (true detection rate, missed detection rate, false alarms).

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