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Design and Implementation of Supervisory Wireless Control: Aircraft Braking System Case Study

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***Abstract*—**There is an increasing interest in the use of wireless communication for aerospace applications especially for closed-loop control applications. This paper presents the challenges associated with wireless closed-loop control in safety-critical aerospace applications. It also highlights the potential advantages of a fly-by-wireless system. A case study of the design and implementation of a wireless feedback control system for an aircraft electric braking system is presented. A sensorless supervisory control approach is proposed for a wireless aircraft braking system. The developed sensorless supervisory control method addresses the issue of lost data packets in feedback loops, a key challenge in wireless implementations. Finally, the implemented algorithm is tested in real-time using a wireless hardware demonstrator. The effectiveness of the algorithm in real-time is assessed by deliberately introducing packet loss and radio interference.

***Keywords*—**Wireless networked control system, Fly-By-Wireless, Kalman Filter, Packet Loss, Supervisory Control, Sensorless feedback control.

Nomenclature

θ_m	=	Rotor position	(rad/sec)
ω_m	=	Rotor speed	(rad/sec)
i_a	=	Armature current	(A)
V_a	=	Input voltage	(volts)
R_a	=	Armature resistance	(ohms)
L_a	=	Armature inductance	(mH)
J	=	Inertia of the motor	(kg-m^2)
T_L	=	Load torque	(N-m)
T_m	=	Motor torque	(N-m)
T_c	=	Gearbox coulomb frictional torque	(N-m)
B_{gear}	=	Viscous damping co-efficient	(N-m/s)
K_b	=	Brake stiffness	(N/m)
s	=	Pitch of the screw	(mm)
K_t	=	Torque constant	(N-m/A)
K_e	=	Back EMF constant	(V.s/rad)
t_{ca}	=	Time delay between controller and actuator	(sec)
t_{ac}	=	Time delay between actuator and controller	(sec)
n	=	Number of turns on feed screw	
b	=	Damping coefficient	

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I. Introduction

TRADITIONALLY, aircraft flight control systems have relied on hard-wired information flows for monitoring and processing data. There is an increasing interest in the implementation of wireless communications in aerospace applications due to the various advantages that wireless approaches could offer such as flexibility, weight reduction and advanced monitoring capabilities. For instance, Messier-Bugatti has developed a full wireless tyre pressure and brake temperature monitoring system for the A380 and Boeing jets. It uses a wireless link to transmit data from the wheel to the landing gear before being sent to the cockpit [1].

The next engineering hurdle is to examine the feasibility of wireless transmission for feedback control systems in aircraft. There are various control systems and actuators on board an aircraft that could potentially benefit from the use of wireless technology, especially systems that have a significantly complex wiring installation, or that operate in environments where wires are routinely subjected to harsh operating environments and susceptible to physical damage. Aircraft control systems are safety-critical systems as any failure or malfunction could cause injury or death, as well as result in environmental harm and cause damage to equipment. Over the past decade, considerable research [2],[3] has been undertaken to identify the issues and possible solutions for implementing wireless for real-time and safety-critical control applications. Implementing wireless technology in closed-loop real-time systems poses significant research challenges.

A wireless networked control system (WNCS) is defined as a control system where sensors, controllers and actuators are placed in a distributed environment and connected through a real-time wireless network. WNCS is a wide research area that has been studied extensively in the past with respect to stability of the control system, network reliability and control strategies, to name but a few [4],[5],[6]. From an industrial perspective, substantial work has not been done yet on solutions for wireless real-time control with packet losses in safety-critical flight control applications. However, a few early initiatives taken in this context is presented here.

NASA has initiated key research work in wireless control to explore the possibilities of interlinking different modules in spacecraft through wireless links, interoperability of wireless standards, and reusability of sensors. A test bed has been developed in NASA-JSC [7] that utilises a TI MSP430 micro-controller and radio modules fixed to specific applications correlated to various aerospace needs. In Europe, the WICAS and SWIFT programmes [8] investigated the wireless monitoring of open loop control of skin friction reduction systems. Other industrial work [9] in this area is restricted to wireless sensing and monitoring. The opportunities and challenges for using wireless in safety-critical avionics and a wireless avionics network using ultra wide band (UWB) technology is discussed in [10].

One of the key issues of using wireless in safety-critical systems is link quality. QoS (Quality-of-Service) parameters are used to evaluate wireless network throughput such as transmission delay, data error rates, network congestion, and jitter that can affect the link quality in wireless links. Issues such as external interference and deliberate jamming can affect QoS and cause data packet loss or lost wireless links. It may be possible to provide these missing samples using model-based control [11]. Gain-scheduled approaches, as discussed in [12],[13], can provide stability for variable time delays. However, there is a difficulty in identifying a scheduling parameter that allows gain to be selected for different delays in real-time wireless control systems. Event-based sampling approaches that utilise threshold detection are used to control network congestion as discussed in [14],[15],[16]. However, this approach needs a number of samples to be logged in a local controller so that the threshold values can be determined. Therefore, it may be unsuitable for high dynamical systems. Co-design approaches [17],[18],[19], that acknowledge the interdependence between control and communication parameters have become popular recently. It is shown that, by utilising variable sampling rates, or adaptive sampling rates based on error rate information, network induced delays can be reduced. However, a good model of the wireless network is needed and this is practically not possible in dynamical systems.

Therefore, there is a need for an integrated design for wireless systems that can supervise the real-time control process for deterioration in QoS parameters as well as address the issues such as lost wireless links. Some early research that suggests such integrated design approaches for wireless networked control systems is discussed in [20],[21]. However, there is a need to evaluate such designs for a practical control system, especially in the aerospace domain. Therefore, in this paper, we propose a supervisory control approach for wireless real-time control in an aircraft application. The advantage of the approach is that while a supervisory unit provides the adjustments to the control demands, a local control unit can take control of the critical loops. The supervisory unit ensures the network stability by utilising a sensorless control approach in case of lost wireless links.

In addition, the existing results in this domain lack an experimental evaluation in a real-time wireless embedded hardware platform. Though such work is scarce in the safety-critical domain, early research in the non-critical domain is highlighted here. The effect of sensing and actuation in real-time systems is studied by controlling an inverted pendulum over a wireless network [22]. It highlights the need for new control-based approaches for real-time control in wireless systems. A model reference adaptive system (MRAS) [23] is used to guarantee the network reliability of a wireless feedback loop for water level control in the 433MHz wireless range. Other studies include demonstrating wireless networking in structural control [24] and in real-time data acquisition. While such systems are considered critical, the sensing or sampling is done at long time intervals that are not feasible in aircraft applications.

Another issue that concerns safety-critical flight control systems is the limitation in implementing the existing model-based solutions in aircraft on-board processors due to their computational complexity. The major problem for such solutions is that there are certification requirements for airborne software systems that must be satisfied.

An aircraft's electric braking system [25],[26] is one of the potential applications where wireless links could be of benefit. This is because the aircraft-braking computer that receives input from the brake pedals usually resides in the avionics bay in an aircraft. From there, conventional wiring is used to transmit the information to the controller in the landing gear undercarriage. In addition, many sensors are involved in measuring the position and speed of the brake discs in order to regulate the braking action. By introducing wireless links to transmit the demand signal and the feedback information, a significant reduction in physical wiring quantity, weight and complexity can be achieved. Therefore, in this paper, an approach to the design of a supervisory real-time wireless control for an aircraft braking control system is considered. The contributions of this paper are as follows:

- a discussion of the issues pertaining to wireless real-time control loops in aerospace applications;
- a proposal for a supervisory wireless real-time control approach for an aircraft braking system that also addresses the issue of lost wireless links/packet loss in feedback control loops;
- an evaluation of the proposed approach in an embedded hardware environment by introducing interference deliberately in the wireless feedback loop; and
- tests of the proposed algorithm's suitability for real-time feedback control of a wireless aircraft braking system (W-ABS)

The paper is organised as follows. Section II presents the advantage of fly-by-wireless technology in the aerospace industry. Section III explains the design and implementation of a supervisory wireless control approach for electric aircraft braking system using the Truetime MATLAB/Simulink simulation tool. Section IV discusses the implementation of a sensorless supervisory control algorithm for addressing the issue of data packets loss over the wireless communication channel in a feedback loop. The simulation results are analysed in Section V. In Section VI, the proposed approach is tested in real-time using a wireless hardware demonstrator. The aim is to assess the performance of the proposed algorithm by deliberately introducing packet loss and radio frequency (RF) interference. Conclusions are provided in Section VII.

II. FLY-BY-WIRELESS CONTROL SYSTEMS

At present, aircraft manufacturers use a Fly-By-Wire (FBW) mechanism for communicating between the flight control system and various actuators. It replaces the traditional mechanical linkages that were previously used for sending control signals in aircraft. In a FBW system, control signals, sensor information, demand signals are all transmitted as electrical signals to various modules distributed around an aircraft. However, due to the improvement in health monitoring strategies, the number of sensors used in aircraft engine health monitoring and structural health monitoring has increased over years [27],[28]. Therefore, the use of communication wires for transmitting the sensing information has doubled. This has resulted in a significant increase in the weight and complexity of the aircraft. For example, the Airbus A380 contains 530 km of wire for 525 seats and produces 75g of CO_2 per passenger kilometre. In the cabin, there are over 100,000 wires and more than 40,000 connectors creating many potential points of failure and areas to inspect and maintain [29].

Wiring faults in aircraft have been a major concern in aging aircraft and in maintenance. A report by the flight safety foundation [30] stated that aircraft electrical wiring damage has led to many incidents thus showing how prone electrical wiring is to damage occurring over time or being introduced during maintenance or modification action. Therefore, interest in fly-by-wireless technology is increasing where the control systems, actuators, sensors in an aircraft can communicate over a wireless channel. A wireless approach will result in a significant reduction in cables and wiring on board an aircraft with all of the benefits that this provides. However, there is a need to identify the potential control applications inside an aircraft where wireless communication would offer a significant benefit.

For Uninhabited Aerial Vehicles (UAVs) and military aircraft, wireless sensors can significantly improve their performance by integrating several control modules on board an aircraft and also to communicate with a ground unit in real-time. In addition, a combination of wireless technology and satellite communication enables the ground-based air traffic control to take over a UAV or military aircraft if the flight deck controls become inoperable or incapacitated [31]. Wireless sensor networks also have great potential in the development of intelligent flight control systems (IFCS).

Currently, the aerospace industry uses a variety of data bus protocols to transmit information across various flight control systems. One such protocol is ARINC 825 that is the standardisation of Controller Area Network (CAN) for airborne use that was initiated by the Airlines Electronic Engineering Committee. The two major aircraft manufacturers - Airbus and Boeing - have already accommodated a fully functional CAN network in their A380 and Boeing 787 aircraft respectively for all sorts of communication between flight control computers, engine control and other electrical systems [32]. Recently, there have been initiatives to develop a hybrid network between CAN and wireless protocols for industrial usage. A framework of such a hybrid network is discussed in [33]. A hybrid wireless RF controller area network (CAN) for wireless monitoring and control with energy-efficient self-powered sensor systems has been developed and commissioned by THHINK Wireless Technologies Limited [34].

III. DESIGN OF SUPERVISORY WIRELESS CONTROL FOR ELECTRIC AIRCRAFT BRAKING SYSTEM

The major aircraft manufacturing companies, Airbus and Boeing, have implemented electric braking systems in the A380 and Boeing 787 Dreamliner respectively [26]. This paper describes one step further than this, a case study of the design and implementation of a wireless feedback control system for an aircraft electric braking system.

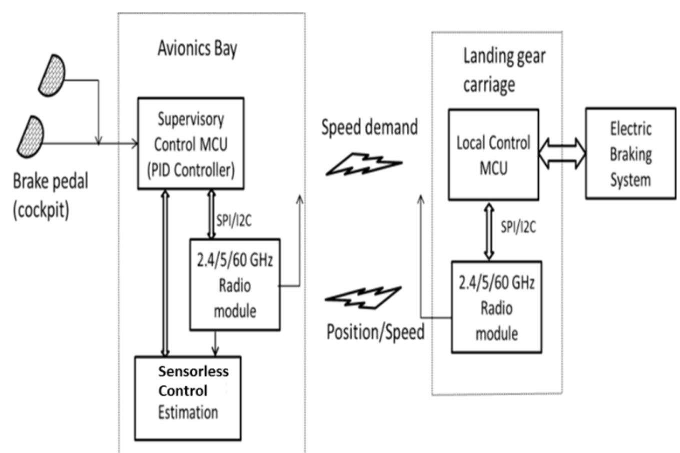

Figure 1 Wireless controlled aircraft braking system

This section explains the design of supervisory wireless control to test the braking performance in an aircraft. The implementation is based on a full feedback wireless control strategy, i.e. both the demand and feedback are sent over the wireless channel. A supervisory unit is used as a master that sends the control demand over the wireless channel to a local control unit. The supervisory unit can be located in the avionics bay in the aircraft. The demand is received from the brake pedal in the cockpit. The local control unit receives the control demand and controls the speed of a brushless DC motor which in-turn actuates the braking discs. The local control unit also computes the speed and position of the braking discs and sends them as feedback information back to the supervisory unit over the wireless channel. **Figure 1** depicts the wireless braking system in an aircraft environment.

A. Modelling of Electro-Mechanical Actuation

The electro-mechanical actuation consists of two phases. The first phase involves the production of rotational motion using a brushless DC motor.

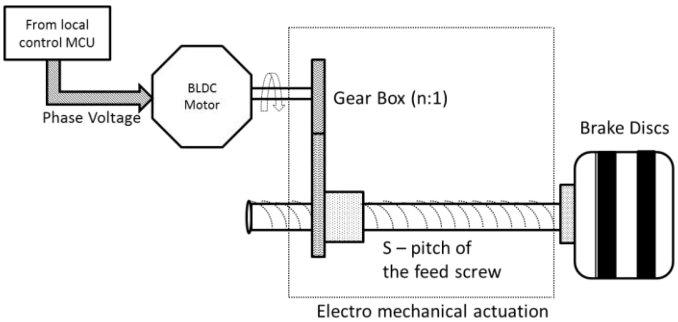

Figure 2 Electric braking system schematic [48]

The second phase then transforms this rotational motion into linear motion that provides the desired mechanical action. This process of converting the rotational motion to linear motion is achieved using a gearbox. An aircraft braking system presents high performance issues and safety concerns. To provide consistent actuation and to avoid skidding the braking must be efficient. Therefore, the coupling mechanism involves both the gearing mechanism and a feed screw coupling to provide the linear motion required. **Figure 2** shows the schematic of an electric braking system in an aircraft.

B. Modelling of Brushless DC (BLDC) Motor

The BLDC motor is modelled as a discrete-time state space model. The system states are $x_1 = \theta, x_2 = \omega, x_3 = i_a$.

Phase Voltage, $$V_a = R_a i_a + L_a \frac{di_a}{dt} + E \quad (1)$$

Electromagnetic Torque, $$T_{em} = J\frac{d\omega}{dx} + b\omega + T_L \quad (2)$$

Rotor Position, $$\dot{x}_1 = \frac{dx_1}{dt} = \frac{d\theta}{dt} = \omega = x_2 \quad (3)$$

Rotor Speed, $$\dot{x}_2 = \frac{dx_2}{dt} = \frac{d\omega}{dt} = \frac{T_{em}}{J} - \frac{T_L}{J} - \frac{b\omega}{J} \quad (4)$$

Rotor Phase Current, $$\dot{x}_3 = \frac{dx_3}{dt} = \frac{di_a}{dt} = \frac{V_a}{L_a} - \frac{E}{L_a} - \frac{R_a i_a}{L_a} \quad (5)$$

Solving (3), (4), (5), the state space representation of the DC motor is given by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{b}{J} & \frac{K_t}{J} \\ 0 & -\frac{K_e}{L_e} & -\frac{R_a}{L_a} \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{J} \\ \frac{1}{L_a} & 0 \end{bmatrix} [V_a \quad T_L] \quad (6)$$

C. Feed Screw Arrangement and Gearing Mechanism

Assuming the energy efficiency of the gear is 100%, the torque on two sides of the gear for a feed-screw drive can be expressed as

$$\frac{T_m}{F_l} = \frac{V_l}{\omega_m} = \frac{x_l}{\theta_m} = \frac{s}{2\pi} = a \quad (7)$$

The gearbox arrangement has been modelled according to the governing equations below. From (7),

Force attained, $$F = x_l K_b \quad (8)$$

The linear displacement of the nut (x_l) is proportional to the nut position (θ_n):

$$x_l \propto \theta_n \qquad \therefore\ x_l = \frac{s}{2\pi}\theta_n$$

The rotor position (θ_m) and the nut position (θ_n) is related by $\theta_m = n\theta_n$,

$$\therefore\ x_l = \frac{s\theta_m}{2\pi n} \quad (9)$$

The torque developed in the nut is proportional to the force output:

$$T_n \propto F \qquad \therefore\ T_n = \frac{Fs}{2\pi} \quad (10)$$

where the rotor torque (T_m) and the nut torque (T_n) is related by

$$T_m = \frac{T_n}{n} \quad (11)$$

Substituting (7), (8), (9) and (10) in (11),

$$T_m = \frac{Fs}{2\pi n} = \frac{x_l K_b s}{2\pi n} = \frac{s\theta_m}{2\pi n} K_b \frac{s}{2\pi n}$$

$$\therefore\ T_m = \left(\frac{s}{2\pi n}\right)^2 \theta_m K_b \quad (12)$$

The brushless DC motor sees the load (braking demand) as a torque requirement. In other words, the motor rotates at its rated speed to achieve the required torque. This required torque to the motor is given as load torque. Therefore, the load torque equation can be given as,

Load Torque, $$T_l = T_m + T_c + B_{gear} \quad (13)$$

Substituting (12) and (13) in (2), the motor speed ω_m can be calculated. The speed along with the rotor position θ_m is sent as feedback data using the Truetime Wireless Network.

D. Truetime Wireless Network

For the simulation model, the Truetime networked control system simulation tool [35] is used to design the wireless network and the controllers. Truetime is a MATLAB/Simulink based simulation tool that can be used to simulate wireless networked control systems. The Truetime kernel is used as the supervisory and local control unit. In order to have a robust control strategy, a cascaded position and speed PID controller is used to decide the control input to the electro-mechanical actuators. The IEEE 802.15.4 radio option is used for wireless transmission. It offers a data rate of 256 Kbps and it is assumed that the network is tightly synchronised for simulation purposes.

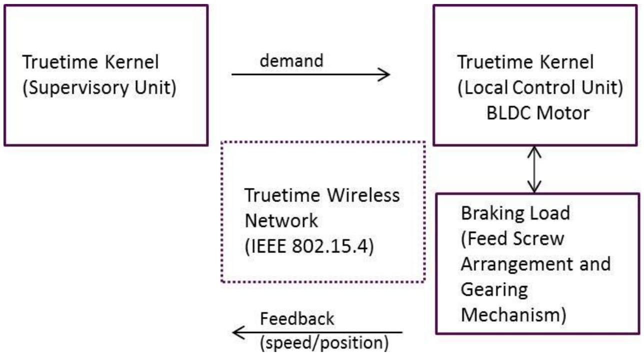

Figure 3 Truetime simulation model

IV. Sensorless Supervisory Control Algorithm

In a safety-critical system such as an aircraft braking control system, the frequent loss of feedback data over the wireless communication channel may induce conditions that may affect the stability of system and may result in dangerous scenarios.

Sensorless control has been an active area of research since the last decade. In the past, this approach has been widely applied to the control of DC and PMSM motors [36],[37]. Utilising sensorless control to address issues in networked control systems [38] is gaining interest in recent years. However, applying them to wireless real-time control is very much at its infancy. Therefore, in this paper, a sensorless supervisory control algorithm based on a Kalman Filter is proposed to predict the feedback data in the case of packet loss in the feedback loop.

A. Discrete Time Kalman Filter

The Kalman Filter is a recursive estimation algorithm that can be used to predict unknown system states, in the case of noisy measurements, based on the underlying system dynamics. It was proposed by Kalman [39] and since its inception, the Kalman Filtering approach has proven beneficial for filtering noisy data in many industrial applications. Application of Kalman Filtering in aerospace applications has been discussed in [40],[41]. Issues such as intermittent observations and partial observations losses arising in wireless sensor networks have been addressed using a Kalman Filter in [42] and [43].

In wireless real-time control systems, the data transmitted and received are discrete in nature. Therefore, a discrete-time Kalman Filter [44] is applied here. The Kalman Filter is used to estimate a discrete-time controlled process that is governed by the following difference equation:

Estimated State, $$x_k = Ax_{k-1} + Bu_{k-1} + m_{k-1} \quad (14)$$

Measurement Data, $$Z_k = Hx_k + n_k \quad (15)$$

where, u_{k-1} is the control input, H is the measurement matrix, m_k is the process noise and n_k is the measurement noise. x_k represents the current state of the system, where k is the current time step. $A_{n\times n}$ represents the state transition matrix and $B_{n\times m}$ represents input matrix (*m* is the number of inputs).

Both the process noise and measurement noise is assumed as a Gaussian, zero mean white noise with normal probability distribution.

The discrete-time Kalman Filter is implemented using a two-step approach [44]. The first step, known as *a priori* state estimation, predicts the system state and the estimation error co-variance for the next time step:

Predicted system state: $$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_{k-1} \quad (16)$$

Predicted error co-variance: $$P_k^- = AP_{k-1}A^T + Q \quad (17)$$

Here $\hat{x}_k^-$ represents the *a priori* state estimate, P_k^- is the *a priori* error covariance estimate, Q is the process noise covariance matrix which represents the uncertainty in the predicted system states. The second step is known as the *a posteriori* estimate or the measurement update. In this stage, the estimated state and the error co-variance are updated using the measurement feedback data. The measured data is weighted using the Kalman gain. The equations are given by:

Kalman Gain: $$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \quad (18)$$

Updated system state: $$\hat{x}_k = \hat{x}_k^- + K_k(Z_k - H\hat{x}_k^-) \quad (19)$$

Updated error co-variance: $$P_k = (I - K_k H)P_k^- \quad (20)$$

The above process is repeated recursively. The time update equations can also be thought of as predictor equations, while the measurement update equations can be thought of as corrector equations. Indeed, the final estimation algorithm resembles that of a predictor-corrector algorithm. The Kalman Filter is a recursive filter and therefore relies on the measurement data for quick convergence. In (19), the difference between the measured data and the predicted data $(Z_k - H\hat{x}_k^-)$ is known as the residual. As long as the measurement is received, based on the discrepancy in the residual, the Kalman gain weights it appropriately and updates the system state. However, as the measurement data is lost frequently, the error discrepancy becomes abnormal. In addition, as Kalman gain depends on the measurement noise covariance matrix R in (18) that is declared initially, the estimated state might exhibit large divergence. Also, if the data is lost for a significant period, then whenever a new measurement arrives, this would result in oscillations in the estimated state.

Kalman Filtering with missing measurements is an active area of research and various solutions have been discussed in [45],[46]. For industrial systems, due to various constraints imposed by embedded microcontroller platforms, some of these solutions are computationally complex. Therefore, in this paper, open-loop Kalman Filtering approach is followed to estimate the system states under packet loss.

According to the open-loop estimation, whenever measurement data is lost, only the first step *a priori* estimate is performed. The *a posteriori* step is skipped in order to avoid the divergence in the estimated state caused by the lost measurement data. Therefore, the Kalman gain is taken to be zero. This result in the system state and error covariance retains its current estimation without affecting them with the lost data. Therefore, under measurement data loss, (18), (19) and (20) become

Kalman Gain: $$K_k = 0 \quad (21)$$

Updated system state: $$\hat{x}_k = \hat{x}_k^- \quad (22)$$

Updated error co-variance: $$P_k = P_k^- \quad (23)$$

As soon as a new measurement is received, the Kalman gain is estimated again, thereby, updating the state and error covariance. It is vital to tune the measurement noise matrix R in accordance with the significance of packet loss. From (18), increasing R would result in a low value of Kalman gain K, and thereby enables the filter to trust its own prediction during packet loss.

B. Theory of Operation

The supervisory unit identifies the lost data packets in the feedback loop as follows. The supervisory unit has an understanding of the round trip delay time t_{rtd} in the wireless network based on the clock synchronisation approach [47].

Round trip delay time: $$t_{rtd} = t_{ca} + t_{ac} \quad (24)$$

Time delay (actuator – controller): $$\therefore\ t_{ac} = t_{rtd} - t_{ca} \quad (25)$$

Real-time control systems have tight deadlines and therefore the feedback data is expected within t_{ac} in order for the control loop to be stable. Whenever the data received exceeds this delay time it is deemed to be a data packet loss. Then the supervisor unit immediately resorts to the Kalman Filter predicted state for that particular time instant. The supervisory unit uses the Kalman predicted states until it receives the next feedback data within the allowed delay time thereby guaranteeing the network stability.

V. RESULTS AND DISCUSSIONS

The wireless braking system performance is tested using an anti-skid braking profile [48]. **Figure 4** shows the anti-skid braking demand profile (solid) and the achieved braking profile (dashed) over the wireless communication channel without packet loss.

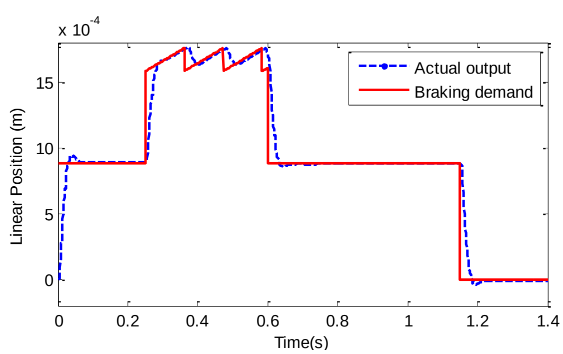

Figure 4 Anti-skid braking position profile [48]

The wireless braking system is then tested by deliberately introducing packet loss into the feedback loop using the Truetime network. The packet loss was introduced from 0.39s to 0.425s and from 0.68s to 0.74s of the simulation time. **Figure 5** shows the braking system going unstable due to the packet loss in the wireless network.

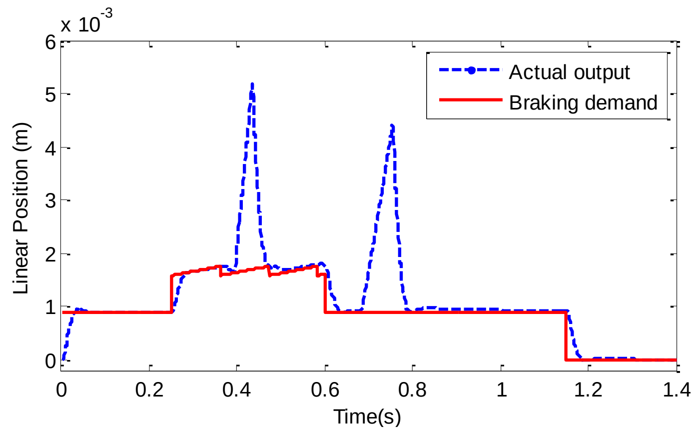

Figure 5 Unstable wireless braking system

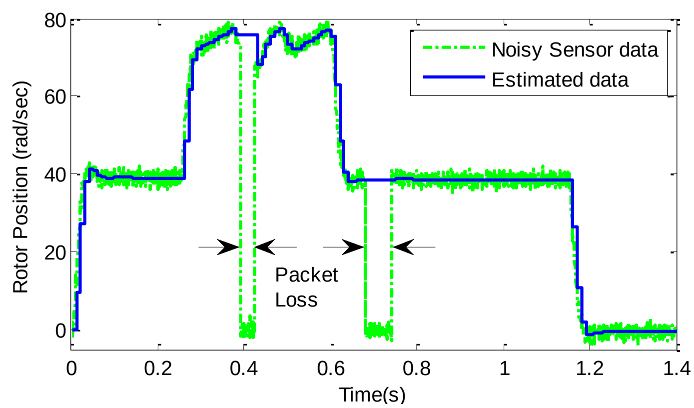

Figure 6 Estimation algorithm performance

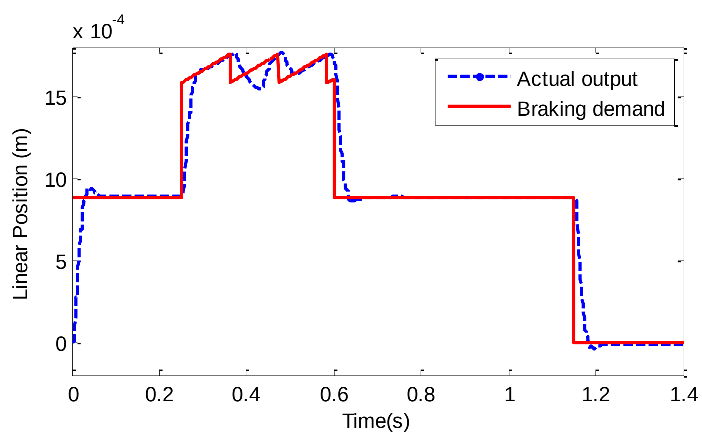

Figure 7 Braking profile under packet loss with sensorless control

Figure 6 shows how the implemented sensorless supervisory control algorithm helps the controller to decide the control demand during packet loss. The dashed plot shows the noisy sensor data. It can be noticed that at 0.4s and 0.7s, the rotor position feedback is lost over the feedback channel. The solid plot shows the rotor position as predicted by the Kalman Filter. It can be noticed that the Kalman prediction due to its open loop nature retains the last predicted value until the next measurement is available. Also, by increasing the measurement noise covariance matrix, R dynamically, the Kalman Filter makes its estimation much closer to the expected demand once a new measurement is available. Once the sensor data is available after the packet loss duration, the controller switches to actual sensor data from the estimator block. **Figure 7** shows the aircraft braking profile under data packet loss with the sensorless supervisory control mechanism. It can be observed that the braking profile is well controlled using the implemented estimation algorithm.

The effectiveness of the approach is analysed using the control demand generated by the supervisory control in **Figure 8**. The solid line shows the control demand input without packet loss. The dashed line shows the large error in the control demand during packet loss duration due to lack of feedback. The thin line shows how the proposed sensorless supervisory control significantly reduces the large error in the control demand, thereby keeping the network stable during packet loss.

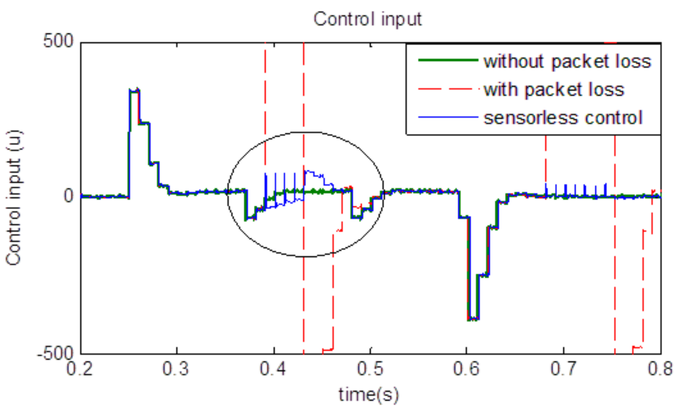

Figure 8 Performance analysis of the proposed algorithm

VI. Hardware Demonstration

This section explains the design of the embedded hardware platform implemented in this research. The hardware implementation is based on a distributed networked control strategy. In order to represent a real-time control system, the speed of a Brushless DC (BLDC) motor is controlled in this experiment. The BLDC motor is a typical component in safety-critical and real-time control systems in the aerospace industry. For instance, in an aircraft environment, DC motors are used in flight controls, braking systems and utility actuation, to name but a few.

A supervisory microcontroller unit is used as a master node that uses a PID controller to calculate the control input based on the user demand. It then sends the control demand over the wireless channel to a local control unit that acts as a slave node. The local control unit receives the control demand and operates a 3-phase inverter and thereby controls a BLDC motor accordingly. Hall sensors are used to estimate the speed of the BLDC motor in real-time. The local control unit sends this data as feedback to the supervisory unit over the wireless channel.

The processor used in the experiment was chosen such that it can handle the motor control algorithm and deal with the radio hardware units for both receiving the speed demand and sending the feedback information. In order to handle such tight real-time demands, the MSP430 series microcontroller [49] from Texas Instruments is used as representative hardware available as cost-efficient, commercially off-the-shelf (COTS) units. TI's CC2500 radio units are used as wireless transceivers [50] in this application and are representative of typical low-power COTS available RF transceiver modules that will operate in the license-free ISM frequency spectrum. The radio follows the direct sequence spread spectrum (DSSS) for modulation and works in the 2.4 GHz frequency band. The RF module is capable of a theoretical peak data rate of 256 Kbps inclusive of overheads. It should be noted that, in this particular configuration, the effective 'payload' data rate is actually closer to a quarter of that claimed figure.

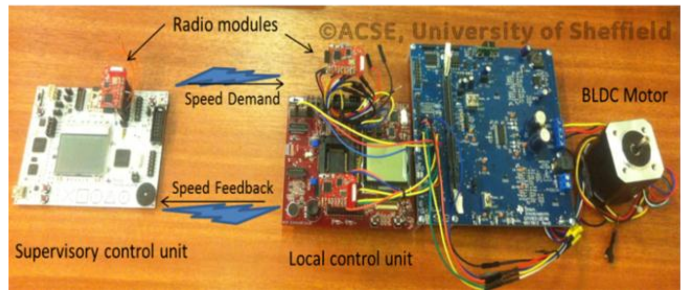

Figure 9 Wireless hardware demonstrator

For this demonstrator, configuration of the low-power wireless network protocol has been examined in detail to optimise its performance and fault-tolerance through systematic link Quality-of-Service (QoS) management. Techniques used in this work include modulating radio output signal strength to address attenuation, data redundancy and error correction techniques to address packet error, message receipt acknowledgement scheme to address lost messages, antenna diversity to mitigate multipath (scatter) issues and frequency diversity to mitigate external interference.

The operation of the wireless control technique has been successfully demonstrated over what might be considered a relatively low-capacity wireless system in this deliberate exercise. This evidence suggests that there is substantial opportunity to maximise the performance of a future system if placed in a position to leverage a high-bandwidth network, operate over a dedicated aero frequency spectrum or with use of a proprietary aero-specific wireless protocol.

The sensorless supervisory control algorithm based on the Kalman Filtering approach proposed in the case study is implemented in the supervisory microcontroller unit along with the PID Controller. Based on the theory of operation explained in Section IV.B, a clock synchronisation accuracy of 1.3 ms is maintained in the wireless hardware demonstrator, thereby maintaining the time delay within a known bound. Therefore, whenever feedback data is lost, the PID controller is supported by the sensorless estimation at that time instant.

Figure 10(a) shows the packet loss observed in the wireless network. The packet loss is observed as an intermittent process where 0 indicates no loss and 1 indicates 100% data loss. For industrial applications, a loss range of (0-40%) is significant. **Figure 10(b)** shows the actual feedback of the motor under packet loss. It can be observed the actual speed of the motor exhibits a large discrepancy from the demand as the packet loss causes significant error in the control output. **Figure 10(c)** shows the received noisy sensor data (dotted line) with packet loss. The packet loss is indicated by sensor data reaching zero. The estimation of speed data by Kalman Filtering is shown by the solid line. It can be observed that the Kalman Filter filters the noisy sensor signal and also predicts the speed whenever a packet is lost in the feedback loop.

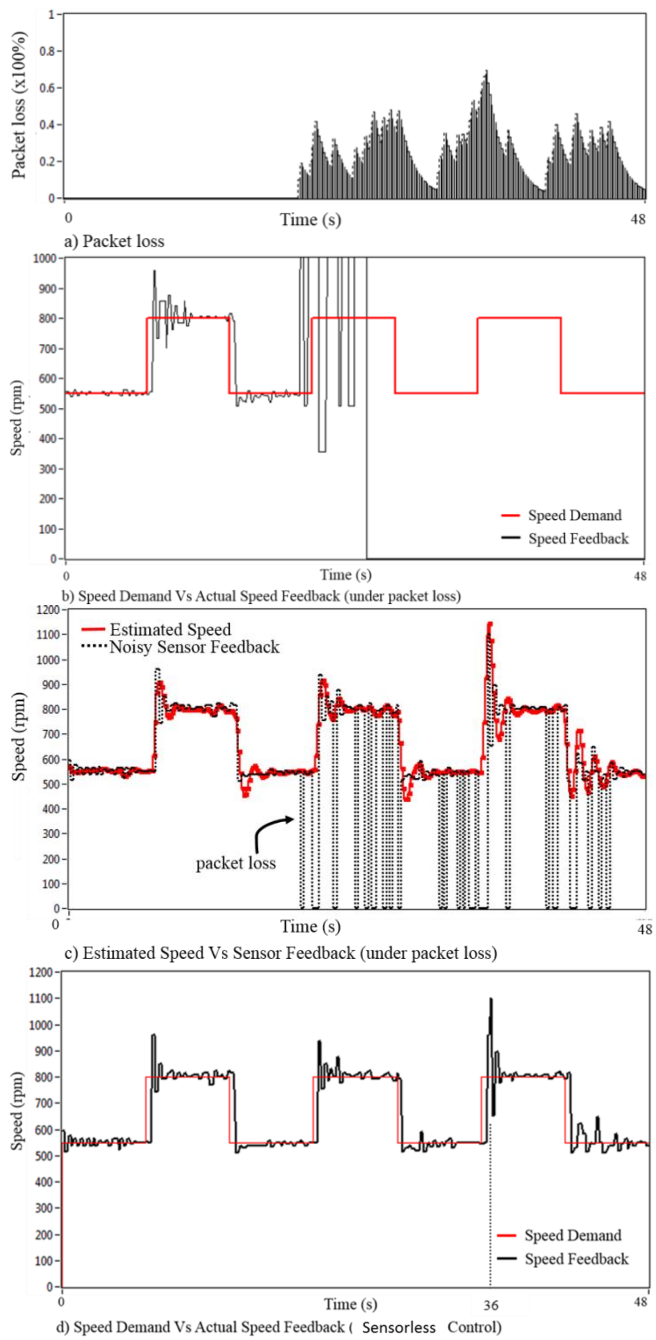

Figure 10 Sensorless supervisory control

Figure 10(d) shows the demand and the actual feedback when implemented with a Kalman Filter. As the supervisory controller is supported by the implemented sensorless control algorithm's estimation during the packet loss, it can be observed that the actual speed of the motor is well controlled even under significant loss in the feedback loop. It can be observed at about 36s, the packet loss reaches 75% and therefore a huge spike is seen in the Kalman estimation. This is typical of open-loop Kalman estimation, as explained in section IV. These overshoots can be minimised by ensuring that the wireless network is synchronised with the overall time delay under a known bound. In addition, as the measurement noise matrix is increased accordingly, the Kalman Filter is able to make its next estimate closer to the demand.

VII. CONCLUSION

There are potential benefits arising from the use of wireless feedback control loops in aerospace applications. Though research has just started for extending wireless services to safety-critical applications, some of the early experiments, as shown here, suggest that there is definite scope for the use of wireless systems in safety-critical and real-time applications. The design and implementation of a wireless aircraft braking system is explained in this paper. A sensorless supervisory control algorithm is proposed to address the issue of data packet loss in the wireless feedback loop. It has been shown that the algorithm assists the supervisory controller in deciding the control demand during packet loss caused by interference in wireless network. Intermittent packet loss causes significant error in determining the control demand thereby rendering the system unstable. The proposed algorithm significantly reduces this error and ensures the reliability of the wireless aircraft braking system. The proposed algorithm is then tested in a practical wireless control loop using an embedded microcontroller platform. The performance is assessed by deliberately introducing packet loss and radio interference. While the results show the effectiveness of real-time control in wireless systems, it is highlighted that there is scope for improvement, as estimated data may exhibit overshoots if the data is lost more than a certain bounded delay in the network. Future research will consider other issues such as deliberate jamming and security in wireless safety-critical systems.

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