Active fault tolerant control applied to REPOINT, a novel railway track switch

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Abstract: Railway networks are fitted with switches and crossings that enable trains to move from one track to another however they present a single point of failure. Existing track switches actuation is performed in the open loop presenting a research gap where closed-loop fault tolerant control can be applied to track switch actuation in order to improve railway network performance. A new railway track switch, REPOINT has been developed at Loughborough University with a new electromechanical design that incorporates actuator redundancy to improve the reliability of track switch operation. This paper looks at the development and validation of a sensor fault detection, identfication and accomodation scheme applied to a detailed non-linear model representing the laboratory scale demonstrator of the REPOINT concept. A residual-based fault diagnosis scheme is developed from the comparison of estimates generated by a bank of observers and output measurements. In the presence of sensor faults, a reconstructed signal from the fault detection algorithm is used to replace the measured signal for feedback control and thus safe switching position control is achieved. The results demonstrate that using a reliable fault tolerant control configuration could increase the availability and reliability of the REPOINT track switch.

Keywords: Fault accommodation; Reconfiguration strategy; Applications and fault tolerant control; reconfigurable control

1. INTRODUCTION

> *"On 10th May 2002, a train travelling from London Kings Cross, United Kingdom derailed at Potters Bar when passing over points 2182A, causing 7 deaths and injuring over 70 people." HSE Investigation Board (2003)*

A railway network is fitted with track switches also known as "points" or "turnouts" that enable railway vehicles to take different routes. The Potters bar and Grayrigg train crashes in the United Kingdom in 2002 and 2007 respectively are examples of implications a track switch failure could have on a railway network (see Gov.uk (2007) and HSE Investigation Board (2003)).

The Office of Rail and Road reported the total asset failure performance in Great Britain from 2008 to 2014 in Dataportal.orr.gov.uk (2013) showing points failures as the largest contributor to failure performance followed by signal failures. There is therefore need to minimise the impact of switch failures.

Existing track switches shown in Figure 2 are an evolution of a single design from the early mining railways in the 1700s as presented by Morgan (2009). Besides incremental changes to the actuation methodology, the same design and operational mechanism has been maintained.

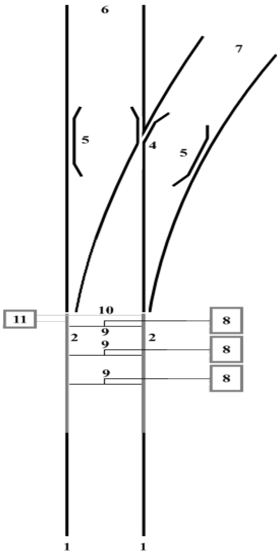

Fig. 1. REPOINT switch

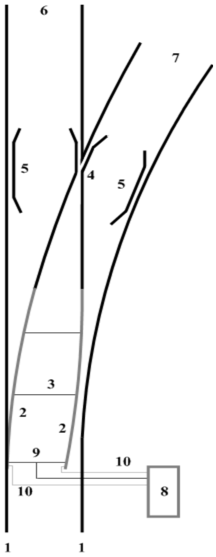

Fig. 2. Traditional switch

1 *Stock Rails*; 2 *Moveable Switch Rails*; 3 *Stretcher Bars*; 4 *Common Crossing*; 5 *Check Rails*; 6 *Straight Route*; 7 *Turnout Route)*; 8 *Redundant Actuators*; 9 *Drive Rod and Linkages* ; 10 *Detection Rods* ; 11 *Blade Position Detection and Feedback Unit*. Figures 1 and 2 are derived

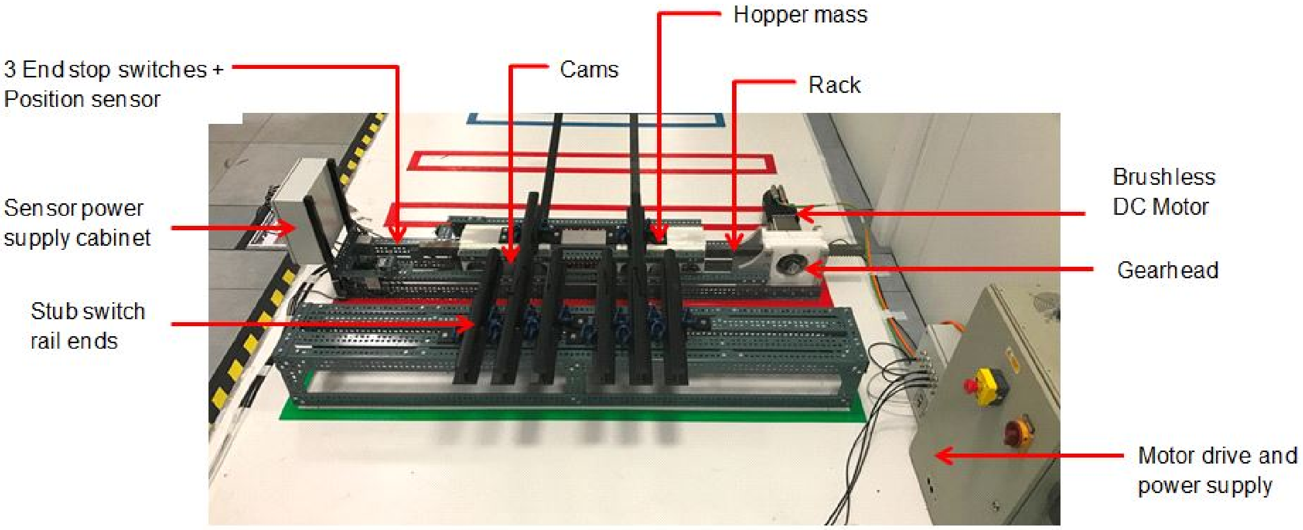

Fig. 3. REPOINT concept laboratory demonstrator

from Wright et al. (2014). Track switch actuation as exists today is performed using open-loop control principles and the system tolerance to sensor faults is non-existent. Track switch operation is described in detail by Hadaway (1950).

A research gap has been identified where tolerance to faults could be applied to railway track switching in order to minimise the impact of track switch failures. A novel patented railway track switch has been developed at Loughborough University called the Redundantly Engineered Point, REPOINT switch with an electromechanical design that offers enhanced reliability and capacity to the railway network shown in Figure 1. More information on REPOINT can be found in Bemment et al. (2017), Bemment (2013), Wright et al. (2014).

REPOINT switch concept is inherently actuator fault-tolerant due to the presence of redundant actuators adopting exisiting methods from safety-critical industries like aerospace and the nuclear indistry. Within a single actuator-bearer on the REPOINT track switch, there is however need to tolerate sensor faults. This paper looks at a sensor fault-tolerant control scheme (FTCS) using fault detection, identification and accomondation (FDIA) algorithms within the switch position control feedback loop applied to the REPOINT concept laboratory demonstrator.

This is the first application of system fault tolerance to sensor faults on the REPOINT track switch and on railway track switch actuation in general. The developed FDIA algorithms have been implemented on a detailed non-linear model of the REPOINT switch laboratory demonstrator to cope with sensor faults.

Reliability can be achieved by two different approaches: perfectness or tolerance. Perfectness refers to avoiding faults and failures whereas tolerance involves trying to contain faults and failures while allowing the system to remain functional, see Isermann (2011). Fault-tolerant control schemes incorporate fault management into the operation of the closed loop system configuration. These schemes are implemented in safety critical industrial systems in order to ensure system reliability and robustness (Alkaya and Eker (2014)). Classical methods of fault detection in the railway industry incorporate limit checking of measurement variables causing system alarms. However, other methods of fault detection could be employed which include using physical or analytical redundancy which is a model-based approach.

In this paper, the analytical redundancy approach is favoured as it is model-based and a validated model representing the system is present. It is particularly useful to detect sensor faults as the loss of a sensor could lead to reduced reliable measurement information causing the system to go unstable if not tolerated. The fault detection approach used is a bank of observers suggested in Clark et al. (1975) and special attention is taken to incorporate false alarm rejection. It is important to note that many of the FTCS concepts work well in theory, however there has been limited industrial application of these concepts.

2. EXPERIMENTAL SET UP

The main operational function of the REPOINT concept laboratory demonstrator shown in Figure 3 is to control the movement of the switch to different track positions.

The set-up consists of a Kollmorgen servo brushless DC motor connected to a gearhead that provides the linear forwards and backwards movement of the rack. This movement is due to the rotational motion of the motor shaft that is coupled to the rack pinion as shown in Figure 4. The cams are connected by the cam pinions to the rack and converts the linear motion of the rack into rotational movement of the cams.

The cams has a follower element, mounted in the form of a hopper mass with stub switch rail ends fitted, that moves

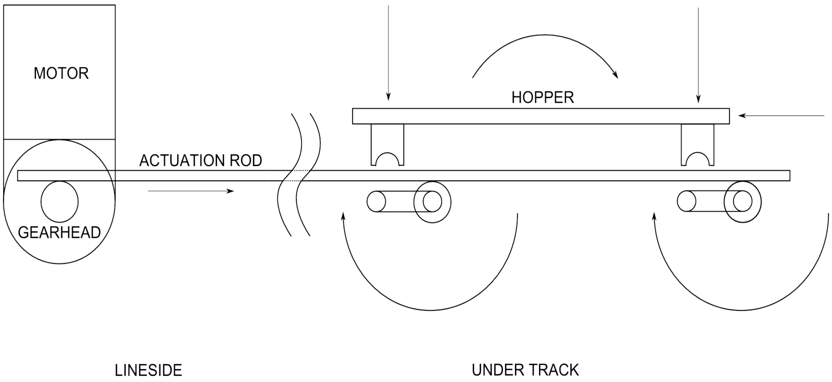

Fig. 4. Diagram showing switching mechanism for the REPOINT switch (Wright et al. (2014))

in an arc pattern as the cams rotates through 180 deg to the desired track switch position. While not being moved, the rails sit on "locking blocks" to ensure there is no movement unless the switch is purposely being moved. All these aspects form the novel innovative apsects of the REPOINT switch.

As this is a concept demonstrator, some aspects of the full REPOINT design are not included such as a rail pair fixed at one end and a bank of three actuators providing actuator redundancy. For the scope of this study, these aspects are excluded in the results gathered in this paper.

MATLAB/Simulink environment is used for model simulations and real time implementation of the proposed fault tolerant control scheme is via a dSPACE 1104 R&D control board and its user interface, Control Desk. The measurement data is transfered to the dSPACE board using a motor velocity encoder for motor velocity; position sensor for rack position and a current clamp sensor for the motor current.

3. ACTIVE FAULT TOLERANT CONTROL SYSTEM (FTCS) DESIGN

Fault tolerant control systems are designed to automatically accomodate system component failures. The three feedback sensors measuring motor current, motor velocity and rack position are used to achieve closed loop position control which can tolerate sensor faults while maintaining the desired control stability and performance requirements. REPOINT sensor faults include: disconnect, noise and drift faults however only disconnect faults are covered in this study. The following five stage FTCS design process in Figure 5 is followed;

(i) Designing a model of the system
(ii) Designing a PI controller for the system with a cascaded outer position, middle velocity and inner most current control loop
(iii) Designing a bank of state observers to estimate the outputs of the system for sensor fault detection
(iv) Residual generation and evaluation in order to flag faults and reject false-alarms
(v) Accomodating the faults within the closed feedback loop

3.1 System Modelling

There are two models used in this study;

- Design model - A linear model used to design the controller and the observer used in the fault tolerant control scheme
- Simulation model - A non-linear model representative of the experimental system used to generate the results herein

Design model: A mathematical linear model of the REPOINT switch is derived from physics first principles analysis of each subsystem. The state space model is used and comprises a reduced third order linear time invariant system. The continuous time state variable equation is described as follows:

$$\mathbf{x}\dot{(\mathbf{t})} = \mathbf{A}x(t) + \mathbf{B}u(t) \qquad (1)$$

$$\mathbf{y(t)} = \mathbf{C}x(t) \times f(t) \qquad (2)$$

with the state vector, $\mathbf{x}$:

$$\mathbf{x} = [i_a \ \theta_m \ x_r]^T \qquad (3)$$

where the state transition, input and observation matrices respectively are:

$$\mathbf{A} = \begin{bmatrix} -Ra/La & -Kv/La & 0 \\ Kt/J_{sum} & D_{sum}/J_{sum} & 0 \\ 0 & R_g/n & 0 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 1/L_a \\ 0 \\ 0 \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (4)$$

The system parameters are detailed in Table 1. The motor load is lumped and it is assumed the total system inertia is a sum of the motor inertia and the reflected intertia in the rack and pinion and cams damping to the motor shaft represented as, J_{sum}. Similarly for the total system damping a similar principle is applied, represented as D_{sum}.

The sensor measurement $y_{sensor}(t)$ may be affected by a sensor fault, $f(t)$. In this paper, sensor disconnect faults are considered and modelled here as multiplicative faults where $f(t) = 0$.

Simulation model: The non-linear model is structurely the same as the linear model, with two non-linearities included in the current, velocity and position. These include; inclusion of maximum limits attainable by the three outputs as exists in the experimental set up and addition

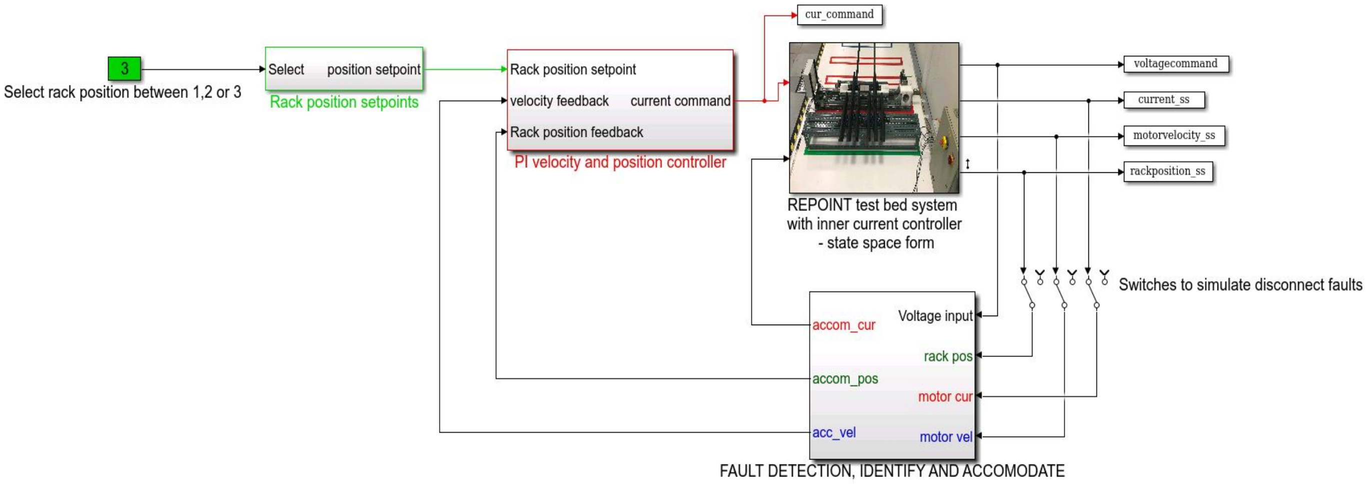

Fig. 5. Simulink diagram of the Fault tolerant control scheme

Table 1. System parameter values

	Parameter	Value	Units
R_a	Rotor resistance	1.97	Ω
L_a	Rotor inductance	0.0079	H
K_v	Back emf constant	0.4899	$Vrms/(rad/s)$
K_t	Motor torque constant	0.8	Nm/A
J_{sum}	Total inertia	0.001	kgm^2
D_{sum}	Total damping	0.01	$Nm/(rad/s)$
R_g	Gearbox pinion radius	0.04	m
n	Gearbox reduction ratio	70	

of representaive noise to the current and velocity measurements that appear on the real sensor measurements.

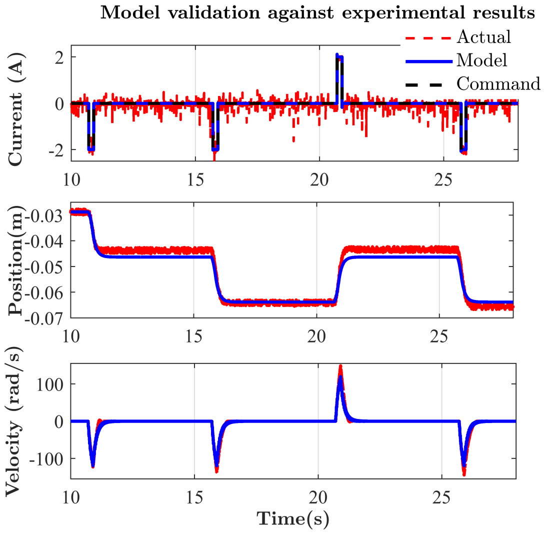

Fig. 6. Model validation against experimental setup

3.2 *P/PI Controller Design*

The objective of the control system is to move the rail pair between different positions associated to the track switch positions. The control objectives for the REPOINT switch are:

- Demanded rack positions at either side of the middle track position
- Settling time within 4 seconds
- Maximum 2% overshoot
- Maximum 3% steady state error
- Gain margin greater than 6dB
- Phase margin greater than 60 deg

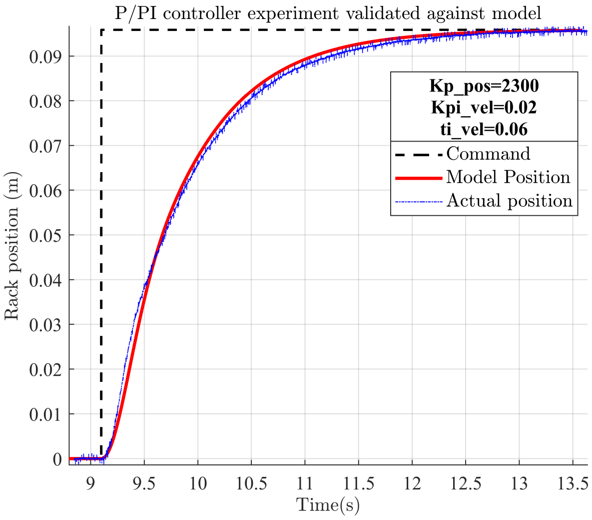

Fig. 7. P/PI controller validation on experimental set up

The inner-most motor current Proportional Integral (PI) controller is inbuilt in the servo motor, the middle loop is a PI velocity controller and the outermost loop is the rack position Proportional (P) controller using the values in Table 2.

The designed controller is validated against the experimental set-up as shown in Figure 7 yielding good results for use of the model as the basis for the FDIA algorithms design.

Table 2. P/PI Controller values

	Velocity control	Positon control
Proportional gain	0.02	2300
Integral time constant	0.06	

3.3 Observer bank design

One method for model-based fault detection is through the use of state observers stated in Isermann (2006). Using the state space model described in Section 3.1, together with the assumption that the structure of the model and parameters are known and all system outputs are measurable, a state observer is designed as follows to reconstruct the outputs of the system from the measurements as described in Isermann (2006):

$$\dot{\hat{x}} = A\hat{x} + Bu(t) + He(t) \tag{5}$$

$$r(t) = y(t) - C\hat{x}(t) \tag{6}$$

However for purposes of observer-based fault detection, all outputs of the system are required to be measurable. The residuals, $r(t)$ are generated for each sensor using dedicated observers driven by the output of each associated sensor that estimates the outputs, $\hat{y}(t)$ and compares against the measured system output $y(t)$. This is particularly useful for fault accomodation.

Pole placement is the observer method used that places the closed loop poles in pre-determined locations for a fast response of the estimator. The poles of the estimator were chosen to have a natural frequency ten times greater than the closed loop poles of the position control system. The poles correspond to the eigen values of the system which control the response characteristics of the system.

3.4 Sensor Fault Detection and Identification

The main aim of this section is to detect a sensor measurement fault on rack position, motor velocity and current based on the assumption that there is no faulty actuator as part of the sensor fault detection and identification scheme. A number of sources cite model-based fault detection methods that use residual error evaluation, these include Patton (1997), Isermann and Rolf (1984), Venkatasubramanian et al. (2003) and Dixon (2004) amongst others. Bennett et al. (2008) also compares a number of residual evaluation approaches. In this paper, the RMS error evaluation method used by Dixon (2004) is used in the fault detection and identification steps.

For each of the three sensor measurements, the detection method uses the models to generate residuals. The root mean square (RMS) value of the residual error over a moving window of N samples is derived as shown by;

$$r_{RMS} = \sqrt{\frac{\sum_{i=k-N}^{k} -r^2(i)}{N}} \tag{7}$$

where $r(k)$ is the value of the residual at the current sample time taken at the kth sample.
The RMS errors from each observer bank are then compared with two tolerance/threshold levels for exceedance.

The first upper tolerance is a fixed threshold value, T_f determined by considering the maximum error values reached by each of the output measurements over a range of tests.

The second lower tolerance is an adaptive tolerance, T_a which is a function of the motor input voltage. The main purpose of which is to reject false alarms by persisting fault flags till the algorithm is sure the fault is no longer present.

Fault flags are activated once the fixed tolerance is exceeded and reset once the residual error RMS is less than the adaptive tolerance indicating the fault has disappeared.

This two stage threshold logic check assists in minimising the false alarm rate whilst allowing for a high sensitivity to faults.

3.5 Fault accomodation

A fault tolerant scheme would not be complete without the ability to accomodate the fault ensuring the system continues to operate in the presence of detected faults.

The accomodation of the faults is enabled by using the observers not associated with the faulty sensors to generate an estimate of the faulty sensor. This fault accomodation scheme together with a robust control design using high gain and phase margins allows for closed-loop stability of the system.

It is important to note that in the presence of a position fault, the velocity observer is initialised to the last known good position. As the position variable is not immediately observable without knowledge of the last known position the system was in, this is a required step.

4. SIMULATION RESULTS

4.1 Position sensor disconnect fault

The position sensor could become unable to measure position on the REPOINT switch giving a zero sensor reading due to poor installation. The results in Figure 8 represent the operation of the system with a position sensor fault injected and FDIA enabled. At 2 s, the position sensor is set to zero (disconnected). Later at 9 s, the position sensor is reconnected. The detection algorithm raises a fault within 1 ms of the fault occuring.

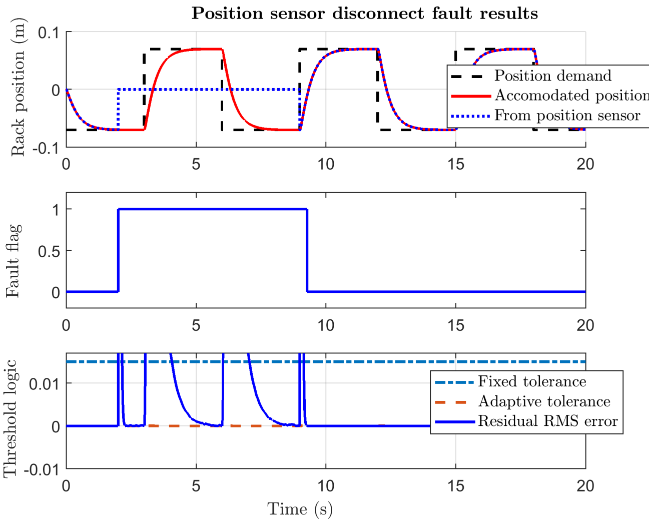

Fig. 8. Position sensor disconnect fault results

The residual RMS error is compared against two tolerance levels where the fault flag is activated as soon as the fixed tolerance level is exceeded. The fault flag persists till the fault disappears and the system only returns to a fault-free state when the position measurement signal is relatively active. The system achieves this by using the second adaptive tolerance threshold shown in the lower plot labelled threshold logic. This adaptive tolerance changes as the input voltage to the motor changes. The residual RMS error is also seen to vary in the first plot of Figure 8 and is lowest when the accomodated position closely matches the position sensor measurement.

4.2 Current and velocity sensor disconnect

Another experiment is performed to test the fault detection and accomodation of the system in the presence of two sensor faults: velocity and current sensors. These sensors on the REPOINT switch could become faulty due to accidental disconnect of the sensor during maintenance or faulty electric citcuitry wiring. Undoubtedly, this failure occuring without accomodation could lead to catastrophic system damage.

The test carried out involved the following: At 3.8 s the current sensor is disconnected and at 6 s the velocity sensor is disconnected. Both sensor readings are unavailable for a few seconds. At 13 seconds, the velocity sensor is reconnected followed by the current sensor at 16. Two fault accomodation scenarios are tested; In Figure 9 the fault occurs when the FDIA scheme is not enabled while in Figure 10 the FDIA scheme is enabled.

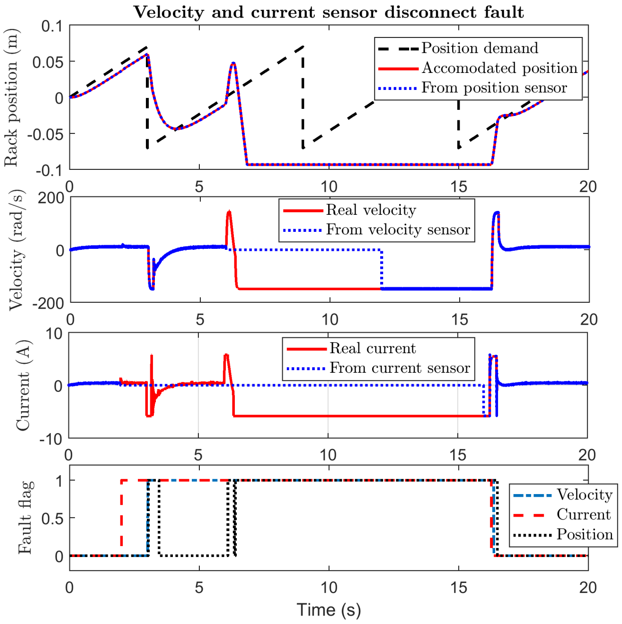

Fig. 9. Current and velocity sensor disconnect faults not accomodated

Figure 9 depicts the event in which the velocity sensor and the current sensor faults are not accomodated. At 3.8 s the current fault flag is raised and the system is still able to cope with accomodating the current signal due to the robustness of the control design. As seen, the demand positon is still followed in the first plot as seen in the first plot of Figure 9. However, a few seconds later at 6 s, a velocity sensor fault is injected and the motor current and velocity signals are seen to operating at their maximum limits. This scenario occuring could lead to significant damage of the switch.

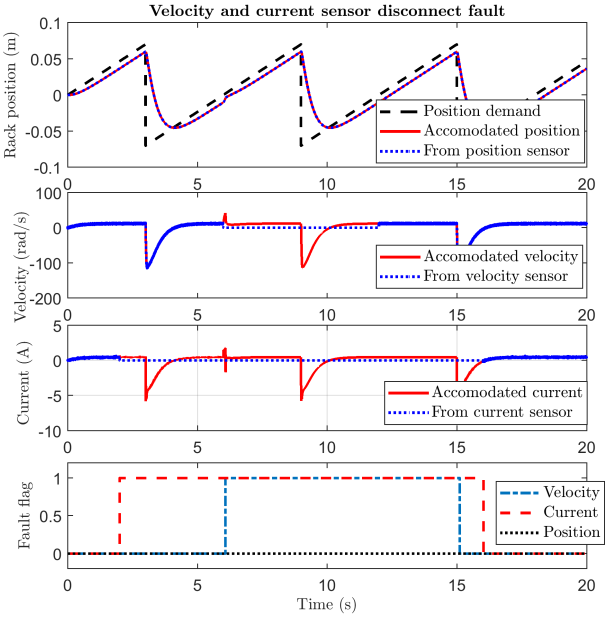

Fig. 10. Velocity and current sensor disconnect faults accomodated

Figure 10 shows that at 3.8 s the current fault flag is raised and a few seconds later at 6 s, a velocity sensor fault is injected, the analytical signal generated by the fault detection algorithm replaces the faulty current and velocity measurement signal and the system continues to operate as shown where the demanded position is followed closely as per the controller specifications. Once the velocity and current fault dissappears and the fault flag is disabled, the system reverts to using sensor measurement signals in the feedback loop. This shows that with FDIA enabled for both current and velocity sensor faults, the system is capable of operating with almost unnoticeable deterioration to the position control achieved within the feeback loop.

5. DISCUSSION AND FUTURE WORK

The design of observers using pole placement requires a careful trade-off between selecting a high observer gain that more accurately estimates the system output but is sensitive to noisy measurement versus a lower observer gain that has a less accurate estimate but is less sensitive to noise on the output measurements. A non-linear simulation model subject to noise on the sensor measurements was used to test the FDIA scheme and presents a good representation of the real system as the non-linear model has been validated against the experimental system.

As satisfactory simulation results have been derived, in future it is intended that this fault tolerant scheme will be tested on the real experimental set up. However the author anticipates that the application of this FTCS scheme in practice will accomodate the faults as there is a validated model of the experimental system. If any changes are required, there will almost certainly be slight changes to the tolerance levels and observer gains used in simulation.

Further investigation of FDIA methods are to be looked into as part of this PhD project including comparison of additional residual generation methods such as the parity equation method and sliding mode observer to the observer bank approach. Additive sensor faults will also be evaluated such as drift and noise faults that may also occur on the experimental system. In addition, using different observer schemes like the Kalman filter to analyse performance of the observers in the presence of sensor noise compared with the pole-placement method.

6. CONCLUSION

This paper has described the design, development and validation of a FTCS scheme applied to a detailed non-linear model of the REPOINT laboratory demonstrator. Different combinations of sensor disconnect faults have been considered, which could occur in an instrumented REPOINT full-scale switch in track. Using the observer based fault detection scheme and a tolerance based isolation of the faults fed back into the control loop, the sensor faults have been detected and accomodated. This FTCS approach was chosen mainly because of its simplicity with the observer design and easy intergration into the exisiting PI controller design. The reconfiguration of the control loop using the analytical FDIA signals lends benefit to the REPOINT switch providing safety-critical performance whereby switching operation continues even in the presence of a sensor fault.

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