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Event-based Hierarchical Control for Power Flow in Vehicle Systems*

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Abstract— **An event-based hierarchical control framework is presented for the control of power flow in vehicle systems. With multiple systems and subsystems interacting over a wide range of timescales, the control performance of vehicle systems can be significantly improved using hierarchical control which directly accounts for interactions among these systems and timescales. However, time-based hierarchical control is highly susceptible to unknown, unanticipated disturbances and faults due to the slow update rates of upper-level controllers. Vehicle systems in particular need the ability to quickly respond and reject the effects of these faults and disturbances. Therefore, an event-based triggering approach is presented, allowing controllers to update in response to a fault instead of waiting for the next time-based update. Results based on a simulated aircraft system show that event-based hierarchical control can significantly reduce the effect of these faults.**

I. INTRODUCTION

Model-based hierarchical control has been proposed to achieve superior control performance in modern advanced vehicle systems such as aircraft and off-road vehicles [1][2]. These vehicles are a heterogeneous mix of complex interconnected systems of various energy domains which require coordinated control efforts in order to maximize the capabilities of the overall vehicle. In addition to power flow of various modalities, such as electrical, mechanical, thermal, and hydraulic, these systems interact over a wide-range of timescales from the sub-milliseconds dynamics of an electrical system to the minutes timescale of the thermal dynamics of a fuel system. Hierarchical control, with multiple levels of control acting at different update rates while coordinating control decisions through communication among controllers, is uniquely well suited to achieve the increasingly high control requirements imposed on these vehicle systems.

Due to the passive nature of these power systems, unlike many control applications, stability is not the primary concern when developing a control strategy. Performance, however, is critical. Due to the long service life of many advanced vehicle systems, these systems are often tasked with operating well outside their initial intended design space. In the absence of system redesigns, the control system is tasked with improving vehicle capability, including increasing range, maximizing system operation duty-cycles, and expanding the overall operating envelop. With the ability to directly coordinate the actions of multiple systems and subsystems over multiple timescales, hierarchical control has the potential to significantly increase the capabilities of these vehicles.

In recent years, hierarchical control has been proposed to solve a number of practical control problems where multiple timescales and multiple interacting systems limit the performance of conventional control frameworks. Hierarchical model predictive control (MPC) has been used to control integrated wastewater treatment systems [3], drinking water networks [4], and multi-source multi-product microgrids [5]. In each of these applications, the hierarchical controller is designed and implemented based on the decomposition of the overall system using a combination of functional, spatial, and temporal partitioning. By directly accounting for the interactions among systems and timescales, hierarchical control effectively and efficiently met the performance requirements of each of these complex systems.

In addition to high performance requirements, vehicle systems face unanticipated disturbances and faults during operation. With an aircraft system, for example, these faults can include overheating in the electrical system due to a short, reduced heat transfer in the thermal system due to a pump failure, or reduced effectiveness of a heat exchanger due to fouling. Often these vehicles do not have the option of shutting down in reaction to such disturbances and must continue operating while attempting to minimize the effect of the fault. Thus a hierarchical control framework must be capable of estimating the presence of faults and making control decisions to mitigate their effect.

One of the main features of a hierarchical control framework is that the lowest level controller can be designed with very fast update rates. These controllers determine inputs only for a small portion of the overall system and only require a small prediction horizon, relying on upper-level controller to provide effective state-trajectories to follow. This results in relatively small optimization problems which can be solved quickly, or even pre-computed offline and implemented as a look-up table [6]. This fast update rate allows the lower-level controller and thus the overall hierarchical controller to have exceptional high-frequency disturbance rejection. However, in the case of large, persistent faults, these lower-level controllers are still required to follow reference trajectories determined by upper-level controllers. Due to the slower update rates of these upper-level controllers, these reference trajectories will be outdated and no longer optimal in the presence of the

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fault until the next upper-level control update which may not be for several seconds or minutes depending on the application. Thus, despite the fast update rate of the lower-level controllers, the overall hierarchical controller is highly susceptible to unanticipated disturbances and faults.

This paper presents an event-based hierarchical control approach to improve control performance of hierarchical control in the presence of faults. In addition to regular, time-based control updates, this approach has the ability to trigger an event in reaction to the detection of a fault. When an event is triggered, upper-level controllers begin to recalculate control decisions based on current state and fault estimates instead of waiting until their next time-based update. Adding event-based control capabilities increases the fault rejection capabilities of hierarchical control, making this control approach better suited for meeting the demanding control requirements for advanced vehicle systems.

The remainder of this paper is organized as follows. Section II addresses the passivity of these power flow systems, where control performance becomes the main objective. The proposed hierarchical control framework and controller triggering strategies are presented in Section III. An aircraft example system is presented in Section IV followed by the graph-based modeling and controller development in Section V. Section VI discusses the potential control improvements of an event-based strategy. Finally, Section VII presents the design of a fault estimator and event-triggering strategy, optimized to maximize the performance of an event-based hierarchical controller.

II. Passivity of Power Flow Systems

This work aims to use hierarchical control to optimize the power flow throughout complex vehicle systems to maximize their capabilities. These power flow systems satisfy conservation equations, such as conservation of mass and energy. Because of this, a common approach to modeling these systems is to develop equivalent resistor-capacitor (RC) networks and graph-based frameworks to capture the relationships between states and power flows in the system, as is done for building thermal systems in [7] and [8]. In fact, [7] shows that systems modeled using these RC networks are passive, satisfying

$$\dot{V} \le u^T y, \tag{1}$$

where u and y are inputs (e.g. power flows) and outputs (e.g. temperatures) of the system and V is a continuously differentiable storage function which can be taken to be $V = x^T C x$, where x and C are the states and capacitances of the system. This passivity implies robust stability as discussed in [9] and [10].

Therefore, while stability of hierarchical control has been the focus of previous work (e.g. [11] and [12]), when applied to power flow in vehicle systems, the main focus of hierarchical control design and evaluation pertains to maximizing control performance in the presence of both known and unknown disturbances and faults. This work introduces an event-based hierarchical control approach to better respond to unknown, unanticipated faults.

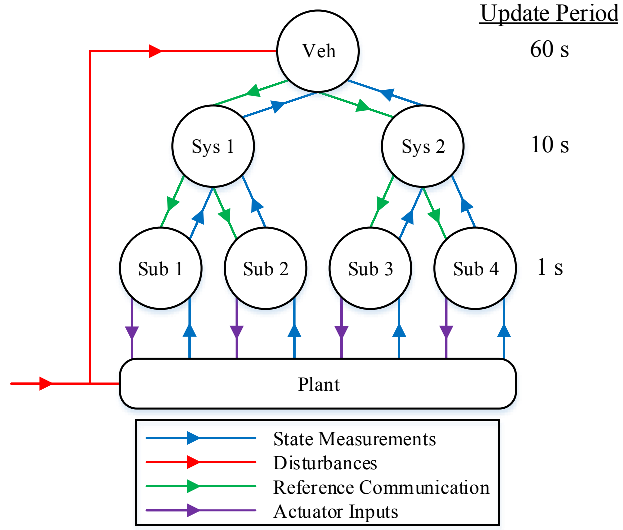

Figure 1. Three-level hierarchical control framework for a vehicle with 2 systems each containing 2 subsystems.

III. Hierarchical Control Framework and Triggering Strategies

Fig. 1 shows an example of a three-level hierarchical MPC-based control framework with a single vehicle-level controller at the top, two system-level controllers in the middle, and four subsystem-level controllers at the bottom of the hierarchy. In this framework, each controller determines the desired state trajectories for the dynamics at the corresponding timescale while attempting to track desired state trajectories for slower dynamics sent down from the controller one level above. The controller also determines the desired power flow throughout its corresponding section of the overall system and communicates the desired power flows and state trajectories to the controllers one level below. Additionally, the highest level controller receives preview information of upcoming disturbances and the lowest level controllers determine the necessary actuator inputs to achieve the desired power flows.

The standard hierarchical control framework utilizes time-based control updates with fixed update periods as indicated in Fig. 1. Fig. 2 compares this time-based hierarchical control update scheme for a three-level hierarchical controller with the proposed event-based approach. At time $t = 0$ s, stored references (green arrows) and control inputs (purple arrows) are passed down the hierarchy and measurements of the current state (blue arrows) of the system are passed up the hierarchy. At this point all controllers start to solve their respective optimization problems. The solution of this optimization is then passed down the hierarchy as either a reference or control input, depending on the level in the hierarchy. However, in the case of a fault (red X), the time-based hierarchical control framework must wait till the next scheduled control update to receive an estimate (brown triangle) of the fault and then wait the length of the update period (ΔT_{sub}, ΔT_{sys}, or ΔT_{veh}) before a new solution (blue circle) can be applied. This introduces a significant delay in response to this fault.

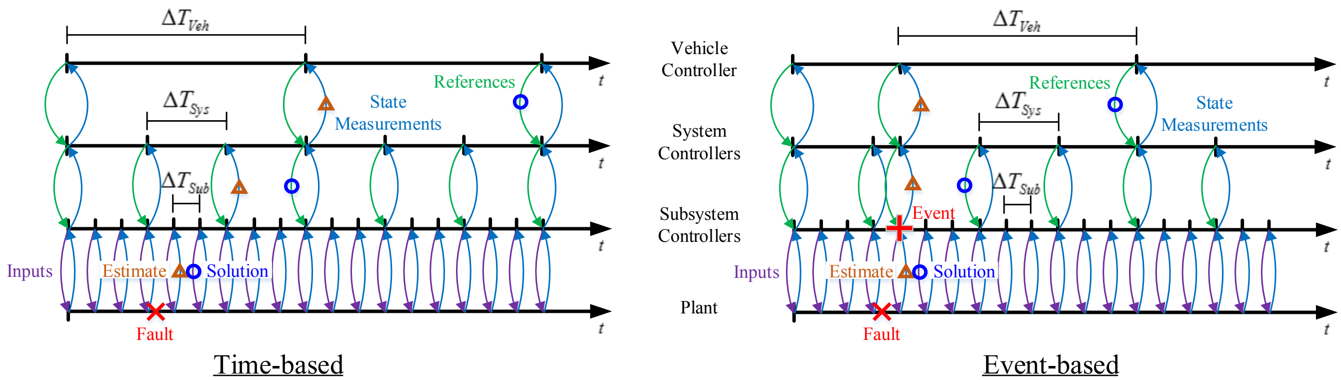

Figure 2. Comparison of time-based and event-based controller triggering of a three-level hierarchy in response to a system fault.

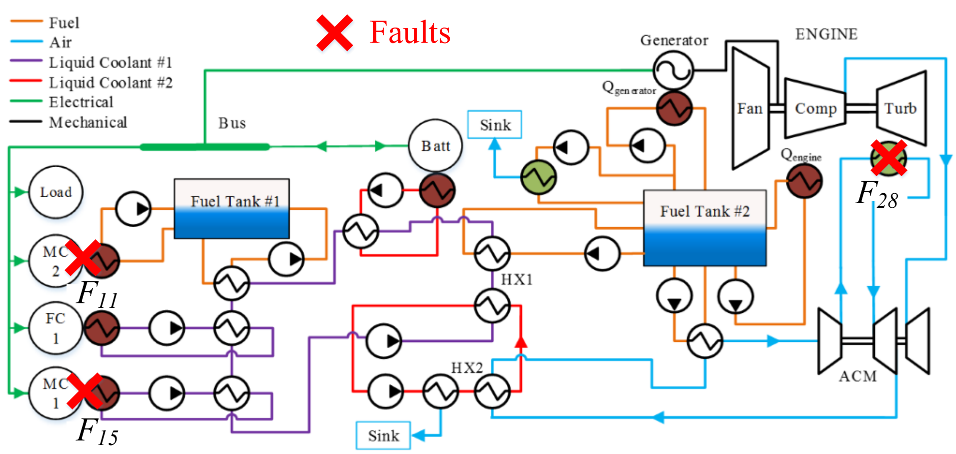

Figure 3. Aircraft example system schematic with three fault scenarios identified.

Alternately, an event-based hierarchical controller has the ability to trigger an event in response to a fault. When an event is triggered, the computations of the upper-level controller are aborted, because their solution would likely no longer be applicable to the system in the presence of the fault, and a new computation is initiated with the current state and fault estimates. As seen in Fig. 2, this can significantly reduce the time between a fault and the appropriate coordinated solution response.

While modifying a hierarchical control framework to accept event-triggered control updates is rather trivial, the decision of when to trigger an event is not. Ideally, the presence and magnitude of a fault could be identified and an event triggered immediately. However, in practice, faults are difficult to identify and require estimation. Based on the aircraft example system architecture presented in the next section, the remainder of the paper addresses the relevant design aspects of estimators to identify faults and how to trigger events based on this estimation.

IV. Aircraft Example System

The example aircraft system, originally presented in [2] and shown in Fig. 3, is used to develop and analyze an event-based hierarchical control strategy. Three different fault scenarios are analyzed which represent additional power draw and heat generation in two different electrical loads, mission critical (MC) loads 1 and 2, and the failure of a bypass heat exchanger used to reject heat from an air cycle machine (ACM) to air in the bypass duct of the engine. These faults are designated F_{15}, F_{11}, and F_{28} based on the corresponding edges of a directed graph used to model the system found in [2].

V. Modeling and Control Development

As in [1] and [2], dynamics of vehicle system are represented using a graph-based modeling framework where vertices represent capacitive elements and edges represent power flows. The directed graph $G=(V,E)$ represents the structure of the dynamics with the set of N_v vertices $V=\{v_i\}, i\in[1,N_v]$ and the set of N_e edges $E=\{e_i\}, i\in[1,N_e]$. Each directed edge is defined by its corresponding tail and head vertices $e_i=\left(v_i^{tail},v_i^{head}\right)$, where power flows from the tail vertex v_i^{tail} to the head vertex v_i^{head}. The power flow along edge e_i is denoted P_i with a corresponding control input u_i. Each of the $N_d \le N_v$ dynamic vertices $v_i \in V^d \subseteq V$, has an associated capacitance C_i and state x_i.

From this graph-based representation, the system $\mathbf{S}$ is defined as

$$\mathbf{S}: C\dot{x}_d = BLP, \tag{2}$$

where $C = diag(C_i)$ are the vertex capacitances, $x = [x_i] \in \mathbb{R}^{N_d}$ are the vertex states, $B \in \mathbb{R}^{N_d \times N_e}$ is a matrix relating power flows to the vertex states, $L = diag(l_i)$ is a diagonal matrix containing each edge effectiveness, and $P = [P_i] \in \mathbb{R}^{N_e}$ are the power flows throughout the system. The effectiveness matrix L is intended to capture the presence of disturbances or faults in the system where power flows deviate from intended. In this work, the following class of faults F_i is considered,

$$F_i : l_i = \begin{Bmatrix} 1 & t < t_{fault} \\ l_i^f & t \geq t_{fault} \end{Bmatrix}, \tag{3}$$

where the effectiveness of edge e_i undergoes a step change from 1 to l_i^f at time $t = t_{fault}$. Due to the often bilinear relationship between control inputs and states found in power flow systems, the power flow along edge e_i is represented as

$$P_i = (u_i + a_i)\left(b_i x_i^{tail} + c_i x_i^{head} + d_i\right), \tag{4}$$

where a_i, b_i, c_i, and d_i are parameters used to capture the relationship between power flow, actuator input, and neighboring states.

To develop an MPC-based hierarchical controller, the system $\mathbf{S}$ is decomposed temporally and functionally and discretized. This decomposition results in the following dynamic representations

$$\mathbf{S^z} : x^z[k_r+1] = x^z[k_r] + \Delta T_r B^z L^z[k_r] P^z[k_r], \tag{5}$$

where $z \in \{veh, sys_1, sys_2, ..., sub_1, sub_2, ...\}$ and

$$r = \begin{Bmatrix} f & z \in \{sub_1, sub_2, ...\} \\ m & z \in \{sys_1, sys_2, ...\} \\ s & z \in \{veh\} \end{Bmatrix}, \tag{6}$$

which represents the fast, medium, and slow update rates of the subsystem, system, and vehicle-level controllers.

Using these models, each controller in the hierarchy solves the constrained quadratic program such as the one formulated in [1]. Note that in these optimization problems, faults are accounted for using an estimate $\hat{L}^z = diag(\hat{l}_i)$ of the effectiveness of each edge. The following sections demonstrate the importance of this effectiveness estimation under both time- and event-based hierarchical control frameworks.

VI. Ideal Event-based Control Performance

As indicated in Fig. 3, three fault scenarios are considered under the class of faults from (3) where F_{11} has $l_{11}^f = 3$, F_{15} has $l_{15}^f = 2$, and F_{28} has $l_{28}^f = 0$, each with $t_{fault} = 61\,\text{s}$. The timing of these faults is chosen as a worst case scenario where the faults occur immediately after the update of the vehicle- and system-level controllers at $t = 60\,\text{s}$.

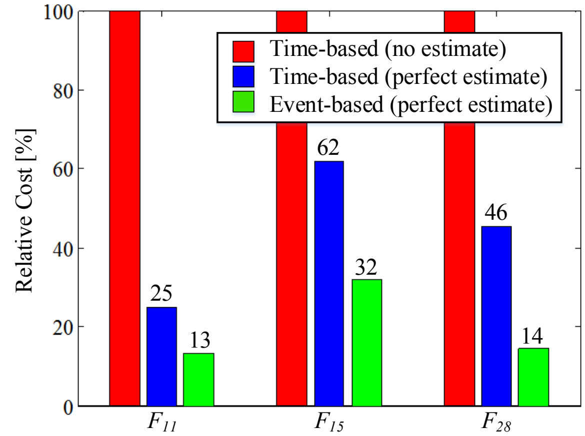

Figure 4. Comparison of relative control cost due to three different fault scenarios using time-based control updates with and without fault estimation and event-based control updates.

To evaluate the benefits of fault estimation and event-based control, the following cost function is used to compare various control performances

$$J = \sum_{k=1}^{T_{sim}} \sum_{i=1}^{N_d} \left(x_i[k] - x_i[0]\right)^2, \tag{7}$$

which penalizes the deviation from initial conditions $x_i[0]$ for each of the dynamic vertices over the course of the T_{sim} second long simulation (perfect fault rejection results in $J = 0$ and larger values of J indicate reduced control performance). For initial comparison, it is assumed that a perfect, one-step estimation of the fault is available, where

$$\hat{l}_i^* = \begin{Bmatrix} 1 & t < t_{fault} + \Delta T_{sub} \\ l_i^f & t \geq t_{fault} + \Delta T_{sub} \end{Bmatrix} \tag{8}$$

and $\Delta T_{sub} = 1\,\text{s}$.

Fig. 4 shows the relative control cost $\bar{J}$ for the time-based hierarchical controller with $\hat{l}_i = 1\ \forall t$ (red bars), and time- and event-based controllers with $\hat{l}_i = \hat{l}_i^*$ (blue and green bars) for the three fault scenarios. While using an accurate estimate of the fault significantly improves the control performance under a time-based control updates, the addition of event-based update provides even greater control performance. The event-based controllers with $\hat{l}_i^*$ represent the lower limit on the relative cost. However, a perfect, one-step estimation of a fault is often unavailable when controlling these systems due to measurement noise and system dynamics. The next section presents the design and analysis of edge effectiveness estimators which attempt to approximate the performance of the one-step estimator by balancing estimation speed and accuracy.

VII. Estimator Design and Event-triggering

The objective of this paper is not to develop novel estimations schemes for estimating edge effectiveness, per se. The authors refer the reader to literature for the design of these estimators [13][14]. However, for any estimation scheme there is a balance between fast estimation and sensitivity to measurement noise. Thus, from an event-based hierarchical control perspective, it is important to understand the tradeoff between fast and accurate estimation and when an event should be triggered based on this estimation. Therefore, for this work it is assumed that an estimator is designed where the edge effectiveness estimation satisfies the following first-order dynamic

$$\dot{\hat{l}}_i = -\frac{1}{\tau}\hat{l}_i + \frac{1}{\tau}(l_i + v_i), \qquad (9)$$

where τ is the time-constant of the estimator and v_i is the measurement noise. For the following analysis it is assumed that v_i has a frequency of $\omega_v = 2\pi/\Delta T_{sub}$ and magnitude $\|v_i\| \le 0.1$. The magnitude of the transfer function

$$\frac{\hat{l}_i(s)}{v_i(s)} = G_i(s) = \frac{1}{\tau s + 1}, \qquad (10)$$

at $s = j\omega_v$ is $|G(j\omega_v)| = \left(\sqrt{1+(\tau\omega_v)^2}\right)^{-1}$. The tradeoff in the choice of τ is shown in Fig. 5 for $\tau = 2$ and $\tau = 6$. If τ is small, the fault estimator rapidly converges to the true edge effectiveness, approximating the one-step predictor $\hat{l}_i^*$. However, the presence of measurement noise v_i corrupts this estimate and thus the actual estimate may be anywhere between the bounds (grey), as shown by the notional estimation (red). Thus, while the estimator converges quickly, the estimates are significantly affected by noise. Alternatively, if τ is large, the noise-free estimation converges slowly but the measurement noise is sufficiently filtered and thus the estimate converges to a smaller neighborhood around the true fault. At this point, it is unclear whether an event-based hierarchical controller benefits most from a fast, but potentially inaccurate, estimate or a slower, more accurate estimate.

As with the tradeoff between estimation speed and accuracy, there exists a tradeoff between reacting quickly and reacting accurately. Independent of the estimator time-constant, it is unclear whether it is better to trigger an event quickly using an inaccurate estimate of the true disturbance or to wait while generating a better estimate. To analyze these tradeoffs, the notion of observation time ΔT_{obs} is introduced where $\Delta T_{obs} = t_{event} - t_{fault}$ and t_{event} is the time an event is triggered. While a large ΔT_{obs} creates a large delay between a fault and the triggering of an event, this delay is used to gather an accurate estimate of the edge effectiveness to be used by the controllers once triggered.

Fig. 6 shows the tradeoff between fast, noisy estimates and slow, accurate estimates by comparing the relative cost $\bar{J}$ over a range of time-constants τ and relative observation times $\overline{\Delta T}_{obs} = \Delta T_{obs}/\tau$ for the F_{15} fault scenario. There exists a well-defined minimum of $\bar{J}^* = 37\%$ at $\tau^* = 2s$ and $\overline{\Delta T}_{obs}^* = 1.7$. Compared to the relative cost of $\bar{J} = 32\%$ for the event-based controller with perfect, one-step estimation,

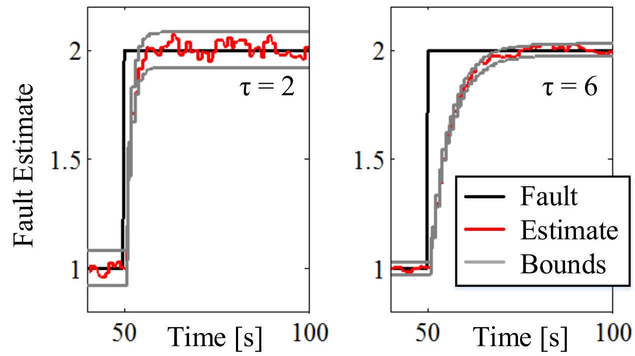

Figure 5. Tradeoff between fast estimation with a small time-constant and slower, less noisy estimation with a larger time-constant.

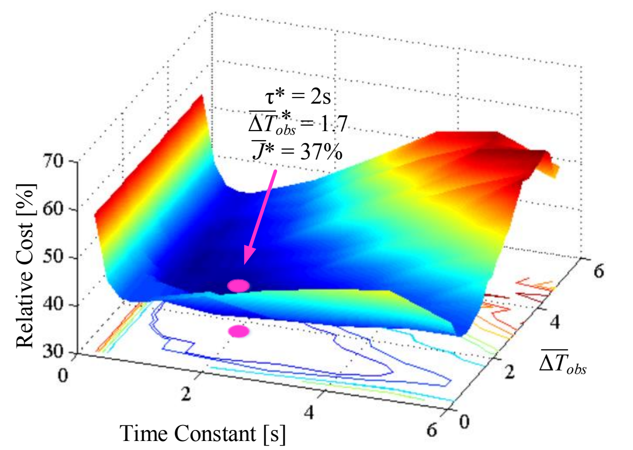

Figure 6. Relative cost revealing an optimal time constant and observation time that balances reacting quickly with reacting accurately.

this minimum shows that a realistic effectiveness estimator has the potential of approximating the performance of the unrealistic one-step estimator. Thus, for this system, the effectiveness estimators should be designed with a time-constant of approximately $\tau = 2\text{s}$ and events should be triggered with $\Delta T_{obs} = 3.4\text{s}$.

While the optimal estimation time-constant and event triggering time have been identified, this event triggering time is not readily implementable because neither the time of the fault t_{fault} nor the magnitude of the fault l_i^f are known a-priori. A common approach in event-based control is to trigger an event once a particular value crosses a predetermined threshold [15][16]. However, the above results show that there is benefit to waiting for an accurate estimate of a fault and it is not always optimal to trigger an event as soon as fault is detected.

A threshold-based strategy can be used to *detect* a fault, while not directly triggering an event. Given the anticipated magnitude of the measurement noise $|v_i|$ and the magnitude of the transfer function for the estimator $|G(j\omega_v)|$, the anticipated variation of the fault estimate prior to the fault is $|\hat{l}_i - 1| = |G(j\omega_v)||v_i|$. Thus, a fault can be detected at time $t = t_{detect}$ if $|\hat{l}_i(t) - 1| \ge |G(j\omega_v)||v_i| + \varepsilon = \bar{l}_i$, where $\varepsilon > 0$ is

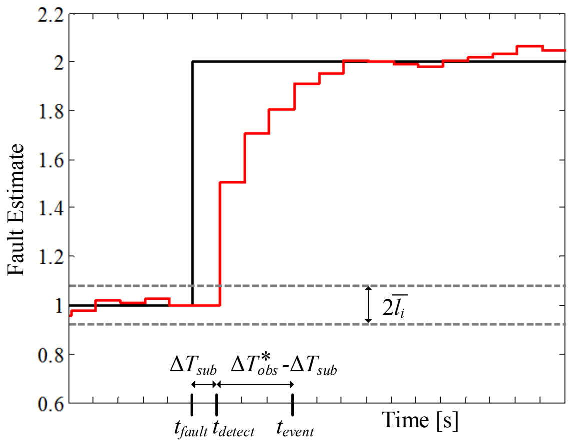

Figure 7. Threshold-based fault detection with optimal observation time prior to event triggering.

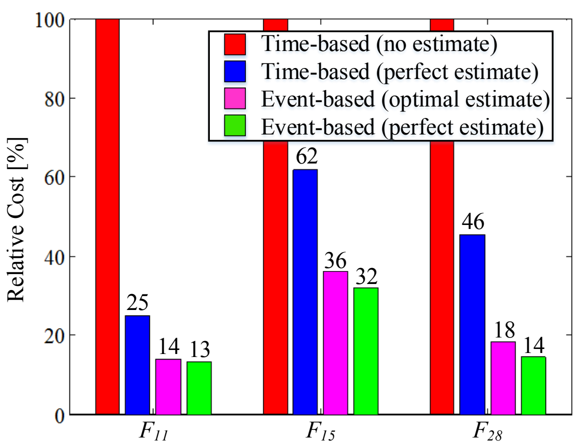

Figure 8. Comparison of relative control costs including the optimal designed estimator and triggering showing how a realistic estimator can approximate the best case control performance of a perfect, one step estimation scheme.

used to add a margin, based on the uncertainty in $|v_i|$, to prevent false positives. With the fault detection threshold $\bar{l}_i$, the time of the fault can be approximated as $t_{fault} \approx t_{detect} - \Delta T_{sub}$. With the optimal observation time identified in Fig. 6, an event should be triggered at $t_{event} = t_{detect} + \Delta T_{obs} - \Delta T_{sub}$, as shown along the time-axis in Fig. 7.

To evaluate the optimally designed estimator and event-triggering scheme, 100 simulations were run using random noise with the assumed $\|v_i\| \le 0.1$ for each of the 3 fault scenarios. The magenta bars in Fig. 8 show the average relative cost from these simulations compared to the relative costs previously presented in Fig. 4. Despite the fact that both τ^* and ΔT^*_{obs} were chosen based on analysis using F_{15}, the optimally design estimator and event-triggering scheme closely approximate the performance of the perfect, one-step estimation event-based control for all three fault scenarios.

VIII. Conclusion

With increasing demands for improved control performance from modern advanced vehicle systems, comes the need for hierarchical control strategies, capable of coordinating control decisions among various systems and subsystems over multiple timescales. Traditionally, these hierarchical control frameworks are highly susceptible to unknown, unanticipated disturbances due to the slow update rates of upper-level controllers. This paper has presented an effective event-based hierarchical control framework where the update of controllers can be triggered in response to estimated faults in the system. The results show that an appropriately designed estimation and event triggering scheme can lead to significant control performance improvements and fault rejection. Future work includes extending this fault estimation and event-triggering framework to a wider-class of faults including non-instantaneous component failures and the identification and isolation of sensor failures.

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