Set-Point Manipulation Approach toward Overcoming Limitation of Closed Architectural Framework

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Abstract—In this paper, a set-point manipulation approach towards achieving control adaptation in a closed architectural control framework is proposed and designed. The approach is designed to allow the flexibility to incorporate control adaptation which is not easily accomplished with a built-in proprietary controller, such as an appropriate anti integral windup measure (AIWM). The approach is amenable to closed systems without the need to replace the built-in controller. The realization of the proposed configuration will be illustrated with respect to a PID controller although the framework proposed is general allowing the use of higher order controller too. Simulation examples and experimental results on the speed control of an electric vehicle will be duly furnished to show the motivation for such an approach and the improved performance achievable with closed-architectural systems.

Index Terms—PID, Closed-Architecture controller, Set-Point Manipulation, Integral Windup.

I. Introduction

PROPORTIONAL-Integral-Derivative (PID) control is generally a popular form of control for applications with modest control specifications and they can be found in a wide and diverse range of applications such as but not limited to process control, automotive, flight control and factory automation. PID controllers can be combined with logic, sequential machines, selectors, and function blocks to build complicated automation systems such as those used for energy production, transportation, and manufacturing. On top of that, many sophisticated control strategies, such as model predictive control, are also organized hierarchically based on PID control. The main reason for its success is that it has a simple structure which is easy to be understood by the engineers and under practical conditions, it has been performing more reliably compared to other advanced and complex controllers. It has remained true that PID controllers are by far the most dominating form of controllers in use today comprising more than 90% of industrial controllers.

Driven by its popularity, PID control has been a de-facto industrial standard and automation equipment and instruments are often provided together with built-in PID control in proprietary and closed architectural forms so that the users and customers do not have to deal with them separately. These built-in solutions will typically restrict the users to input fixed control gains and the reference signal. Unfortunately, such a bundled solution poses serious constraints when there arises needs to incorporate modifications and adaptation in the controller in situations when simply tuning the control gains in the closed system cannot achieve the performance needed. Two examples of such scenarios arising would be the need to bundle a suitable anti-windup mechanism for the integral control action and the flexibility to adapt control gains on the fly when faced with nonlinear or time varying processes. These scenarios are cumbersome to handle in a closed-architectural proprietary setup without tearing apart the overall system to retrofit an alternate controller and separate instrument to allow such flexibilities, incurring cost, time and a possible void of warranty on the equipment since that will be counter acting the intention of the manufacturer.

Integral windup commonly occurs due to control input limitation and saturation nonlinearity of the physical systems. When windup steps in, the performance of the closed-loop system significantly deteriorates yielding a larger overshoot, slower settling time and lower stability [1][2][3][4]. Thus, anti-integral-windup mechanisms (AIWM) are necessary to counter this phenomenon. Built-in PID controllers may or may not have an AIWM provided. When the built-in control is not equipped with an AIWM, anti-windup can be mediated with a low integral control gain. Even if it is equipped with AIWM, there are different types of AIWMs and each strives in a specific situation. Thus, the AIWM provided may not be suitable for the actual application and changes to the AIWM configuration parameters have to be done continuously to retain it, or an alternate one has to be employed. These are not easily done with a closed framework.

In this paper, we propose an approach towards achieving control adaptation which cannot be achieved easily with a closed-architectural system, such as incorporating an appropriate AIWM. There are other applications of the approach such as realizing a high order controller or a signal processing filter. The approach leverages on a set-point manipulation mechanism which allows the additional modifications to be done outside of the main closed-loop without affecting the closed-system. It will be shown that the proposed configuration is equivalent to the original closed-architectural control system in terms of the closed-loop relationships, but with all the flexibilities needed for user customization to yield improved performance. Results from both simulation examples and a real-time implementation on an autonomous vehicle with a closed-architectural control system will be furnished to show the effectiveness of the proposed approach.

II. Review of Anti-Integral-Windup Mechanisms

A number of AIWMs has been introduced in the literature and the majority of them can be categorized into three different kinds: conditional integration, back tracking calculation and limited integrator schemes [5]. In conditional integration schemes [6][7][8], the integral action is suspended and only the PD control is activated when control input is saturated. In back tracking calculation schemes [1][9][10][11][12], the difference between the saturated and unsaturated control input signals is used to generate a feedback signal to moderate the integrator's output. In limited integrator schemes [13], the integrator value is limited with a high-gain dead zone to ensure operation in the linear range.

Limited integrator schemes are not commonly used especially in built-in controllers as they are not amenable to general usage [14]. Back tracking calculation and especially conditional integration schemes are more commonly found in these built-in controllers. But even under the commonly used conditional integration schemes, there are four main types.

1) Type A: the integral term is limited to a predefined value.

2) Type B: The integration is stopped when the error is greater than a predefined threshold, when the process variable is too far from the set-point.

3) Type C: The integration is stopped when the control variable saturates.

4) Type D: The integration is stopped when the control variable saturates and the control error and the control variable have the same sign.

Type A requires a predefined cut-off and Type B requires a predefined threshold to be configured for proper implementation of the control application. The limitation of the integral term in Type A can prevent the control from attaining set-point tracking. Likewise, the predefined threshold in Type B may cause the control to be trapped in an unreachable state wherein the control error remains above the threshold. In other words, setting the above two parameters too high allows significant build-up of the integral windup and setting them too low will prevent the integral from correcting the steady stage error. Thus, these parameters should be set just enough so that the integral is able to correct the steady stage error, which is highly dependent on the process static gain. As a result, in order to achieve the optimal anti integral windup measure with Types A and B, these parameters should be set accurately according to the process static gain. In a nonlinear process wherein the DC gain is varying, these pre-set values do not match the actual gains and thus, the closed loop systems with Types A and B can result in a steady-state error [14].

The issues relating to steady-state error with Types A and B above can be avoided by using Type C or D. Comparing these two types, Type D offers the significant advantage that the integrator is not inhibited as it helps to push the control variable away from saturation. In cases when the process and the instrument are separate entities, these two types require the knowledge of the process saturation region in order to set a suitable value to the maximum instrument output parameter. However, when the process saturation region is varying and unpredictable, setting appropriate values for this parameter is often challenging. An inadequate parameter can result in steady-state error or deterioration in the closed-loop performance [14].

Thus, there is no single AIWM which fits all situations and the mechanism provided in a built-in controller may not be suitable for the actual process. Replacing one with another more suitable mechanism is then required and this is not a simple task in a closed-form control system. Even if the mechanism is suitable for the nominal plant, process model variation can happen either due to process modification or due to nonlinearities and disturbances occurring over time. As a result, parameters such as the predefined value, the threshold, and the maximum output allowable need to be updated continuously on the fly.

III. Proposed Configuration and Approach

Consider a general closed-loop control system in Fig. 1, using a built-in controller $G_C = G_{C1}G_{C2}$ (shown in the dotted box) to control the process G_P. r, w, y represent the set-point, disturbance and process variable respectively. Modern devices may even bundle the controller G_C and process G_P as a single entity. The controller will typically receive as user inputs the set-point r and a set of fixed control gains.

The closed-loop transfer function between y and r is given by

$$G_{yr} = \frac{G_{C1}G_{C2}G_P}{1 + G_{C1}G_{C2}G_P}, \tag{1}$$

and the closed-loop transfer function between y and w is $G_{yw} = \frac{G_P}{1 + G_C G_P}$

Now consider the proposed control configuration to allow control adaptation in the closed architectural control system as shown in Fig. 2.

The part of the controller in the dotted box can be thought as a set-point manipulator transforming the original set-point r into a new one $\bar{r}$ for the controller G_{C1} which directly manipulates the process. The closed-loop transfer functions between y and inputs r, w can be shown to be

$$G_{yr} = \frac{G_{C1}G_P(\bar{G}_C + 1)}{1 + G_{C1}G_P(\bar{G}_C + 1)} \tag{2}$$

$$G_{yw} = \frac{G_P}{1 + G_C G_P} \tag{3}$$

Thus, it can be observed that the proposed control configuration in Fig. 2 is equivalent to the closed-architectural control of Fig. 1 in terms of the closed-loop relationships if

$$\bar{G}_C = G_{C2} - 1 \tag{4}$$

This implies that under the proposed configuration, a part or the full ($G_{C2} = G_C$ and $G_{C1} = 1$) built-in controller G_C can be realized outside of the built-in control system,
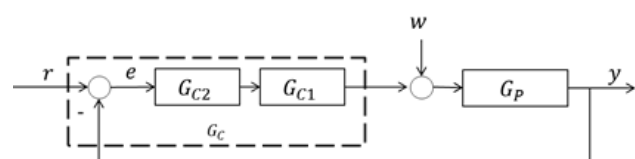

Fig. 1. Block Diagram of Closed-loop Control System with Built-in Controller
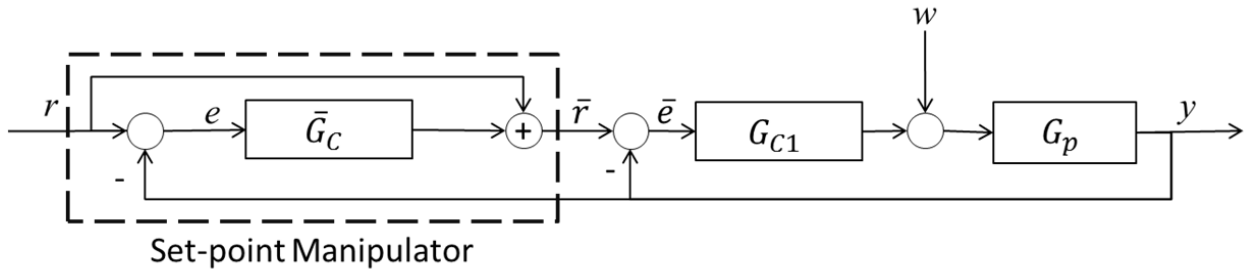
Fig. 2.   Block Diagram of Proposed Control Configuration

thus enabling the flexibility for control adaptation including but not limited to the implementation of AIWMs and gain scheduling schemes.

Consider a PID realization of the proposed configuration where the built-in controller G_C is a PID controller. Different variants of PID realizations can be possible under the proposed configuration. For example, PD control $G_{C1} = K_{C1}(1 + K_d s)$ can be retained in the built-in control and PI control $G_{C2} = K_{C2}(1 + \frac{K_i}{s})$ shifted outside of the built-in loop. If the full proportional gain is retained in the built-in control, i.e., $K_{C2} = 1$, then $\bar{G}_C = \frac{K_i}{s}$. A pure integral control can be realized outside of the built-in control loop and equivalent set-point tracking and load disturbance attenuation is still achieved.

Alternatively, with $G_{C1} = K_{C1}$ and $G_{C2} = K_{C2}(1 + \frac{K_i}{s})(1 + K_d s)$, the full PID control can be shifted outside of the built-in loop and only a proportional gain is applied for stabilization of the built-in control loop.

Remarks:

1) The integrator part of the control can be realized outside of the main control loop along with an appropriate AIWM. This allows an AIWM to be efficiently applied to the existing built-in control without one or an appropriate AIWM to replace an inappropriate built-in AIWM.

2) A gain scheduling strategy can be effectively realized with PID gains varying with respect to operating point or with time. This is achieved within the set-point manipulator.

3) A high order controller or a signal processing filter can be achieved with the built-in PID control, with the additional order of control incorporated into G_{C2}.

IV. INCORPORATING AIWM INTO PROPOSED CONFIGURATION

In this section, the approach to incorporate a suitable AIWM into a closed-architectural PID control system either without one or with an inadequate AIWM will be elaborated. Without loss of generality, we will use proportional control in the built-in controller, i.e., $G_{C1} = K_P$. The saturation condition is thus given by:

$$u = \bar{e}.K_P > u_{max} \quad or \quad u = \bar{e}.K_P < u_{min} \qquad (5)$$

where $\bar{e} = y - \bar{r}$, and u_{max} and u_{min} are the higher and lower saturation limits of the input to the process respectively. We will elaborate the implementations of the Type C AIWM and the back tracking AIWM as examples in the following subsections. Simulation will be carried out in Section (V) to show that these approaches to implement
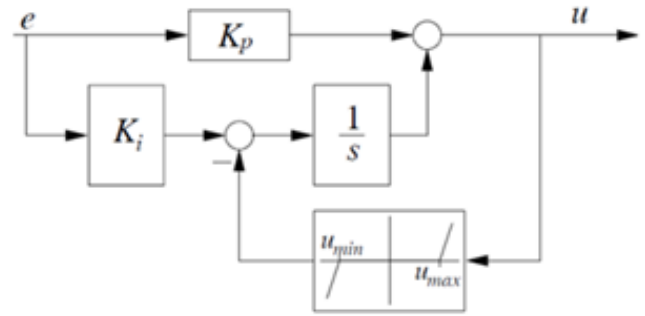

Fig. 4.   Back Tracking AIWM with PI Control

AIWM achieve the same results as though the AIWM is incorporated into the built-in controller.

A. Implementation of Type C AIWM

The conditional function of the Type C is given by

$$e = \begin{cases} r - y & \text{if } \delta < \bar{e} < \sigma \\ 0 & \text{otherwise} \end{cases} \qquad (6)$$

where $\bar{e} = y - \bar{r}$, $\sigma = \frac{u_{max}}{K_P}$ and $\delta = \frac{u_{min}}{K_P}$.

The implementation of the Type C AIWM in the proposed configuration is shown in Fig. 3.

B. Implementation of Back Tracking AIWM

The typical implementation of a back tracking AIWM in a PI controller is shown in Fig. 4 [14] [15].

With the proposed configuration, the back tracking AIWM can also be realized outside of the P-only control loop as shown in Fig. 5.

V. SIMULATION RESULTS

Two simulation examples are furnished in this section. These examples will highlight the efficiency of incorporating the Type C AIWM and the back tracking AIWM into a closed-architectural system without any AIWM. Improved control performance will be illustrated. In addition, the performance is shown to be the same as having the same AIWM within the built-in control.
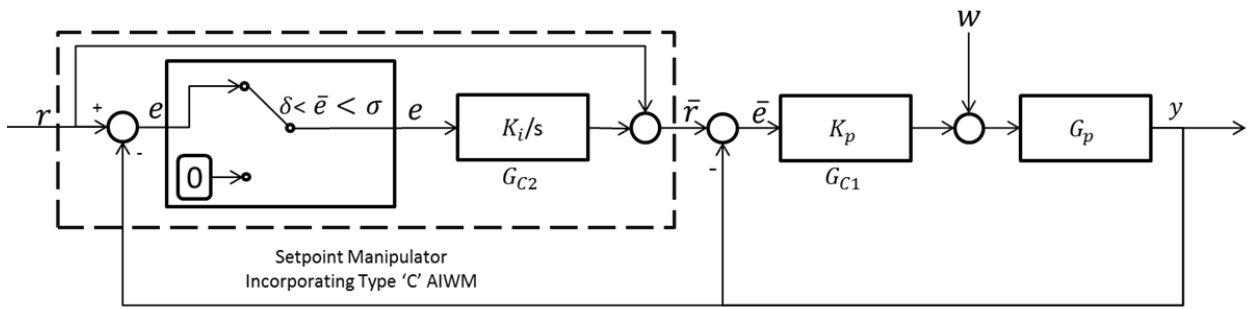
Fig. 3.   Implementation of Type C AIWM in the Proposed Configuration
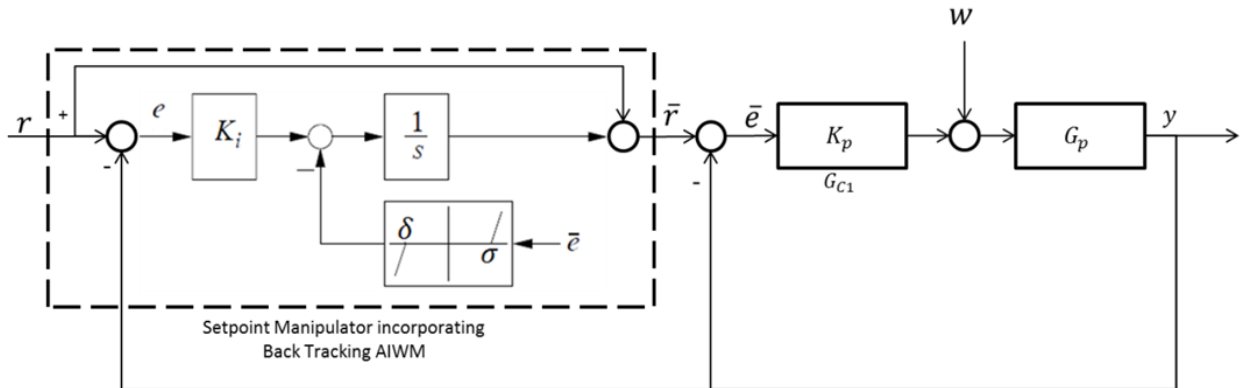

Fig. 5.   Implementation of back tracking AIWM in the Proposed Configuration

A. Performance of Type C AIWM in the Proposed Configuration

The simulation is based on the process being a first order process with time delay given by:

$$G_P = \frac{0.5}{s + 1.5}e^{-0.1s} \qquad (7)$$

Saturation limits of saturation of ± 10 are simulated for the control variable. A disturbance $w = 0.2$ is also introduced at some point into the simulation to show the disturbance rejection performance. The built-in controller is a PI controller with $K_P = 20$ and $K_i = 3$.

Type C AIWM of Fig. 3 is incorporated and simulated. The set-point tracking and load disturbance rejection performance is shown in Fig. 6 against the performance from the built-in PI control without AIWM but with the same PI control gains. The improved performance is clearly evident with the AIWM incorporated. The same AIWM is also simulated in the built-in controller and an identical performance is verified via simulation as also seen in Fig. 6.

B. Performance of Back Tracking AIWM in the Proposed Configuration

The same process and limits as in section (V-A) are used in this simulation. Back tracking AIWM of Fig. 5 is incorporated and simulated. The set-point tracking and load disturbance rejection performance is shown in Fig. 7 against the performance from the built-in PI control without AIWM but with the same PI control gains. The improved performance is clearly evident with the AIWM incorporated. The same AIWM is also simulated in the built-in controller
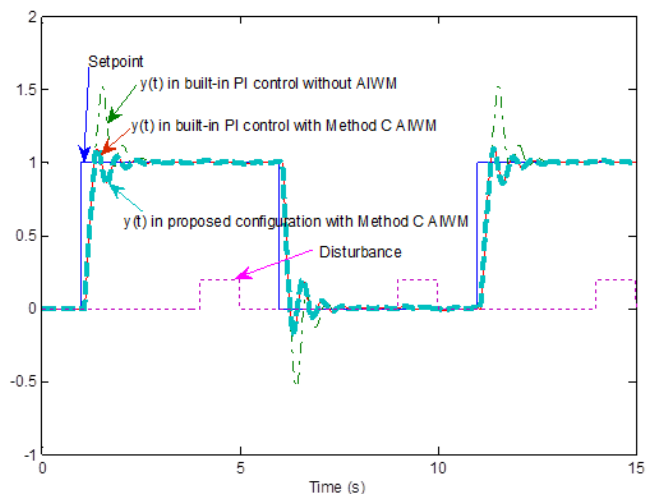

Fig. 6.   Performance of Type C AIWM

and an identical performance is verified via simulation as also seen in Fig. 7.

These simulation examples highlight the equivalence in performance with the AIWM incorporated in the set-point manipulator and the improved performance achieved over a built-in controller without an AIWM.

VI. EXPERIMENTAL VERIFICATION

The proposed control configuration was applied to the autonomous control of a single seater Micro Electric Vehicle (MEV) manufactured by Toyota Autobody as shown in Fig. 8. The MEV is equipped with a built-in PID controller with
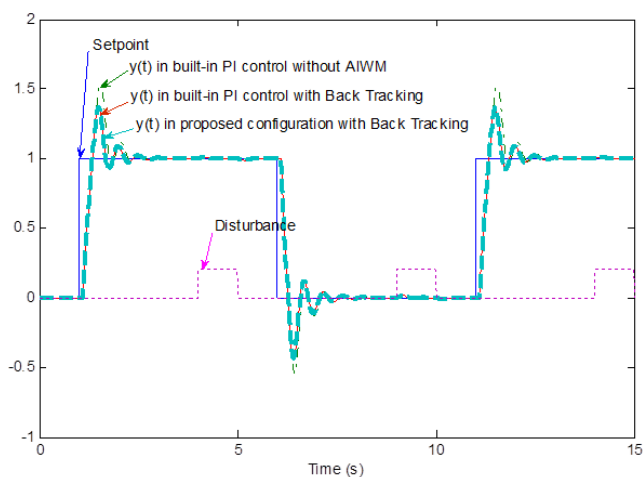
Fig. 7.   Performance of Back Tracking AIWM
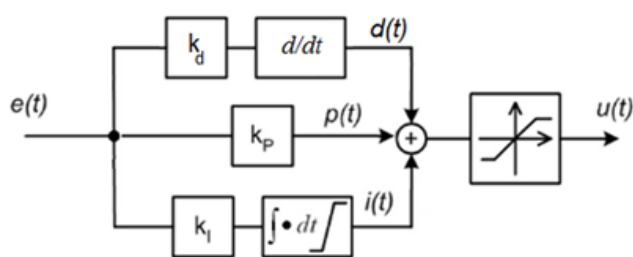

Fig. 8.   Single Seater MEV

Fig. 9.   Built-in Control with Type A AIWM Provided

Fig. 10.   Hardware Block Diagram of the Drive Motor Control System

Fig. 11.   Hardware Picture of Drive Motor Assembly

TABLE I
AN EXAMPLE OF A TABLE

Surface	Gain	Similarity to gain on flat surface
Flat	0.063	100%
Up Slope (20 Degree)	0.098	156%
Down Slope (20 Degree)	0.019	30%

a Type A AIWM as shown in Fig. 9. The saturation function acts on the PID control signal to limit it to the specifications of the motor drives. The MEV uses two drive motors which are mounted at the rear wheels and these are integrated with an embedded PID controller which can accept only input of fixed control gains as well as the reference speed signal through the Controller Area Network (CAN) bus from the Main CPU of the EV as shown in Fig. 10. The drive motor assembly is shown in Fig. 11. The MEV represents a typical real example of an AIWM provided in the built-in control system.

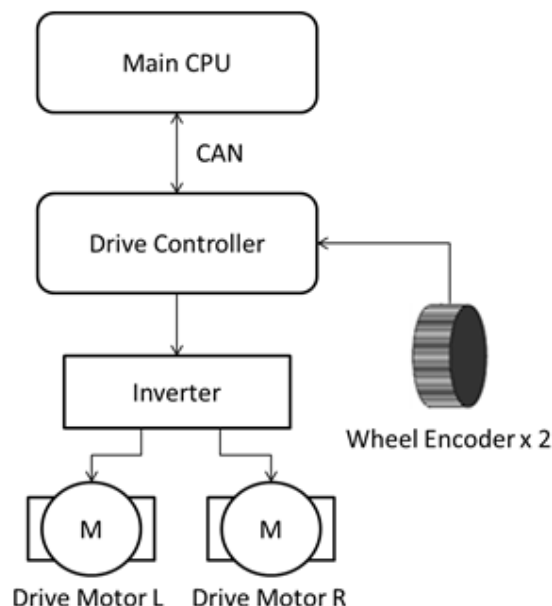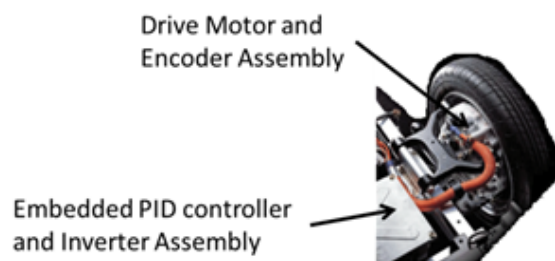The static gain of the speed-input relationship of the motor was calibrated by evaluating the steady state offset of the speed control with a proportional only controller. Table I shows the variation in the gain with different slopes of the road. It can be observed that the variation in the static gain is significant. Thus, the Type A AIWM is not ideally suited for the speed control of the MEV.

A set of PI gains (i.e., $K_P = 0.6$ and $K_i = 0.02$) was determined in a rigorous tuning session for the built-in control to work the best it could over different profiles of the road. The MEV was driven over a stretch of road with flat, up slope and down slope profiles at a constant target speed of $5 km.h^{-1}$. The speed recorded over this travel is shown in Fig. 12. The passenger seated in the MEV can clearly experience the jerky movements due to fluctuations in the velocity of the MEV.

The speed fluctuations are due mainly to the Type A AIWM which is inadequate to cope with the varying static gain. To minimize these undesirable oscillations, the proposed control configuration was adopted and the Type C AIWM scheme was used instead as shown in Fig. 13. The PI gains remained the same and the same route was used to
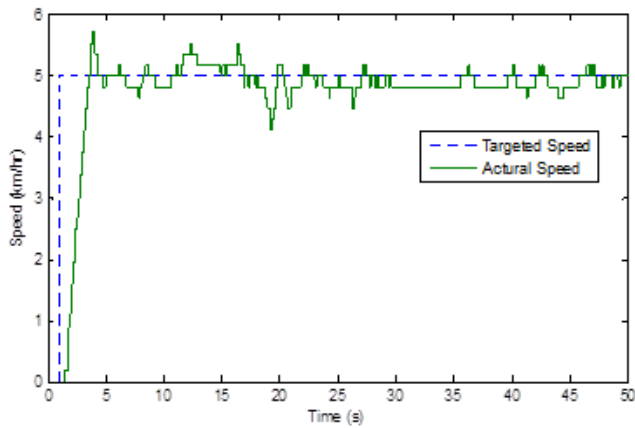
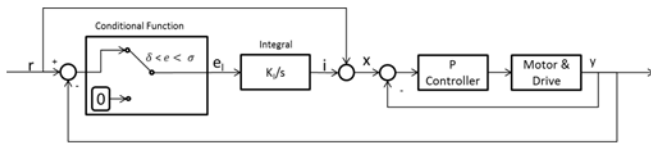Fig. 12.   Speed of the MEV with the built-in PI controller

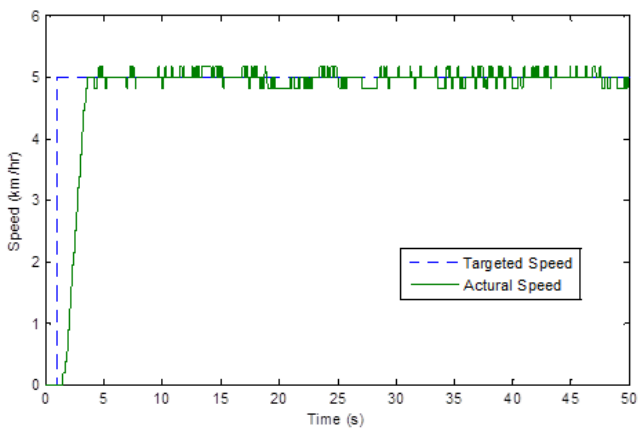Fig. 13.   Block Diagram of the Improved Speed Controller

Fig. 14.   Speed of the MEV with the proposed control and AIWM

capture the speed variation with the alternate AIWM. The clearly improved results are shown in Fig. 14.

As seen in Fig. 14, the amount of oscillation is significantly reduced from a RMS value of 0.20 to 0.11 resulting in a clearly smoother driving experience to the passenger. This improvement is achieved with no physical alteration done to the built-in controllers integrated to the motor drives.

VII. Conclusion

In this paper, a set-point manipulation approach towards achieving control adaptation in a closed architectural control framework is proposed and designed. Such an approach allows the flexibility to incorporate an appropriate AIWM and enabling adaptive control which cannot be achieved effectively with a built-in proprietary controller. The approach can be adopted without having to remove or decommission the built-in controller. While the realization of the proposed configuration is with respect to a PID controller, the framework proposed is general allowing the use of higher order

controller too. The motivation for such an approach was duly elaborated and verified using simulation examples as well as a real-time experimental verification on a MEV which is supplied with built-in PID controllers for the motor drives and a AIWM which is adequate if the road surfaces on which the MEV is driven is relatively flat. The results show that the approach can achieve enhanced performance even when the road surface is not flat by switching to an alternate AIWM not provided by the built-in controller and incorporating it in the set-point manipulator which resides outside of the closed system.

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