

PROACTIVE CONTROL OF CURING COMPOSITES

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ABSTRACT

Self directed (or intelligent) control systems have been developed which use knowledge of a material's processing characteristics, in conjunction with real-time sensor data, to control the cure of composites. These systems have been shown to lead to shorter, higher quality, cures and have been implemented in autoclave, press molding, and repair processes. These systems are *reactive* in nature as they can only respond to the data currently supplied by the sensors. This has resulted in the inability of these systems to control the cure of thick parts due to the inherent thermal lag of these parts, and requirement that control actions be made well before time at which a sensor would provide a feedback of an undesirable cure state. These systems have also been vulnerable to sensor failures.

A *proactive* control system is presented herein. This system's control software has a predictive cure model imbedded in it to allow it to make control decisions based on anticipated future cure states. This enables it to deal with the large time lags which result in the cure of thick parts. Sensor inputs are not only used to determine the current cure state but also used to update the model predictions to minimize modeling error. The cure model predicts future cure states and present them as virtual sensor inputs to the control system to allow the system to make control decisions based on future expectations. Other virtual sensors based on modeling of material states, such as degree of cure and viscosity, also enable the system to infer these states by using only temperature (thermocouple) measurements. The system is demonstrated for the cure of a thick epoxy composite. The demonstration includes control of the rheology and reaction rate of a curing composite using thermocouple sensors only.

KEY WORDS: Composite Materials, Process Control, Process Modeling

1. INTRODUCTION

Closed-loop feedback control of the cure cycle has been used for a number of years. Most composite cure cycles are controlled by this method today. Typically, these systems use thermocouples, pressure transducers, etc. to determine the process states and use them in feedback control loops to control the heaters, coolers, pressure valves, etc. of the process equipment as required to meet a specific time-temperature-pressure profile which was previously determined using laboratory test methods such as Differential Scanning Calorimetry (DSC), and/or Rheometric Dynamic Spectroscopy (RDS) [1]. Although changes are not made within a cure cycle, they may be made to subsequent cycles once the composite has been cured and evaluated. These systems can only blindly perform the pre-determined cure cycles and hence are incapable of dealing with variations in a real-world environment.

Process models have been developed which simulate the cure of a thermosetting material (e.g. see Loos and Springer [2]). These models use mass, momentum and energy balances to describe the manufacturing process. Use of these models has the advantage that they can be run repetitively at relatively low cost and can be used to investigate a variety of situations such as variations in processing conditions, part properties and geometry. However, they are generally based on a number of rather crude rheometric and kinetic assumptions and become less accurate at predicting what will occur at a points further out in the future.

More recent approaches have been proposed which employ a number of sensors, coupled to a computer, which can be used to alter the cure in real time based upon observed (e.g. thermal and/or rheological) changes taking place in the resin. These newer approaches fall into the category of self-directed control [3]. Although these initial self-directed control systems represent significant accomplishments in themselves none of them are currently in production use. Reason's for this include the fact that they can require a high degree of expertise to run and they have been vulnerable to sensor failure. In addition, these systems are *reactive* in nature, just as any feedback system, as they can only respond to the data currently supplied by the sensors. Hence they are incapable of controlling the cure of thick composites due to the inherent thermal lag of these parts and requirement that control actions be made well before time at which a sensor would provide a feedback of an undesirable cure state such as a run-away reaction.

A *proactive* control system is presented herein. This proactive system has a predictive model imbedded in it's control sequence. This allows the system to make control decisions based on future expectations thus enabling it to deal with the large time lags present in the cure of thick parts. Sensor inputs are used to update the model predictions in addition to providing data for short-term/inner-loop feedback control of the process. This has a synergistic effect of minimize modeling error. Note that the idea of the use of process models in control is not necessarily a new idea. For example, Kline et al. [4] developed a system which compares cure model predictions with sensor data then selects and initiates a new cure cycle from pre-stored sets of cycles when differences arise. This system, as described, would be reactive in that it responds to current differences between model predictions and sensor outputs. In addition, this system also requires monitoring (measurement) of material parameters other than temperature, such as degree-of-cure or viscosity [4]. The proactive system described herein has no such requirement.

2. PROACTIVE CONTROL SYSTEM DESCRIPTION

The proactive control system incorporates a cure model into Aerospace Service & Control's (ASC) Composite Processing Control (CPC) System [5]. CPC is a modular PC-based, user programmable controller which readily accommodates incorporation of virtually any sensor. CPC is capable of multi-loop "cascade" control which allows for regulating one control parameter (e.g. autoclave air temperature) by measuring another (e.g. part temperature). The control strategy is expressed as rules in CPC's "curefile". These rules in the curefile are programmed in "segments" where specific criteria ("watch variables") must be met before control is passed to the next segment. For example, it is possible to specify that a dielectric loss factor must reach a predetermined value or trend before moving to the next segment. The watch variables also make it possible to revert back to a conventional time-based control scheme in the event of sensor failure. In addition, the software has a number of built-in features such as temperature-rate-correction control. The temperature-rate-correction control forces all part temperatures to be within a specified limit by automatically adjusting the heat-up and cool-down rates. This allows for optimal heat-up and cool-down rates in a process while avoiding unacceptable thermal gradients. CPC also has built-in features which force the system to recover and/or sound alarms when any specified variable's value is exceeded at any point in the process. The option to turn on or off data filters can be used on all of the input channels. Sensor data and equipment status information are saved to an output file at user defined intervals. CPC has been successfully adapted to self-directed control [6].

The cure model used is similar to the "thermal-chemical" model first proposed by Loos and Springer [2]. This model computes the temperature distribution, degree-of-cure, and viscosity of a composite as it undergoes cure. This model is based on the solution of a one-dimensional heat conduction problem with internal heat generation. The governing partial differential equation is:

$$\frac{\partial T}{\partial t} = \frac{K}{\rho C} \frac{\partial^2 T}{\partial x^2} + \frac{1}{C} r w H_u \quad (1)$$

where T is the temperature, t is the time, x is the through thickness position, ρ is the density, C is the specific heat, K is the thermal conductivity, r is the reaction rate, w is the weight fraction of resin, and H_u is the heat of reaction. It can be seen that $r w H_u$ is the rate of heat generated by the curing reaction. The boundary conditions are the upper and lower laminate surface temperatures which vary with time. The initial conditions are the temperature distribution and degree-of-cure inside the laminate at the start of the process. Solution to this equation requires knowledge of the reaction rate, r . A functional form used herein to express the reaction rate for multiple parallel reactions is the Arrhenius equation. This was found necessary to adequately describe the behavior of many of today's high performance resins. In this treatment, each individual reaction is described by its own reaction rate (r_i) and degree of cure (α_i) such that the degree of cure for each reaction reaches unity at completion. The overall rate (r) and the overall degree of cure (α) are then the weighted sums of the individual ones. The weights are the fractions of the total heat of reaction contributed by the individual reactions. In the form of equations this approach can be generalized as follows:

$$H_u = \sum_i H_{ui}, \quad r = \sum_i f_i r_i, \quad \text{and} \quad \alpha = \sum_i f_i \alpha_i; \quad (2a)$$

$$\text{where } f_i = \frac{H_{ui}}{H_u} \text{ and} \quad (2b)$$

$$r_i = \frac{d\alpha_i}{dt} = A_i e^{-E_{ai}/RT} (1 - \alpha_i)^{n_i} \quad (2c)$$

The parameters H_{ui} , A_i , E_{ai} , and n_i are determined from DSC data. The solution of Equation (1) requires the use of a finite difference method. An implicit form of solution was used here as it guarantees stability of the numerical solution [7]. Solution of Equation (1), followed by back substitution into Equation (2), provides the temperatures and degree of cure as a function of both time and position. Once these are known some parameter indicative of the resin state may be calculated. Choices include a measure of viscosity such as G' (the “kinematic viscosity”), or the electrical resistivity [8] of the material. A functional form is also used here which can be determined from DSC and RDS data. Again, the choice of an Arrhenius type expression according to Ciriscioli and Springer [9] was used:

$$V' = V'_m e^{(E_v/RT + k\alpha)} \quad (3)$$

where V' is some measure of the viscosity and V'_m , E_v , and k are material constants. Note that the weighted average degree of cure (Equation 2a) was used to describe α .

Modifications were made to the CPC system to incorporate the cure model. Incorporation of the cure model provides real-time estimates of current as well as future predictions of temperature, degree of cure, viscosity, and DC resistance. The current and future estimated values of these parameters are then available as virtual sensor inputs to the system, along with the customary measured part and vessel temperatures, pressure, and vacuum. This enables CPC to act upon or control these variables through instructions stated in the curefile.

A noteworthy capability resulting from the use of such virtual sensors is the ability to control the process using a targeted degree of cure or cure rate value. The degree of cure mode of control can be applied early in the cure where a limit on the advancement of the cure must be maintained. Cure control allows ramping of the vessel temperature to initiate cure then progressively reducing the vessel temperature as the cure limit value (setpoint) is approached. This is useful for preparing the resin for applying pressure, as viscosity is declining, before significant resin advancement has occurred.

Analogously, cure rate control limits the cure reaction rate of the laminate to a specified value. Cure rate control is useful later in the process, where control of exotherm is paramount. This mode provides for a limitation of the rate of cure as the mechanism for maintaining control of the rate of the cure and the consequent release of heat that is proportional to the reaction rate. The system calculates both the current and future predicted values for cure rate, and uses the higher value (now or future) for control. If the future cure rate value exceeds the setpoint, thus predicting a possible rapid exotherm in the future, the system responds by reducing the rate applied to determine the next temperature setpoint, so as to avert this occurrence.

3. SYSTEM IMPLEMENTATION AND ASSESSMENT

The implementation began with determination of the material parameters required of the model. The material used in this demonstration was S2-glass/8552-epoxy. The physical properties for the S2/8552 material were obtained using standard laboratory methods. Arrhenius model parameters for the reaction rate, viscosity, and DC resistance were determined from DSC and RDS tests performed on prepreg samples. The DC resistance data were obtained simultaneously with the RDS tests by using the rheometer's parallel plates as electrodes.

This resin showed two reaction peaks superimposed over one another. Hence, to obtain the reaction rate model parameters it was necessary to first deconvolute the reaction peaks as shown in Figure 1. Equations 2a-c were used to describe the reaction rate behavior. The model parameters were obtained from DSC scans. Of the total heat released from the reaction, 72.5% is from reaction 1 and 27.5% from reaction 2. The overall reaction rate and degree of cure are the weighted sum of the individual ones.

The model parameters for the viscosity and DC resistance models were determined using data from a 2°C/min scan on the RDS. It can be seen from Figure 2 that models for DC resistance and viscosity fit quite well.

The system was demonstrated for the cure of a thick (128-ply) S2/8552 (glass/epoxy) test panel. Instrumentation included three through thickness thermocouples (one top, one mid and one bottom) and a mid plane thermocouple wire DC resistance sensor [8]. The DC resistance sensor was used as an independent check on the model predicted viscosity. In addition to providing temperature measurement and control the three through thickness thermocouples were used as a pseudo-thermopile to provide an independent check on the reaction rate prediction. The pseudo-thermopile follows that proposed by Lee and Rice [10] who have shown that the reaction rate, r , of a curing composite can be estimated by :

$$r = m [\Delta T - A \Phi(T)] \quad (4)$$

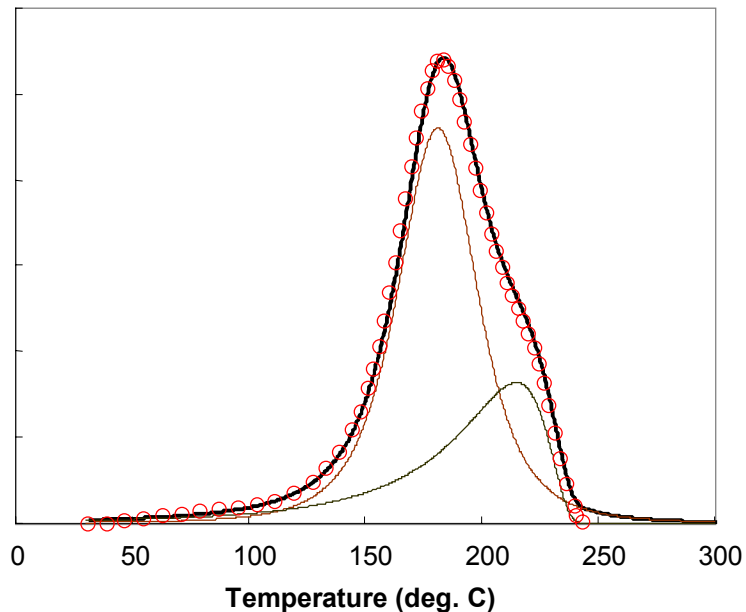


Figure 1: Reaction Rate of S2/8552 and the Deconvoluted Peaks

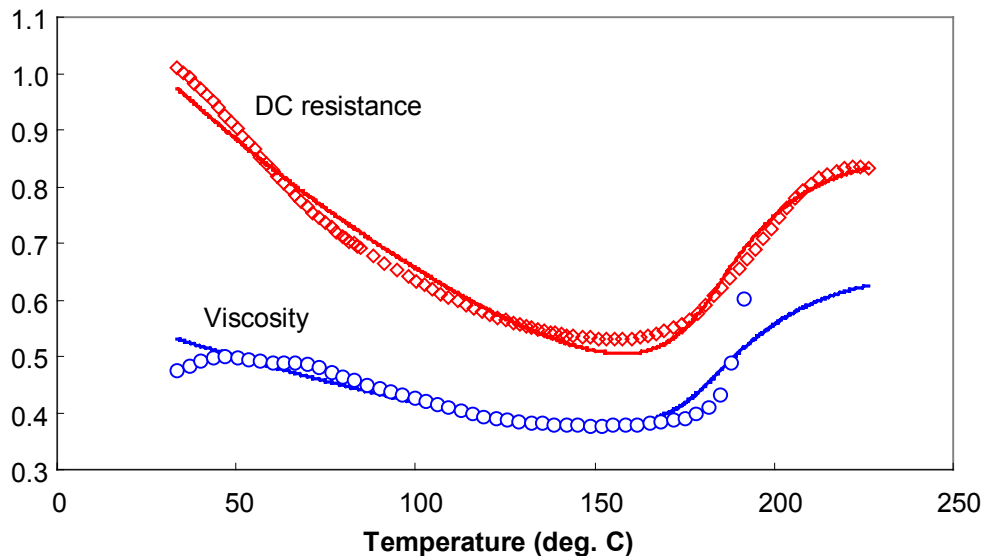


Figure 2: Measured and Model Predicted Viscosity and DC resistance of S2/8552

where ΔT and $\Phi(T)$ can be measured on-line from $T_j^i - T_j^{i-1}$ and $T_{j-1}^i - 2T_j^i + T_{j+1}^i$, respectively. The indices i and j represent time and spatial (through thickness) increments, respectively. The value of the constant m is determined by the size of the increments, and that of A is a function of the thermal diffusivity of the composite.

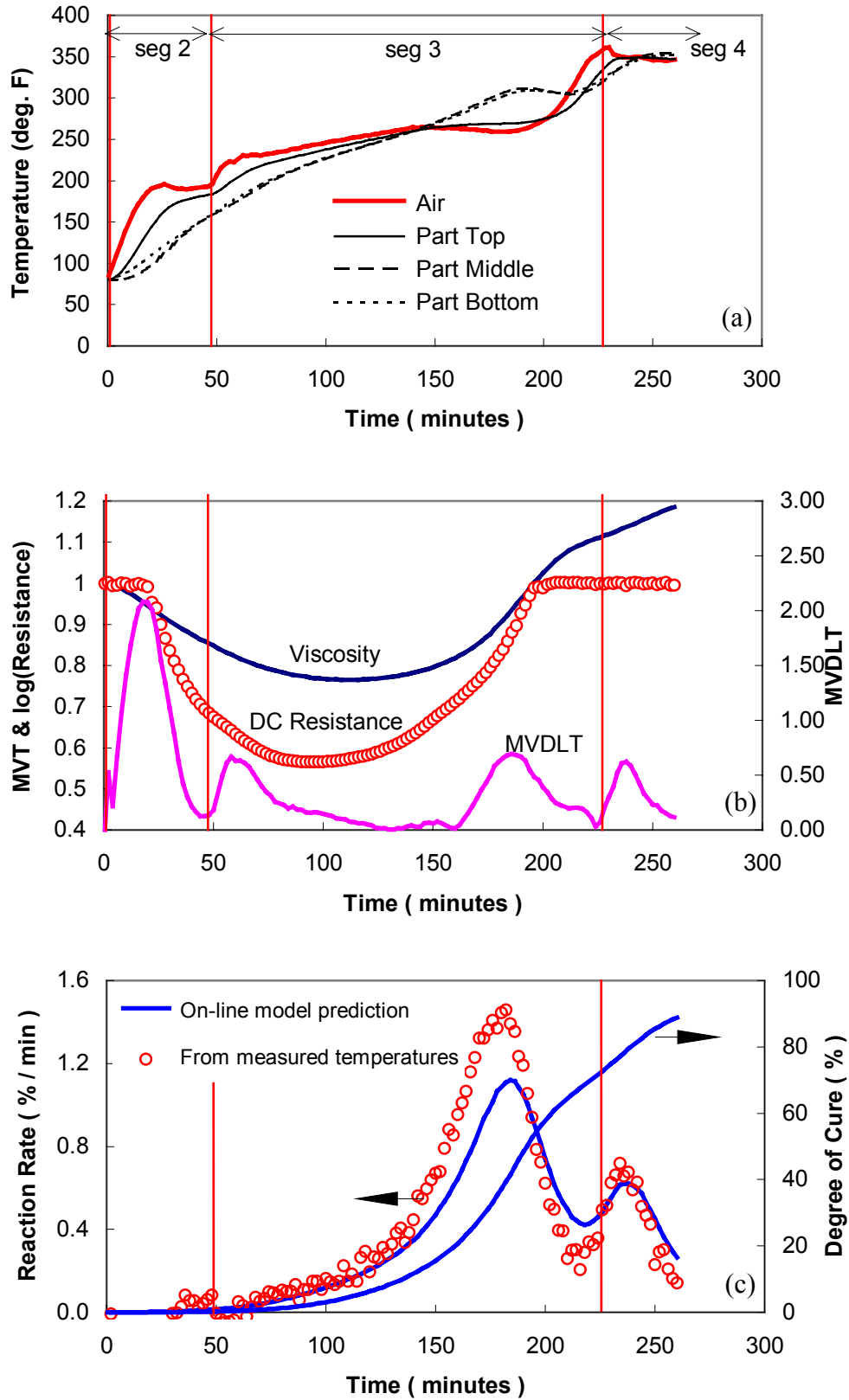
The curefile used in this demonstration is shown in Table 1. This cure utilizes both degree of cure and cure rate control. In segment 1, initial conditions for temperature and operation are set. The degree of cure control is enabled for segments 1 and 2 with the cure rate mode disabled. A degree of cure limit of 2% is set in segment 1. Segment 2 specifies an ultimate part temperature setpoint of 350°F with a maximum ramp rate of 5°F per minute. Segment 2 also stipulates a compound watch criterion that must be satisfied before proceeding on to segment 3. Control passes to segment 3 when the model estimated log-viscosity (normalized) is less than 85±2% ("MVT" and "MVDLT"), at every point through the thickness. Actual top and bottom temperatures are used as inputs (boundary conditions) to the model which computes the internal temperatures, viscosity, etc. in both the present and in the future. The intent of the control provided in these first two segments is to heat the material, as rapidly as possible, to a lowering viscosity point while maintaining a nearly uniform rheological state through the thickness. This establishes a favorable condition for consolidation. Once in segment 3 the system continues to ramp the temperature, as rapidly as possible, to a value of 350°F with the cure rate control enabled. A cure rate limit of 1% per minute is set in segment 3. The model computes both current and future (out to 60 minutes ahead) values of the degree of cure and cure rate. The system reacts to the larger of either the current or future predicted cure rates by reducing the heating rate until the limit rate condition is satisfied. The intent of this is to cure the material as rapidly as possible without allowing an uncontrolled exotherm to occur. Control is passed to segment 4 when the lowest part temperature ("LAG") is greater than 340°F. In segment 4 a constant setpoint of 350°F is maintained for 2 hours. This, in combination with the highest part temperature ("LEAD") control condition set in segment 1, drives the material to a temperature between 340°F and 350°F throughout the thickness, and holds while the cure is completed. After 2 hours, control is passed to segment 5 where the material is cooled. After cooling the system is shut down in segment 6.

Table 1: Demonstration Run Curefile

Seg Time (or END)	Seg1	Seg2	Seg3	Seg4	Seg5	Seg6
Temp Control T/C	LEAD			2H		END
Rate		5				
Value	CURR	350			150	
Cascade In	A					
Cascade Out	A					
Watch #1		MVDL T	LAG		LAG	
Criterion (if)		<2	>340		<150	
Action (then)		AND	GO		GO	
Watch #2		MVT				
Criterion (if)		<85				
Action (then)		GO				
Blower Fan	ON					OFF
Heat Enable	ON					OFF
CureRate Cntl Enable	OFF		ON			
CureRate Limit			1			
Deg Cure Cntl Enable	ON		OFF			
Deg Cure Limit	2					

The results of this demonstration are shown in Figures 3 (for the first three segments). In Figure 3a, the air temperature is the boundary condition determined by the controller according to the curefile specifications. The resulting laminate temperatures are also shown. Parts (b) and (c) of Figures 3 also show some of the model predicted variables such as reaction rate and viscosity that were used for control purposes. The vertical lines demarks the segments. Also shown in Figures 3b and 3c are verifications of model predictions. In Figure 3b, a post-run analysis of temperature data was performed according to Equation 4 to obtain the shown reaction rate. It can be seen that the model prediction is quite accurate. In Figure 3c, the validity of the predicted viscosity is confirmed by the on-line monitored DC resistance.

Referring to Figure 3, the degree of cure reached the cure limit of 2% at about 17 minutes into the cure, as prescribed in segment 1, and inherited by segment 2, of the curefile, the controller caused the temperature to level off. The viscosity delta ("MVDLT") dropped to a local minimum and the viscosity value ("MVT", the normalized log of the predicted viscosity) decreased towards the 85% level after about 48 minutes into the cure. These conditions satisfied the segment 2 watch criteria and the cure entered segment 3. In segment 3 control changed from degree of cure control to cure rate control. A future cure rate prediction of over 1% per minute brought about a leveling off in air temperature at about 150 minutes as can be seen in Figures 3a and 3c. The peak in the reaction rate later occurred at about 175 minutes and is controlled to only slightly above the 1% per minute value (based on model) specified in the curefile. As the lowest part temperature ("LAG") became greater than 340°F at 238 minutes the process transitioned to segment 4. Note that although not implemented in this demonstration, it is possible to specify a watch criterion on segment 4 to require a specified degree of cure value (e.g. > 95%) or a specified viscosity value be achieved before passing control to segment 5 in place of the specified 2 hour hold.



Figures 3. Demonstration of the Proactive Controller for Curing a 128-ply S2/8552 Test Panel.

4. CONCLUSIONS

A proactive self-directed control system was developed and applied to the cure of a thick glass/epoxy composite. The system was shown capable of first driving the material to a low, uniform, rheological state in preparation for consolidation. The system was then shown capable of controlling the cure reaction rate to avoid an undesirable exotherm. All this was accomplished through the use of only three through thickness thermocouples. This was made possible by the incorporation of a cure model which provides the ability to look-ahead into the future and to provide virtual sensor inputs into the control loop.

5. ACKNOWLEDGEMENT

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