

Integrated Switching and Feedback Control for Mold Filling in Resin Transfer Molding

Prabir Barooah

Berna Berker

J. Q. Sun

Mem. ASME

Department of Mechanical Engineering,
University of Delaware,
Newark, DE 19716

Two recent advances in controlling flow progression in RTM are the sequential logic control and the optimal feedback control. Both methods have powerful features as well as limitations. However, they complement each other very well. In this paper we propose an integrated control scheme combining both of them. In this paper the theory of the sequential logic control and the optimal control for flow progression manipulation in RTM is reviewed first. An integrated control approach is then proposed. Simulation results show that the control authority of the system is considerably expanded by the combination of the two. The integrated switching and feedback controller gives excellent performance of mold filling even in the presence of wide variations of the preform properties.

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1 Introduction

Resin transfer molding (RTM) is a high performance net-shape manufacturing process for polymer composite parts, especially in aircraft and automobile industries. It is particularly suitable for producing large and geometrically complex parts. However, at present, part fabrication by RTM is a very expensive proposition due to the typically long process development time, limiting the potential use of the process [1]. RTM consists of the following steps: (a) preform fabrication, (b) preform placement inside the mold, (c) mold filling by resin injection, (d) curing, and finally (e) demolding of the finished part. The inherent variations of the process make it difficult to predict what happens inside the mold during the filling and curing stages and therefore what the properties of the resulting part will be. Both filling and curing are critical steps, though successful mold filling without dry spots is the first step to having a defect free part.

Ideally, the resin flow should progress so that the last part of the mold to be filled is near the vents, and the preform is wetted out completely without leaving any dry spots. The flow pattern in the mold depends on such parameters as preform porosity and permeability, and resin viscosity. These properties are required as input parameters for the physical models used to simulate mold filling. However, the permeability and porosity cannot be estimated accurately beforehand as compaction, preform preparation, etc. all affect their values. A common problem is the edge effect called racetracking which makes the resin flow faster along the edges of the preform. These random, unpredictable variations in the preform properties make it extremely difficult to predict resin flow progression accurately, which in turn makes it difficult to design an effective injection and venting scheme without trial and correction cycles (see Bickerton [2] and references therein).

The trial and correction cycles result in a long and expensive process development, and the high cost of manufacturing with RTM. Cost reduction will be realized if the manufacturing process is automated to provide uniformly high quality parts at a rapid rate. Control strategy development for mold filling in RTM is a key step toward automation. The control strategy should accomplish such tasks as driving the flow front to an optimal profile, avoiding the formation of voids and weld lines, and reducing the process time while keeping the control effort and the necessary hardware expenditure at a reasonable level.

Since gate and vent location is an important issue for RTM,

there have been efforts to find the optimum gate/vent locations. Some of these are aimed at finding the best vent locations to avoid void formation [3–5], while others concentrate on finding optimum gate locations to produce minimum part warpage, dimensional instability, filling pressure etc. [6–8].

There have been studies on controlling the flow progression in RTM by using neural networks. Smith and Dagli have trained a back-propagation neural network for the process control of an injection molding process [9]. Souder and Woll have developed a back-propagation neural network to model the injection molding processes and identify defects, and suggested that the neural network models can serve as a basis for adaptive control [10]. Choi and co-workers have used neural networks to model the injection molding process, and developed an adaptive optimization scheme to find optimal process parameters [11]. Demirci and Coulter have shown that the actual flow front profile in RTM can be driven to reach a previously determined desired profile by manipulating the injection flow rate through the neural network based control schemes, but the controllability is lost when the flow front advances to a distance greater than half of the mold width [12–16]. The neural network controller is further extended in Lafferty and Pitchumani [17] and Nielsen and Pitchumani [18] by integrating with the fuzzy logic. Kranbuehl and co-workers have utilized the frequency dependent electromagnetic sensor (FDEMS) system for monitoring resin properties for quality assurance and for intelligent control of the process [19]. Mychajluk and Manoochehri have developed a model to calculate the process set point values that correspond to minimum cycle time in RTM while maintaining a constraint such as void minimization [20]. Yu and Young have considered the problem of determining optimal process parameters that will result in a short cycle time and a suitable part quality, and have utilized generic algorithms (GAs) [21].

Most of the studies on controlling the flow front shape are based on neural networks. The training of the networks is usually done by using hundreds or even thousands of simulated different scenarios as the training set, since conducting a large number of RTM experiments to gather real data is not feasible. Therefore these neural networks suffer from the same limitations as the mold filling simulations do. Moreover, as we have shown later in Section 2, the number of possible scenarios grows exponentially as the complexity of the mold increases. This makes it impractical to train the network even on the cases that are known to be possible.

To overcome these limitations, Berker et al. [22] have proposed a nonlinear optimal feedback control algorithm for controlling the flow front based on real time sensing and system estimation. The control objective is to drive the flow pattern toward a predeter-

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mined shape. A local adaptive model of the transfer function from the inlet conditions to the flow front location was proposed and was estimated by using the lineal flow sensor signals. In this control scheme, a performance index is defined based on the difference between the flow front set points and the actual flow front as measured by the sensors, and the control input is determined so as to minimize the performance index.

Another class of research is aimed at developing switching controls by opening or closing gates and vents. Based on the sensor information, different injection ports are switched on or off. This approach can decrease the cycle time and the injection pressure. A “sequential multiple port” resin injection method for decreasing mold filling time and void formation was proposed in Chan and Morgan [23], and was illustrated for one dimensional flow. An extension of this methodology, called the sequential logic control, was proposed by the authors in Berker, Barooah, and Sun [24].

In this paper, we propose to combine the sequential logic control and the optimal feedback control to take advantages of both. A comparison of the two control schemes show that they complement each other very well; the strength of one is the weakness of the other. This motivates the integration of the two control schemes. Combining the two control schemes will incur additional cost to the eventually automated injection equipment. This cost will be offset in two ways. First, the mold design and fabrication that may otherwise need a lot more vents and gates will be simplified. Second, feedback control offers another dimension of quality assurance that can potentially save an expensive composite part from being wasted. Furthermore, it should be pointed out that because of the rapid advances in computer and high tech industry, the cost of implementing even a large dimensional feedback control system is not significant at all when compared with the cost of manufacturing a sophisticated mold and complex composite parts.

The outline of the paper is as follows: In the first two sections, Sections 2 and 3, sequential logic control (SLC) and feedback control are briefly discussed. In Section 4, we propose an integrated control structure consisting of both these control schemes. The performance of the proposed integrated control methodology is examined through simulations. These results are discussed in Section 4. The paper concludes in Section 5.

2 Sequential Logic Control (SLC)

Sequential logic control (SLC) consists of a series of decisions regarding closing vents and opening gates upon arrival of the fluid at their locations. The foundation of the control algorithm is built on a proper, preferably optimized, vent and gate configuration for a given mold. Automatic gates, automatic vents, and vent-to-gate converters are used for implementing the control logic. These are hardware elements used for automating the injection and venting process. The methodology is examined in detail in Berker, Barooah, and Sun [24]. Here it is briefly explained, and the pros and cons are examined.

SLC was initially derived from studies of mold filling schemes for long and narrow molds, where the aspect ratio of length to width is large. To extend the sequential logic to two-dimensional mold geometries, where the flow pattern can be complex, the concept of sub-domains is utilized. A complex mold is divided into simpler regions, called sub-domains. A sub-domain can either be a channel or a block. A *channel* can be simply defined as a region inside the mold, demarcated by physical boundaries of the mold or the rigid inserts, or by imaginary lines. The flow front in a channel does not bifurcate to more than one sub-flow front. Regions where the width and length dimensions are comparable are called *blocks*. In general, any sub-domain which cannot be approximated by a channel is a block. Note that channels or blocks need not be rectangular. When several sub-domains are viewed as channels, SLC can be applied to each channel individually. However, SLC has difficulty in dealing with blocks with a small number of gates and vents.

Consider a rectangular mold with two inserts shown in Fig. 1(A), hereafter referred to as mold A. The mold is divided into four sub-domains marked as 1, 2, 3 and 4. The first three are channels. We consider two extreme scenarios with the help of simulations for the mold having no vents: (a) when there is no racetracking anywhere, and (b) when there is racetracking along all edges of the mold. By examining the location of the voids formed in the channels, we decide the placement of control elements including gates, vents and vent-to-gate converters.

Note that the placement of gates and vents is a large optimization problem itself. SLC does not address this issue explicitly. The approach based on the studies of “extreme scenarios” helps intuitively place the gates and vents. This placement is by no means the best or optimal.

The results of applying SLC to this mold are shown in Figs. 1(B) and (C), when there is no racetracking and when there is racetracking on all edges, respectively. As seen from the simulation results, the sequential logic control is able to successfully fill the mold without entrapping any voids in both of these cases. More examples of SLC applications in other complex molds can be found in Berker, Barooah, and Sun [24].

Limitations of SLC. We have applied SLC to complex 2-D molds by dividing the molds into channels, where the placement of gates and vents, and the control logic are fairly intuitive. However, no general guidelines have been found for molds with truly 2-D flow. The placement of gates and vents based on a study of two extreme cases clearly cannot cover many other possible scenarios. For example, what happens if the resin racetracks along some edges but not along others? The resulting complex flow front due to asymmetric racetracking, in general, does not resemble the flow fronts of the two extreme cases considered in the

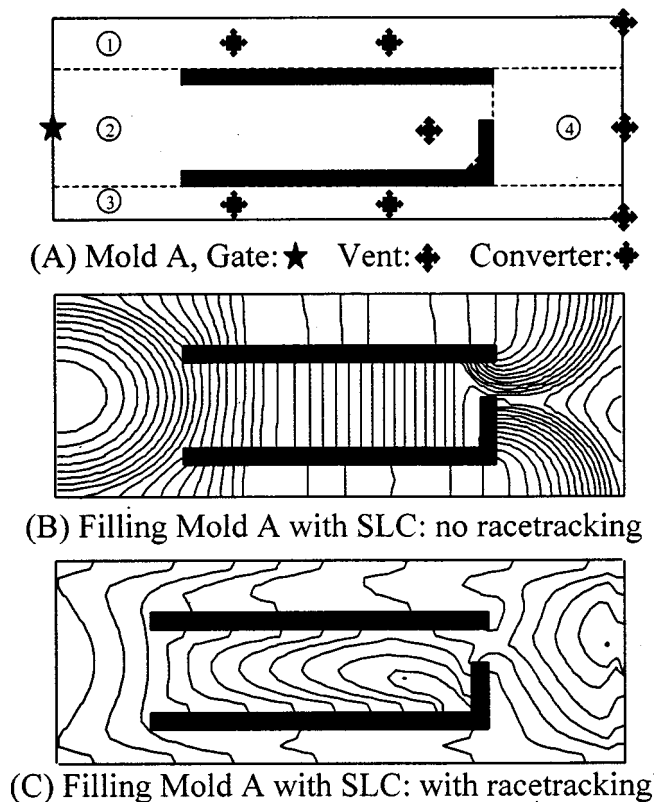


Fig. 1 Mold A: (A) channels and placement of control elements, (B) mold filling with SLC for no racetracking, (C) mold filling for racetracking

design stage. The controller cannot work well when there are wide variations in the preform properties inside the mold. This high sensitivity to parameter variation is a limitation of SLC.

To study the limitation of the sequential logic control, we have reconsidered mold A with different racetracking. Thirteen cases of asymmetric racetracking were examined through simulation. SLC could successfully fill only three. It is evident that SLC cannot handle all possible variations with a given placement of gates and vents [24].

If an SLC controller is to be designed by considering all possible extreme cases, we have to conduct a large number of simulations. There are a total of ten edges in mold A along which racetracking can occur (excluding the very short ones). Since all the channels and blocks are of different shapes and sizes, racetracking along each edge creates a unique scenario. The total number of unique cases of racetracking is given by $N=2^{10}=1024$. This formula only considers yes/no racetracking along an edge, and does not consider the degree of racetracking, or other possible parameter variations such as that of porosity and fluid viscosity, which will increase the number of possible cases even further. It is not feasible to simulate all these cases in order to design a gate and vent configuration for SLC.

The SLC controller makes a decision based on discrete sensors, and does not take into account the shape of the flow front. However, in a general 2-D mold, the shape of the flow front becomes very important, and cannot be deduced by looking at signals from only a few discrete point sensors. This brings us to another limitation of SLC. It only decides to open or close a gate or a vent. Opening a gate, even though it has a large effect on the flow front progression, is not always enough to control the shape. To control the shape of the flow front, the gate pressures have to be adjusted appropriately. The inability of SLC to change the flow front to a desired shape was the motivation for developing a feedback control [22], which is described briefly in the next section.

3 Feedback Control of RTM

Feedback control of RTM aims at controlling the flow front in the mold by adjusting the inlet conditions. The controller regulates the actual flow pattern toward a predetermined shape. An important element of this control is sensing the flow front. Lineal sensors have been developed for this purpose [25]. Lineal sensors consist of a pair of closely placed conductive wires, and can be placed in the mold to determine the location of the flow front. A local adaptive model of the transfer function from the inlet conditions to the flow front sensors have been developed and on-line estimation algorithms have been applied to update the local model. A performance index is defined based on the difference between the flow front set points and the actual flow front as measured by the sensors. The control input is determined by minimizing the performance index. The basics of this control strategy are discussed in the following section. A more complete description can be found in Berker, Barooah, Yoon, and Sun [22].

Resin flow in RTM is governed by the conservation law of the mass as well as Darcy's law for viscous flow through porous media. Darcy's law is stated as

$$\mathbf{V}(\mathbf{x}) = -\frac{\mathbf{K}}{\mu} \nabla \mathbf{P}(\mathbf{x}), \quad (1)$$

where $\mathbf{V}(\mathbf{x})$ is the volume averaged Darcy velocity of the fluid, \mathbf{K} is the preform permeability tensor, $\mathbf{P}(\mathbf{x})$ is the pressure field and μ is the resin viscosity. The analytical solution of Eq. (1) for the complex boundary conditions is not available. With poorly known permeability of the preform as well as variations in μ , combined with the computational burden of solving for the equation, even well developed finite element codes cannot provide a reliable predictive model for real time control. Moreover, in order to control the flow front shape by manipulating the gate pressure or flow rate, we need a model that relates the inlet condition (inputs) to the flow front sensor (output).

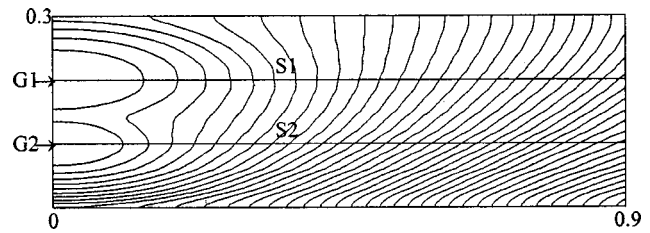


Fig. 2 Uncontrolled flow front

To this end, we have proposed the following model for 2-D flow in RTM:

$$\mathbf{s}_{k+1} = \mathbf{s}_k + \mathbf{C}_k \mathbf{u}_k \Delta t, \quad (2)$$

where \mathbf{s}_k is a $n \times 1$ vector representing the flow front, consisting of measurements from n lineal sensors, \mathbf{u}_k is a $m \times 1$ vector of m control inputs, \mathbf{C}_k is the $n \times m$ system model coefficient matrix evaluated at the k^{th} sample step, and Δt is the time interval: $\Delta t = t(k+1) - t(k)$. Evaluation of \mathbf{C}_k can be done on-line either by a least square estimation method or by a perturbation method [22]. Equation (2) represents the general expression of local models for multiple input and multiple output liquid injection molding systems. This model forms the basis for feedback control formulation. The reader is referred to Barooah, Berker, and Sun [25]; Barooah [26] for more discussions on how to design and implement a set of lineal sensors for measuring the resin flow front as a function of time.

Let $\mathbf{s}_{k+1(ref)}$ denote the sensor signal vector representing the desired flow front pattern at the sensor locations at the $(k+1)^{\text{th}}$ time step, and let \mathbf{e}_{k+1} be the difference between the actual sensor signals \mathbf{s}_{k+1} and the desired $\mathbf{s}_{k+1(ref)}$, i.e., $\mathbf{e}_{k+1} = \mathbf{s}_{k+1} - \mathbf{s}_{k+1(ref)}$. From Eq. (2), we obtain a state equation for \mathbf{e}_{k+1} .

$$\mathbf{e}_{k+1} = \mathbf{e}_k + \mathbf{C}_k \mathbf{u}_k \Delta t + \mathbf{s}_{k(ref)} - \mathbf{s}_{k+1(ref)} \equiv \mathbf{f}_k(\mathbf{e}_k, \mathbf{u}_k). \quad (3)$$

A performance index J_{k+1} can be defined as $J_k = \mathbf{e}_{k+1}^T \mathbf{e}_{k+1}$. Minimizing J_{k+1} with respect to \mathbf{u}_k will minimize the norm of the tracking error \mathbf{e}_{k+1} in the next time step. The optimality condition is $\partial J / \partial \mathbf{u}_k = 0$, which yields the optimal \mathbf{u}_k^* as

$$\mathbf{u}_k^* = -(\mathbf{C}_k^T \mathbf{C}_k)^{-1} (\mathbf{s}_k - \mathbf{s}_{k+1(ref)}). \quad (4)$$

A more general control formulation with range and rate saturation of actuators can be found in Berker, Barooah, Yoon, and Sun [22].

Figure 2 shows a rectangular mold with two injection ports and two lineal sensors placed in it. The permeability values of the preform linearly decrease from the top to the bottom of the mold. At a constant injection pressure at both gates, the flow front naturally takes a skew shape, as shown in the same figure. The control objective here is to change the flow front to a straight "vertical" line. Figure 3 shows the resulting flow front shapes with optimal feedback control.

The estimated coefficients \mathbf{C}_k with the least squares method for the first gate are depicted in Fig. 4. The optimal injection values are depicted in Fig. 5. Since the permeability values are lower along the first gate compared to the second gate in Fig. 2, the flow

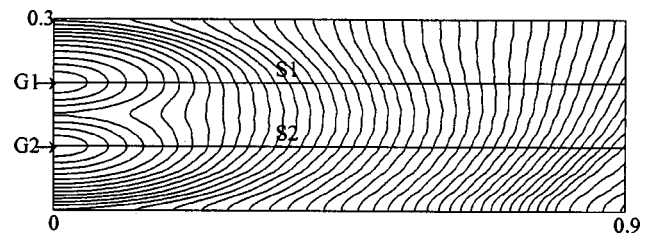


Fig. 3 The flow front under the optimal feedback control

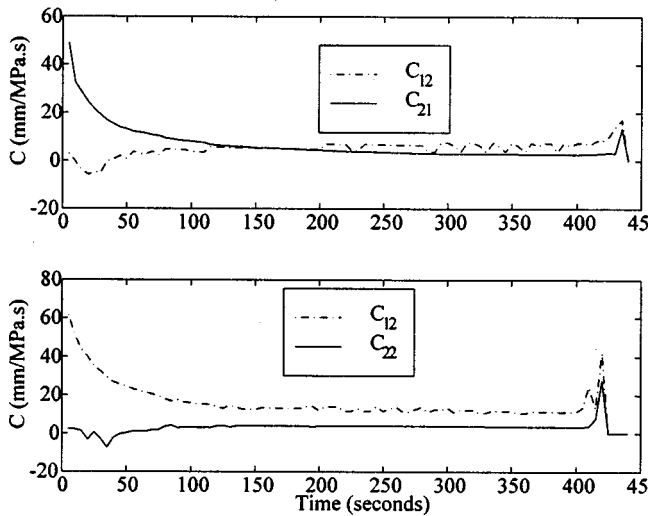


Fig. 4 The system transfer function coefficients as a function of time. Top: the coefficients of G1, Bottom: the coefficients of G2.

progresses more slowly along the first sensor. In order to keep the flow front along both the sensors at the same rate, the injection at the first injection gate reaches the upper limit while the second gate reaches the lower limit.

At the beginning of filling, the control is able to alter the flow front in the desired manner. As the flow front progresses further away from the injection ports, the controller's ability to affect the flow reduces and the natural slanted flow front shape takes over. The "controllability" is lost when the distance between the gates and the flow front is between 0.5 and 0.6 m. The error between the desired and the actual location of the flow on the sensors is depicted in Fig. 6. It is interesting to point out that the rising trend of the error indicates the loss of "controllability."

Limitations of Feedback Control. It is evident from the above discussions that feedback control is effective in relatively small regions of the mold. In order to have "controllability" during the entire mold filling, there must be sufficient number of gates distributed over the mold area and the feedback controller has to be reconfigured with different gates and vents in different stages of filling.

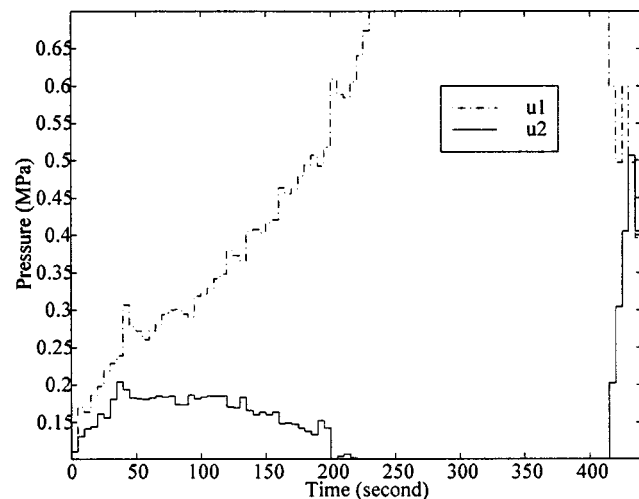


Fig. 5 The optimal injection pressures of the controller. u_1 : pressure at G1, u_2 : pressure at G2.

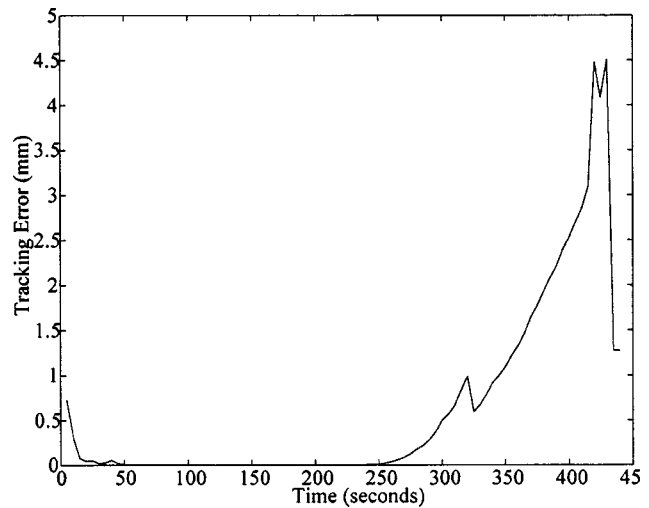


Fig. 6 The tracking error $\|s_k - s_{k,ref}\|$ as a function of time

A Summary. Table 1 summarizes the comparison of the relative strengths and weaknesses of SLC and feedback control. The first three points in the table are already discussed in previous sections. The fourth one, namely "sensitivity to parameter variation" is a measure of the robustness of the control, i.e., how well the control works when the permeability and other parameters vary spatially inside the mold. Since feedback control estimates the system properties on-line, it is able to track the system parameters in real time and take appropriate control action. SLC, however, is based on a predesigned gate and vent locations. Hence the effectiveness of SLC is dependent on the system behavior being close to that in the examined scenarios. Table 1 clearly indicates that these two control strategies complement each other well.

4 Integrated Switching and Feedback Control

The discussion in the previous section leads to the conclusion that there is much to be gained from combining SLC and feedback control. The integrated controller will involve two levels of decision making. First, it carries out switching commands of opening or closing gates and vents. Then, it has to adjust the injection pressures at the gates according to a feedback control. This control structure is called the *integrated switching and feedback control*. The block diagram in Fig. 7 illustrates the main concept of the control method. The control approach and the associated issues are further illustrated with the help of an example in the following.

Application of the Integrated Controller to Mold Filling.

In this section, we demonstrate the ability of the integrated switching and feedback control through simulated experiments on mold A. The simulations were done with the help of the finite element program LIMS and Matlab.

The mold is divided into five sub-regions: block 1, channels 1, 2 and 3, and block 2 as shown in Fig. 8. It is seen from simulations that for an injection starting at the left, the speed of resin flow in the three channels are not equal due to the different sizes of the channels; and in the presence of non-uniform racetracking

Table 1 Comparison of the optimal feedback control and SLC

Control methodology	SLC	Feedback
Effect on the flow front progression	more	less
Accurate control of the flow front shape	less	more
Region of effectiveness	large	small
Sensitivity to parameter variation	more	less

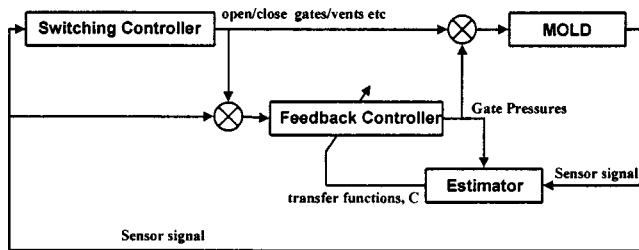


Fig. 7 The block diagram of the integrated switching and feedback control

along the edges of the inserts, they can be widely different. As a result, the flow fronts in the three channels arrive in the last region at different times, sometimes causing flow from one channel to get into another channel. This makes the resulting flow front shape extremely complex, especially in block 2. In such a situation it is virtually impossible to predict what will be the last point to fill in that region in order to locate a vent there.

Hence we decided to control the mold filling with the help of the feedback controller such that the flow fronts in the channels arrive at block 2 at the same time. Then, block 2 can be filled by opening a gate at its bottom left corner and driving the flow front to a vent placed at the top right corner.

The gates, vents and vent-to-gate converters, and lineal sensors in the mold are also shown in Fig. 8. $G1$, $G2$ and $G3$ denote gates. $VGC1$, $VGC2$ and $VGC3$ denote vent-to-gate converters. $V1$ and $V2$ denote vents. $S1$ through $S6$ are six lineal sensors. The flow chart of the control system is shown in Fig. 9. First we inject from $G1$. When all three converters detect resin arrival, $G1$ is closed, the vents of $VGC1-3$ are closed, and injection continues at $VGC1-3$ initially at the nominal pressure. The nominal pressure is half the maximum available pressure ($P_{max} = 5 \times 10^5$ Pa).

The injection pressure at $VGC1-3$ is regulated by a feedback controller to make the average flow front location in the three channels the same. When $S1$, $S2$ and $S3$ signal that the channels are fully filled, $VGC1-3$ are closed, and $G2$ is opened by the controller. $G3$ is also opened when the flow front in the region has advanced sufficiently towards $V1$. This decision is based on the reading of at least 0.1 m from $S5$. $G3$ was incorporated to deal with severe recetracking cases when injection from only $G2$ is not

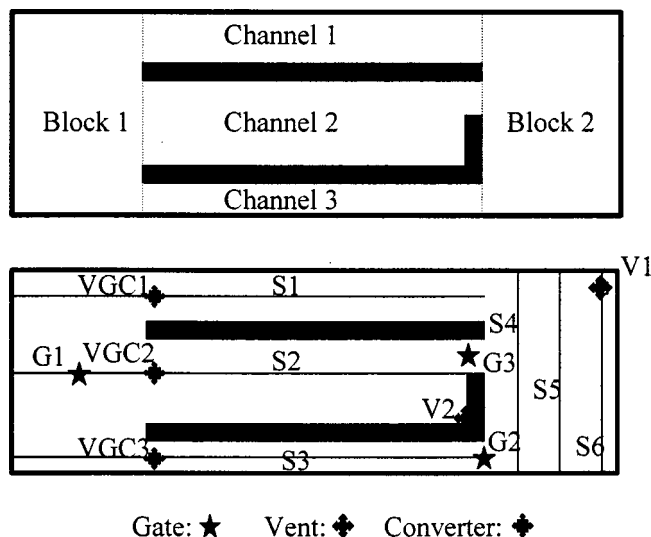


Fig. 8 Top: the sub-domains of mold A. Bottom: location of control elements and lineal sensors in mold A.

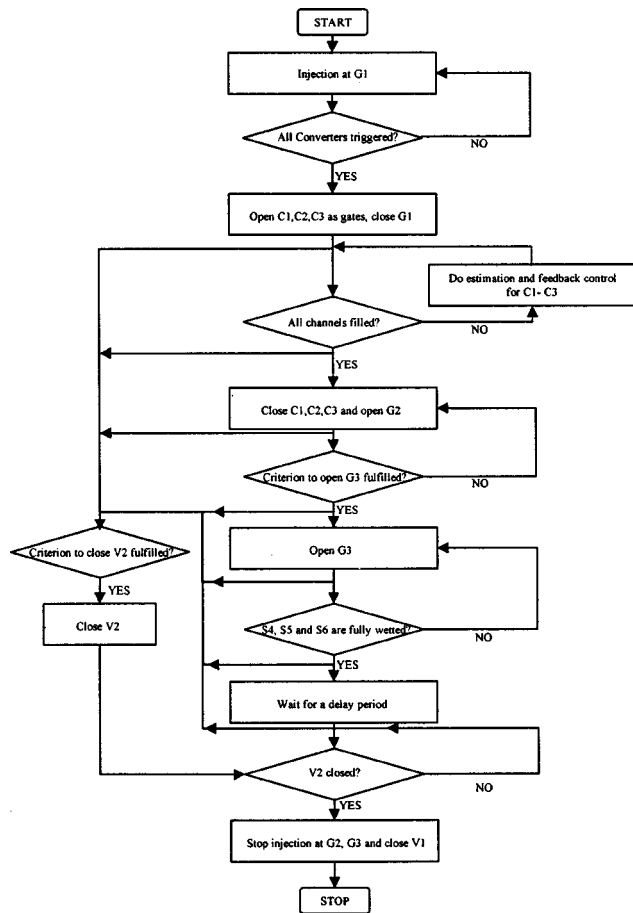


Fig. 9 Flow chart of the integrated control logic for mold filling in mold A

enough to avoid dry-spots in block 2. Injection from $G2$ and $G3$ continues at maximum pressure till the three lineal sensors $S4$, $S5$ and $S6$ in the last block are saturated and resin is detected at $V1$. This indicates complete filling of block 2. After a 10 second delay to allow air to escape, injection is stopped.

The detection of resin at $V1$ does not always mean complete filling of block 2 since recetracking might occur to create dry-spots near the vent. That is why the lineal sensors are placed in that region to sense the presence of voids. $V2$ is closed by the switching controller upon resin arrival and after the reading from $S2$ shows the flow front is sufficiently close to the end of channel 2.

The converters $VGC1-3$ can be expected to mostly affect their corresponding channels only, i.e., $VGC2$ in the middle channel does not affect the flow front in the top and the bottom channels, and vice versa. This assumption makes C_k diagonal. Since we have only one gate per channel, the pressure of the gate would only affect the average location of the flow front in the corresponding channel.

The objective of the feedback control is simply to create an average flow front across these channels to form a straight line perpendicular to the top and bottom edges of the mold. The set point of the average flow front is determined by $a_k = \text{mean}(s_k + C_k u_k \Delta t)$ where $\Delta t = 10s$ is the control time interval.

The estimation of C_k is done using a least squares method. Note that estimation can be done at the speed of data acquisition, if sufficient computational power is available. However, the actuators to control injection pressures have a finite rise time, and hence it is not possible to update the control actions at a high speed.

Example 1. We first apply the controller to the mold without racetracking. The controlled flow pattern is shown in Fig. 10. The flow front pattern shows that the control was able to accomplish the objective.

The time history of the control is shown in Fig. 11, and the estimated values of C_k are shown in Fig. 12. The feedback control loop was active for less than half of the total filling time. At other times, switching dictated the injection process. Due to uniform properties of the preform and no racetracking, the flow in all three channels behaved similarly. This indicates that the flow front would gradually take on a “vertical” straight line shape even without control. Hence, the feedback controller did not have to expend much effort as shown in Fig. 11. The injection pressures at VGC1-3 for the most part were close to the nominal pressure values. Figure 13 shows the values of the tracking error as a function of time.

The difference between the predicted flow front by the system model of Eq. (2), and that simulated by LIMS s_k^{LIMS} is shown in Fig. 14. The error is defined as $e_k = \|s_k^{LIMS} - (s_{k-1} + C_{k-1}u_{k-1}\Delta t)\|$. The magnitude of the error was always less than 4.5 cm.

Example 2. When racetracking is introduced along the edges located in the top half of the mold, the fluid can move faster in the top half than in the bottom half. Since the controller is designed to

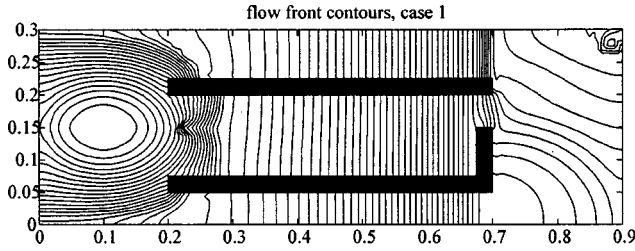


Fig. 10 The flow front contours for controlled mold filling simulation in mold A with the integrated switching and feedback control

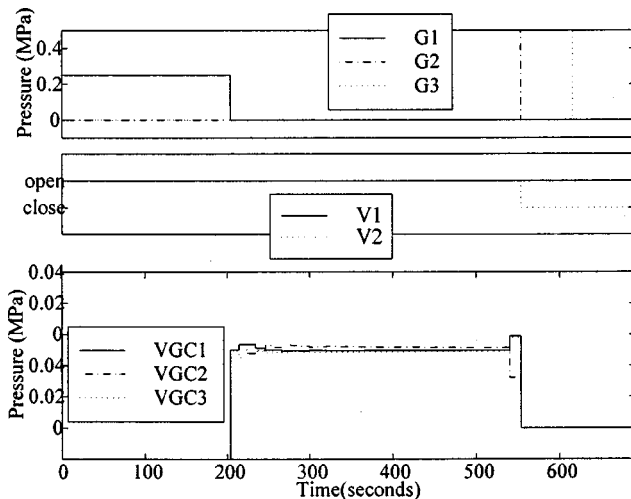


Fig. 11 The time history of the control for mold A by the integrated controller. The first plot shows the pressures at gates G1, G2 and G3. The second plot shows the operation of the vents. The third plot shows the pressures at the three vent-to-gate converters regulated by the feedback control. A negative pressure indicates that a converter is kept open as a vent. A zero pressure indicates that the injection gate of the converter is closed.

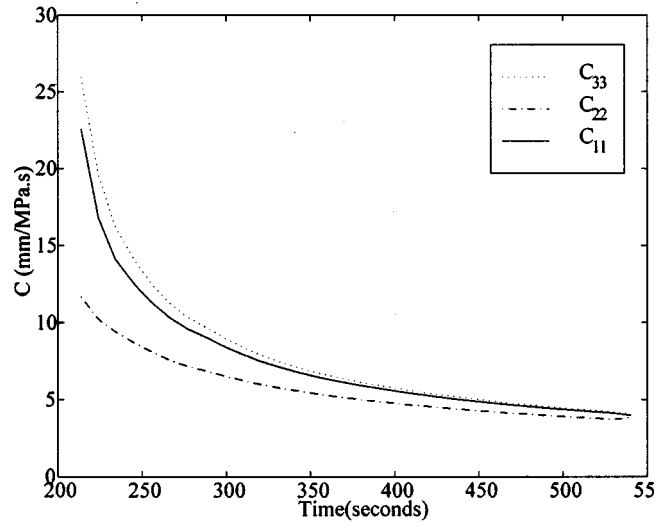


Fig. 12 The real-time estimated system coefficients when the feedback control loop was active. Since C_k is diagonal, only the three diagonal terms are shown.

drive the flow front from the bottom to the top right corner in the last region, this tendency of the flow is opposite to the control objective. The ability of the controller will be seriously tested.

Eighteen cases of racetracking with different number and location of the edges involved are studied. The performance of the controller for these cases is summarized in Table 2. The edges are numbered as shown in Fig. 15. N_{nf} in Table 2 is the number of nodes of the meshes for the mold that were not filled after filling was stopped. A larger N_{nf} indicates a bigger void entrapment and a smaller N_{nf} indicates a smaller void entrapment. A zero N_{nf} means a completely successful mold filling. The total number of nodes in the mesh was 1741. The mesh size is 12.5×12.5 mm². As seen from the table, the integrated switching and control approach was successful in filling the mold for most of these cases. Note also that cases 4 and 18 in the table takes very long to fill the mold completely so that N_{nf} goes zero due to the numerical algorithm used in the finite element code. In practice, it may not take as long.

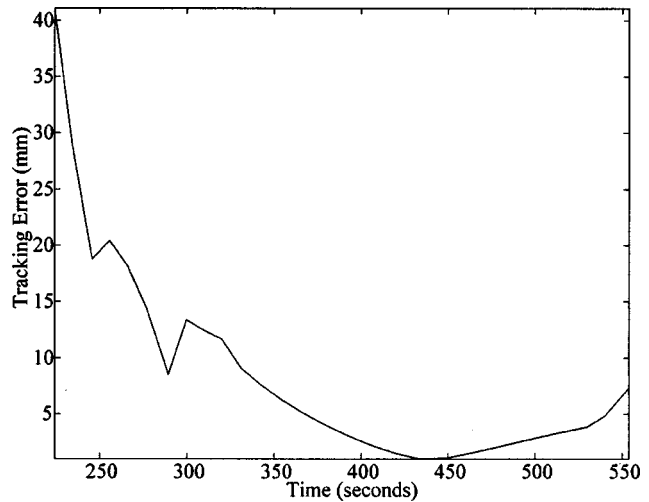


Fig. 13 The tracking error of the feedback control in channels 1 to 3

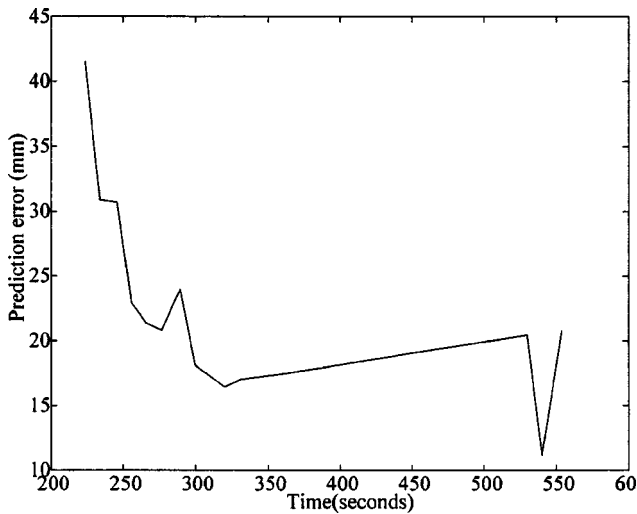


Fig. 14 The error in predicting the flow front with the proposed system model

5 Conclusions

We have presented an integrated switching and feedback control approach for regulating the resin flow progression during the mold filling stage of RTM. The integrated control has the advantages of both the switching control and the feedback control, and

Table 2 Performance of the integrated controller in the non-uniform racetracking cases

case #	Racetracking edges	Filling time(s)	N_{nf}
1	none	690	0
2	all(1-10)	400	0
3	1,2,3,4,5	450	0
4	1,2,3,4,6,7	400	3
5	1,2,3,4,5	430	0
6	1,2,3,4,8	420	0
7	1,2,3,4,5,6	410	4
8	1,2,3,4,7,8	430	0
9	1,2,3,4,5,6,7	440	0
10	1,2,3,4,6,7,8	410	0
11	1,2,3,4,5,6,7,9	400	0
12	1,2,3,4,6,7,8,9	400	0
13	3,5,9	460	0
14	3,4,5,7	480	0
15	1,3,4,5,7,8,9,10	450	0
16	3,4,5,7,8,9,10	440	1
17	2,3,4,6,7,9,10	500	3
18	2,3,4,7,10	480	3

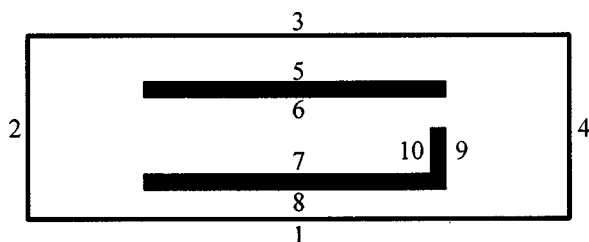


Fig. 15 The numbered edges of mold A

has much larger control authority than the feedback control alone, and has a better ability for flow front shape control than the switching control. It has been shown through simulations that the proposed integrated control is quite effective in successfully filling a mold with a complex geometry as well as a wide range of variations of system properties. Integration of two control strategies incurs additional cost. However, the cost of implementing a feedback controller is not significant thanks to the rapid advance of computer and high tech industry. The value of such an integrated system will ultimately be justified by the savings one may gain in fabricating less complicated molds and reducing the waste in the actual manufacturing process.

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References

- [1] Advani, S. G., Bruschke, M. V., and Parnas, R., 1994, "Flow and Rheology in Polymeric Composites Manufacturing," Chap. 12, *Resin Transfer Molding*, pp. 465-516, Elsevier Publishers, Amsterdam.
- [2] Bickerton, S., 1999, *Modeling and Control of Flow during Impregnation of Heterogeneous Porous Media, with Application to Composite Mold Filling Processes*, Ph.D. dissertation, University of Delaware.
- [3] Boccard, A., Lee, W. L., and Springer, G. S., 1995, "Model for Determining the Vent Locations and the Fill Time of Resin Transfer Molds," *J. Compos. Mater.*, **29**, No. 3, pp. 306-333.
- [4] Chen, Y. F., Stelson, K. A., and Voller, V. R., 1997, "Prediction of Filling Time and Vent Locations for Resin Transfer Molds," *J. Compos. Mater.*, **31**, No. 11, pp. 1141-1161.
- [5] Liang, E. W., Wang, H. P., and Perry, E. M., 1993, "Integrated Approach for Modeling the Injection, Compression, and Resin Transfer Molding Processes for Polymers," *Adv. Polym. Technol.*, **12**, No. 3, pp. 243-262.
- [6] Pandelidis, I., and Zou, Q., 1990, "Optimization of Injection Molding Design, Part I, Gate Location Optimization," *Polym. Eng. Sci.*, **30**, No. 15, pp. 873-882.
- [7] Lee, B. H., and Kim, B. H., 1995, "Automated Selection of Gate Location Based on Desired Quality of Injection Molded Part," *ANTEC'95*, pp. 554-560.
- [8] Young, W.-B., 1994, "Gate Location Optimization in Liquid Composite Molding Using Genetic Algorithms," *J. Compos. Mater.*, **28**, No. 12, pp. 1098-1113.
- [9] Smith, A. E., Dagli, C. H., and Raterman, E. R., 1991, "An Empirical Analysis of Back-Propagation Error Surface Initiation for Injection Molding Process Control," *IEEE Pub.*, pp. 1529-1534.
- [10] Souder, B., Woll, S., and Cooper, D., 1994, "Advanced Methods for Monitoring Injection Molding Processes," *Proceedings of the 52nd Annual Technical Conference ANTEC 94*, Vol. Part 1 (of 3) San Francisco, California, pp. 644-650.
- [11] Choi, G. H., Lee, K. D., Chang, N., and Kim, S. G., 1994, "Optimization of Process Parameters of Injection Molding with Neural Network Application in a Process Simulation Environment," *CIRP Ann.*, **43**, No. 1, pp. 449-452.
- [12] Demirci, H. H., and Coulter, J. P., 1994, "Neural Network Based Control of Molding Processes," *J. Mater. Process. Manuf. Sci.*, **2**, No. 3, pp. 335-354.
- [13] Demirci, H. H., and Coulter, J. P., 1994, "Intelligent Control of Resin Transfer Molding Processes (RTM) Utilizing Neural Networks and Nonlinear Optimization Methods," *Proceedings of Processing, Design, and Performance of Composite Materials*, **52**, Chicago, Illinois, pp. 13-28.
- [14] Demirci, H. H., and Coulter, J. P., 1995, "Control of Flow Progression during Molding Processes," *J. Mater. Process. Manuf. Sci.*, **3**, No. 4, pp. 409-425.
- [15] Demirci, H. H., and Coulter, J. P., 1995, "Comparative Study of Neural Network Architectures Applied to the Manufacturing of Composite Materials," *Proceedings of the 1995 ASME International Mechanical Engineering Congress and Exposition*, Part 2 (of 2), Vol. 69-2, San Francisco, California, pp. 1173-1192.
- [16] Demirci, H. H., and Coulter, J. P., 1996, "Comparative Study of Nonlinear Optimization and Taguchi Methods Applied to the Intelligent Control of Manufacturing Processes," *J. Intell. Manufact.*, **7**, No. 1, pp. 23-38.
- [17] Lafferty, P. D., and Pitchumani, R., 1998, "An Intelligent Model-Predictive Process Control Framework for RTM," *Proceedings of the 13th Technical Conference of the American Society for Composites*, pp. 213-225.
- [18] Nielsen, D., and Pitchumani, R., 1999, "An Intelligent Simulation-Based Optimal Control of Liquid Composite Molding Processes," *Proceedings of the ONR Sponsored Conference on On-Line Sensing and Control for Liquid Molding of Composite Structures*.
- [19] Kranbuehl, D. E., Kingsley, P. J., Hart, S. M., Hasko, G., Dexter, B., and Loos, A. C., 1994, "In Situ Sensor Monitoring and Intelligent Control of the Resin

- Transfer Molding Process," *Polym. Compos.*, **15**, No. 4, pp. 299–305.
- [20] Mychajluk, G., and Manoochehri, S., 1994, "Integrated Process Model and Cycle Time Optimization for Resin Transfer Molding," *Proceedings of the 1994 International Mechanical Engineering Congress and Exposition-Advances in Computer-Aided Engineering (CAE) of Polymer Processing*, Vol. 49, Chicago, Illinois, pp. 225–237.
- [21] Yu, H.-W., and Young, W.-B., 1997, "Optimal Design of Process Parameters for Resin Transfer Molding," *J. Compos. Mater.*, **31**, No. 11, pp. 1113–1140.
- [22] Berker, B., Barooah, P., Yoon, M. K., and Sun, J. Q., 1999, "Sensor Based Modeling and Control of Fluid Flow in Resin Transfer Molding," *J. Mater. Process. Manuf. Sci.*, *in press*.
- [23] Chan, A. W., and Morgan, R. J., 1992, "Sequential Multiple Port Injection for Resin Transfer Molding of Polymer Composites," *SAMPE Q.*, **24**, No. 1, pp. 45–49.
- [24] Berker, B., Barooah, P., and Sun, J. Q., 1997, "Sequential Logic Control of Liquid Injection Molding with Automatic Vents and Vent-to-Gate Converters," *J. Mater. Process. Manuf. Sci.*, **6**, No. 2, pp. 81–103.
- [25] Barooah, P., Berker, B., and Sun, J. Q., 1998, "Lineal Sensors for Liquid Injection Molding of Advanced Composite Materials," *J. Mater. Process. Manuf. Sci.*, **6**, No. 3, pp. 169–184.
- [26] Barooah, P., 1999, *Lineal Sensors for Flow Sensing and Optimal Control of Flow Progression in Resin Transfer Molding*, M. S. thesis, University of Delaware.