A New Design Method for T-S Fuzzy Controller with Pole Placement Constraints

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ABSTRACT

A new design method for Takagi-Sugeno (T-S in short) fuzzy controller which guarantees global asymptotic stability and satisfies a desired performance is proposed in this paper. The method uses LMI (Linear Matrix Inequality) approach to find the common symmetric positive definite matrix P and feedback gains K_i, $i=1, 2, \cdots, r$, numerically. The LMIs for stability criterion which treats P and K_i's as matrix variables is derived from Wang *et al.*'s stability criterion. Wang *et al.*'s stability criterion is nonlinear MIs since P and K_i's are coupled together. The desired performance is represented as r LMIs which place the closed-loop poles of r local subsystems within the desired region in s-plane. By solving the stability LMIs and pole placement constraint LMIs simultaneously, the feedback gains K_i's which guarantee global asymptotic stability and satisfy the desired performance are determined. The design method is verified by designing a T-S fuzzy controller for an inverted pendulum with a cart using the proposed method.

I. Introduction

Application of fuzzy logic to control problems has been an important issue for past two decades since Zadeh's seminal paper [1]. Main stream of research has been focused on its application to industrial systems and a lot of successful results have been reported in the literature. There has been, however, few research on the development of systematic design methods for fuzzy controllers. It has been a major obstacle of wide acceptance of fuzzy control in the field of automatic control.

It is usual to categorize the fuzzy controllers by so-called Mamdani type and T-S type according to its appearance of consequence part. T-S type can adopt local linearlized model as its consequence part while Mamdani type uses pure linguistic one. Therefore, it is hopeful to seek systematic design methods for T-S type fuzzy controller, which is the goal of the new design method in this paper.

In the literature, there was an important breakthrough in 1992 in the field of fuzzy control. Tanaka and Sugeno [2] proposed a theorem on the stability analysis of T-S fuzzy model. It says about sufficient condition which guarantees the stability of T-S fuzzy model in the sense of Lyapunov. It can be summarized as "finding a common symmetric positive definite matrix which satisfies n simultaneous Lyapunov inequalities." Wang *et al.* [3] proposed the so-called PDC(Parallel Distributed Compensator) as a design

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framework and also modified the Tanaka's stability theorem to include control. An important observation in the paper is that the stability problem is a standard feasibility problem with several LMIs and can be solved numerically using an algorithm so-called interior-point method. It is, however, not a design method since it needs pre-determined feedback gains. Wang's method can be considered as a stability checking method for pre-designed system and needs trial-and-error for control design. Therefore, it is still necessary to develop systematic design methods which guarantee stability and desired performance.

A new design method, which guarantees stability in the sense of Lyapunov and satisfies a desired performance by placing the closed-loop poles within the inside of desired region in s-plane, is developed in this paper. It is accomplished by including LMIs about pole placement constraints to the LMIs about Wang *et al.*'s stability conditions.

This paper is organized into five sections. Section I is an introduction. Some background materials about Tanaka's stability theorem and Wang *et al.*'s PDC are summarized in the Section II. Section III is the main part of this paper and explains the proposed new design method. A T-S type fuzzy controller for an inverted-pendulum is designed using the proposed method in Section IV as an illustrating example. Concluding remarks are in Section V.

II. Background Materials

2.1 Takagi and Sugeno's Fuzzy Model

Takagi and Sugeno [4] proposed an effective way to represent a fuzzy model of a dynamic system. It uses a linear input-output relation as its consequence of individual plant rule. A T-S fuzzy model is composed of r plant rules that can be represented as

Plant rule i : if $x_1(t)$ is M_1^i and $x_2(t)$ is M_2^i and$\cdots$and $x_n(t)$ is M_n^i

$$\text{then } x(t) = A_i x(t) + \cdots + B_i u(t),\ i = 1, 2, \cdots r \quad (1)$$

where

x_j : jth state (or linguistic) variable,
M_j^i : a fuzzy term of M_j selected for plant rule i,
M_j : fuzzy term set of x_j,
$x(t)$: state vector and $x(t) = [x_1(t) \cdots x_n(t)]^T \in R^n$,
$u(t)$: input vector and $u(t) = [u_1(t) \cdots u_m(t)]^T \in R^n$,
$A_i \in R^{n \times n}$,
$B_i \in R^{n \times m}$.

For any current state vector $x(t)$ and input vector $u(t)$, the T-S fuzzy model infers $\dot{x}(t)$ as the output of the fuzzy model as follows:

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} w_i [A_i x(t) + B_i u(t)]}{\sum_{j=1}^{r} w_j} \quad (2)$$

where

$$w_i = \prod_{k=1}^{r} M_k^i (x_k(t)). \quad (3)$$

For a free system (i.e., $u(t) \equiv 0$), (2) can be written as

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} w_i A_i x(t)}{\sum_{j=1}^{r} w_j}. \quad (4)$$

It is assumed, from now on, a proper T-S fuzzy model in the form (1) is available.

2.2 Sufficient Condition for Stability of T-S Fuzzy Model

Tanaka and Sugeno [2] suggested an important criterion for the stability of the discrete-time T-S fuzzy model. It is summarized in the Theorem 1 with conversion to continuous-time T-S fuzzy model.

Theorem 1. [Tanaka and Sugeno [2]]

The equilibrium of the fuzzy system (4) (namely, $x = 0$) is globally asymptotically stable if there exists a common symmetric positive definite matrix P such that

$$A_i^T P + PA_i < 0 \text{ for all } i = 1, 2, \cdots, r. \quad (5)$$

■

It should be noted that (5) is a sufficient condition for stability but not necessary condition. Therefore there may exist better criterion for stability of T-S fuzzy model.

2.3 Parallel Distributed Compensation and Its Stability Criterion

A T-S fuzzy controller which uses full state feedback is composed of s control rules that can be represented as

Control rule i : if $x_1(t)$ is M_1^{*i} and $x_2(t)$ is M_2^{*i}
and $\cdots$ and $x_n(t)$ is M_n^{*i} (6)
then $u(t) = K_i x(t)$, $i = 1, 2, \cdots s$

where upper script * is used to distinguish the term sets in the control rule from the term sets in plant rule (1) and s means that the number of control rule is not necessarily equal to the number of plant rule r.

For any current state vector $x(t)$, the T-S fuzzy controller infers $u(t)$ as the output of the fuzzy controller as follows:

$$u(t) = \frac{\sum_{i=1}^{s} w_i^* K_i x(t)}{\sum_{j=1}^{s} w_j^*} \quad (7)$$

where the upper script * is also used to distinguish w_i's in (7) from w_i's in (2)-(4).

Wang *et al.* [3] proposed a framework which can be used as a guideline to design a T-S fuzzy controller using existing T-S fuzzy model. It can be summarized as

"A T-S fuzzy controller can be designed using T-S fuzzy model by using the antecedent part of the T-S fuzzy model as that of T-S fuzzy controller."

It means that the upper script * in (6) and (7) is omitted and the number of rules in (1) and (6) is the same, say r. In this case, we can use a proper linear control method for each pair of control rule and plant rule. Wang *et al.* [3] named it PDC (Parallel Distributed Compensation). It has very important advantage because it makes easy (or manageable) to apply (7) to (2). Therefore the closed-loop behavior of the T-S fuzzy model (1) with the T-S fuzzy controller (6) using PDC can be obtained by substituting (7) into (2) as follows:

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} \sum_{j=1}^{r} w_i w_j (A_i + B_i K_j) x(t)}{\sum_{i=1}^{r} \sum_{j=1}^{r} w_i w_j}. \quad (8)$$

The corresponding sufficient condition for stability of (8) can be easily obtained and summarized in the Theorem 2.

Theorem 2. [Wang *et al.* [3]]

The equilibrium of the fuzzy system (8) (namely, $x = 0$) is globally asymptotically stable if there exists a common symmetric positive definite matrix P such that

$$(A_i + B_i K_j)^T P + P(A_i + B_i K_j) < 0 \text{ for all } i, j = 1, 2, \cdots, r \quad (9)$$

■

It is suggested that P can be determined numerically by solving LMIs in (9). It should be noted that (9) has r^2 LMIs. Wang et al. rewrote (8) by grouping same terms as follows:

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} w_i w_i (A_i + B_i K_j) x(t) + 2 \sum_{i<j}^{r} w_i w_j G_{ij} x(t)}{\sum_{i=1}^{r} \sum_{j=1}^{r} w_i w_j}. \quad (10)$$

where

$$G_{ij}=\frac{(A_i+B_iK_j)+(A_j+B_jK_i)}{2}, i<j. \quad (11)$$

The corresponding sufficient condition for stability of (10) is summarized in the Corollary 1.

Corollary 1. [Wang *et al.* [3]]

The equilibrium of the fuzzy system (10) (namely, $x=0$) is globally asymptotically stable if there exists a common symmetric positive definite matrix P such that

$$(A_i+B_iK_i)^T P+P(A_i+B_iK_i)<0, i=1, 2,\cdots r \quad (12)$$
$$G_{ij}^T P+PG_{ij}<0, i<j\le r$$

■

The number of LMIs for (12) is $\frac{r(r+1)}{2}$. Therefore the number of LMIs to be solved is reduced greatly from r^2 of (9) to $\frac{r(r+1)}{2}$.

Remark 1: It should be noted that the advantage of (12) over (9) is not only the number of LMIs to be solved but less conservativeness of stability criterion of (12) even though it is not mentioned by Wang *et al.* [3]. Author's experience says that some standard feasibility problems which are infeasible from (9) can be solved from (12). Therefore, the stability criterion in (12) is used throughout this paper.

Remark 2: The sufficient condition for stability (12) can be used only for the purpose of checking of the stability of the T-S fuzzy system (10) in which feedback gains K_i's, $i=1, 2,\cdots,r$, is pre-determined by a proper linear controller design method.

Ⅲ. A New Design Method with Pole Placement Constraints

A new design method in this section determines feedback gains K_i's, $i=1, 2,\cdots,r$, numerically which guarantee stability in the sense of (12) and satisfy desired performance by placing closed-loop poles within the desired region in s-plane. It is explained in the following subsections in detail.

3.1 LMIs for Stability Criterion

The stability criterion (12) is not LMIs when K_i's and P are considered as matrix variables since they are coupled. It should be emphasized that K_i's and P are both matrix variables since they should be determined simultaneously. So, (12) should be reformulated to be LMIs.

Substitution of (11) into (12) yields

$$(A_i+B_iK_i)^T P+P(A_i+B_iK_i)<0, i=1, 2,\cdots,r.$$
$$(A_i+B_iK_j)^T P+(A_j+B_jK_i)^T P+P(A_i+B_iK_j) \quad (13)$$
$$+P(A_j+B_jK_i)<0, i<j\le r$$

If we let $Q=P^{-1}$ and pre-and post-multiply (13) by $Q>0$ then the negative definiteness of (13) will not be changed since Q is positive definite. Equation (13) becomes

$$QA_i^T+A_iQ+QK_i^TB_i^T+B_iK_iQ<0, i=1, 2,\cdots,r.$$
$$QA_i^T+A_iQ+QA_j^T+A_jQ+QK_j^TB_i^T+B_iK_jQ \quad (14)$$
$$+QK_i^TB_j^T+B_jK_iQ<0, i<j\le r$$

Now, we can obtain LMIs by letting $K_iQ=N_i$ as follows:

$$QA_i^T+A_iQ+N_i^TB_i^T+B_iN_i<0, i=1, 2,\cdots,r$$
$$QA_i^T+A_iQ+QA_j^T+A_jQ+N_j^TB_i^T+B_iN_j \quad (15)$$
$$+N_i^TB_j^T+B_jN_i<0, i<j\le r$$

where Q and N_i, $i=1, 2,\cdots,r$ are new matrix variables of LMIs. Equation (15) is used as LMIs for stability criterion for the new design method in this paper.

3.2 LMIs for Pole Placement Constraints

Chilali and Gahinet [5] proposed that a convex region in s-plane which represents the desired closed-loop pole-placement constraints can be represented as LMIs. It is summarized in this subsection briefly.

The closed-loop poles lie in the LMI region

$$D=\{z\in C\,|\,f_D(z):=L+Mz+M^T\bar{z}<0\} \tag{16}$$

iff there exists a symmetric positive definite matrix X_{pol} satisfying

$$[\lambda_{ij}X_{pol}+\mu_{ij}(A+BK)X_{pol}+\mu_{ij}X_{pol}(A+BK)^T]_{1\le i,j\le m}<0. \tag{17}$$

Here, z is a complex variable, A, B, and K are system, input, and feedback gain matrices of a linear system, respectively, and $L=L^T=[\lambda_{ij}]_{1\le i,\ j\le m}$ and $M=[\mu_{ij}]_{1\le i,\ j\le m}$ are known real matrices which can be determined by specifying desired closed-loop pole region in s-plane. The notation in (17) represents $m\times m$ matrix whose $(i,\ j)$ element is the very one in the bracket of (17). The size of the matrix (17), i.e., m, is determined by the subjective way of representing closed-loop pole regions in s-plane. Two useful LMI regions are introduced as follows:

- conic sector center at the origin and with inner angle θ

$$f_D(z)=\begin{pmatrix}\sin\frac{\theta}{2}(z+\bar{z}) & -\cos\frac{\theta}{2}(z-\bar{z})\\ \cos\frac{\theta}{2}(z-\bar{z}) & \sin\frac{\theta}{2}(z+\bar{z})\end{pmatrix} \tag{18}$$

- vertical strip $h_1<x<h_2$

$$f_D(z)=\begin{pmatrix}2h_1-(z+\bar{z}) & 0\\ 0 & (z+\bar{z})-2h_2\end{pmatrix}. \tag{19}$$

Therefore, we can obtain L and M using (18) and (19).

Now, we can apply the Chilali and Gahinet's LMI regions [5] to each local T-S fuzzy controller in order to specify the desired closed-loop performance. It is proposed as a design method for each local T-S fuzzy controller and it is motivated by Wang et al.'s PDC. Therefore, we have r LMI regions corresponding to r local T-S fuzzy controller as follows:

$$[\lambda_{kl}X_{pol}+\mu_{kl}(A_i+B_iK_i)X_{pol}+\mu_{lk}X_{pol}(A_i+B_iK_i)^T]_{1\le k,l\le m}<0,\quad i=1,2,\cdots,r. \tag{20}$$

We can combine (20) with (15) by letting $X_{pol}=Q$ since Q is symmetric positive definite.

Therefore, we obtain

$$[\lambda_{kl}Q+\mu_{kl}A_iQ+\mu_{kl}B_iN_i+\mu_{lk}QA_i^T+\mu_{lk}N_i^TB_i^T]_{1\le k,l\le m}<0,\quad i=1,2,\cdots,r \tag{21}$$

where $K_iQ=N_i$ is used. From now on, r LMIs in (21) is used as the desired closed-loop pole placement constraints in this paper.

3.3 A New Design Method

Combination of (15) and (21) gives a new design method for a T-S fuzzy controller as discussed so far. It is proposed as Theorem as follows.

Theorem 3. A T-S fuzzy controller which guarantees stability in the sense of (12) and satisfies desired performance by placing closed-loop poles for each local model in (1) within the desired region in s-plane can be designed by solving

$$\begin{aligned}&QA_i^T+A_iQ+N_i^TB_i^T+B_iN_i<0,\ i=1,2,\cdots,r\\ &QA_i^T+A_iQ+QA_j^T+A_jQ+N_j^TB_i^T+B_iN_j+N_i^TB_j^T\\ &+B_jN_i<0,\ i<j\le r \qquad (22)\\ &[\lambda_{kl}Q+\mu_{kl}A_iQ+\mu_{kl}B_iN_i+\mu_{lk}QA_i^T+\mu_{lk}N_i^TB_i^T]_{1\le k,l\le m}<0,\\ &i=1,2,\cdots,r\\ &Q>\alpha I,\ \alpha=\text{positive constant}\end{aligned}$$

In Equation (22), $Q>\alpha I$ is included in order to avoid a trivial solution and easily differentiate between feasibility and infeasibility. If $\alpha=0$, we have original constraint on Q, i.e., positive definiteness.

We can obtain Q and N_i, $i=1,2,\cdots,r$, by solving (22). And then the common symmetric positive definite matrix P and feedback gains K_i, $i=1, 2,\cdots,r$, can be determined as follows:

$$P=Q^{-1}$$
$$K_i=N_i Q^{-1}=N_i P,\ i=1, 2,\cdots,r. \tag{23}$$

Ⅳ. Simulated Example

The proposed design method is verified by designing a controller for an inverted pendulum on a cart which is adopted from Wang *et al.* [3]. The equations of motion for the pendulum are

$$\dot{x}_1=x_2$$
$$\dot{x}_2=\frac{g\sin(x_1)-amlx_2^2\sin(2x_1)/2-a\cos(x_1)u}{4l/3-aml\cos^2(x_1)} \tag{24}$$

where x_1 is the angle (in radians) of the pendulum from the vertical, x_2 is the angular velocity, and u is the control force (in Newton) applied to the cart. The other parameters are as follows:

g: the gravity constant (9.8 m/s^2),
m: mass of the pendulum (2.0 kg),
M: mass of the cart (8.0 kg),
$2l$: length of the pendulum (1.0 m),

$$a=\frac{1}{m+M}.$$

The T-S fuzzy model of (24) in Wang *et al.* [3] is adopted in this paper. It is composed of two plant rules.

Plant rule 1: if x_1 is about 0
then $\dot{x}=A_1x+B_1u$
Plant rule 2: if x_1 is about $\pm\frac{\pi}{2}$ $(|x_1|<\frac{\pi}{2})$ (25)
then $\dot{x}=A_2x+B_2u$

where

$$A_1=\begin{bmatrix}0 & 1\\ \frac{g}{4l/3-aml} & 0\end{bmatrix},\quad B_1=\begin{bmatrix}0\\ -\frac{a}{4l/3-aml}\end{bmatrix}$$

$$A_2=\begin{bmatrix}0 & 1\\ \frac{2g}{\pi(4l/3-aml\beta^2)} & 0\end{bmatrix},\quad B_2=\begin{bmatrix}0\\ -\frac{a\beta}{4l/3-aml\beta^2}\end{bmatrix}$$

and where $\beta=\cos(88°)$. Refer to Wang *et al.* [3] for detailed description. Membership functions of "about 0" and $\pm\frac{\pi}{2}$ are shown in Fig. 1.

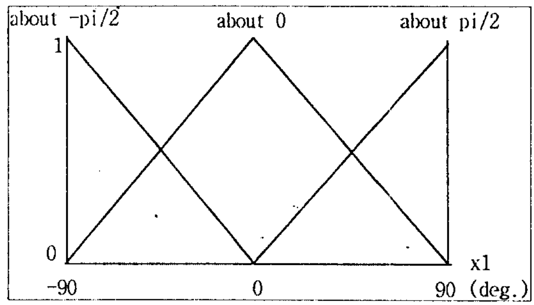

Fig. 1. Membership functions of "about 0" and "about $\pm\frac{\pi}{2}$"

A T-S controller has the following structure according to PDC framework.

Control rule 1: if x_1 is about 0 then $u=K_1x$ (26)
Control rule 2: if x_1 is about $\pm\frac{\pi}{2}$ $(|x_1|<\frac{\pi}{2})$ then $u=K_2x$

and the resulting output of the controller is

$$u=w_1K_1x+w_2K_2x \tag{27}$$

since $w_1+w_2=1$ from Fig. 1. Here, w_1 and w_2 are membership grades of antecedent parts of control rules 1 and 2 respectively. It should be noted that K_i, $i=1, 2$, are not determined in advance, i.e., they are unknown feedback gains to be designed. Wang *et al.* [3] and Tanaka *et al.* [6] suggested to predetermine the K_i, $i=1, 2$, using a proper design method and then check its stability through (12).

The design purpose of this example is to place the closed-loop poles of each local model, i.e., plant rule 1 and 2, within the desired region as shown in Fig. 2 as shaded polygon. It corresponds to restrict damping and response time within certain range. Since the plant is the 2nd-order system, the response should be

$$\zeta > 0.995 \text{ or } \%\,OS < 2.55 \times 10^{-12}(\%) \text{ and } T_s < 2.67 \text{ (sec)}. \quad (28)$$

It can be shown that the %OS is almost zero in this example. This particular value is chosen to show the validity of the proposed method for such a narrow LMI region. It should be noted that zero can not be used for %OS since the LMI region has no area in that particular case.

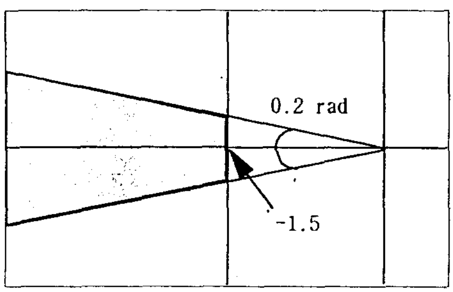

Fig. 2. Desired Pole Placement Constraint Region

From (16), (18), and (19), the LMI region is defined by L and M matrices as

$$L=\begin{bmatrix} 3 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad M=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.09998 & -0.995 \\ 0 & 0.995 & 0.0998 \end{bmatrix} \quad (29)$$

where L and M are constructed by arranging two constraints as block diagonal matrices. Therefore, $m=3$ in this case and the size of LMI in (21) becomes 3×3 matrix.

Now, we have to solve six LMIs in (22) since $r=2$. The interior-point method yields Q, N_1, and N_2. The MATH WORKS' LMI Control Toolbox [7] for MATLAB is used to solve the LMI problem. The desired solution can be determined from (23) as

$$P=\begin{bmatrix} 1.129 \times 10^{-1} & 4.005 \times 10^{-2} \\ 4.005 \times 10^{-2} & 1.465 \times 10^{-2} \end{bmatrix} \quad (30)$$

$$K_1=[1029.9\ 356.7],\ K_2=[6978.9\ 2437.4]. \quad (31)$$

The P in (30) is obviously symmetric and positive definite since the eigenvalues are 1.271×10^{-1} and 3.885×10^{-4}. Furthermore, it can be easily checked that the stability criterion (12) is satisfied. Therefore, the feedback control system (25) and (26) with feedback gains (31) is globally asymptotically stable. The stability of the proposed design method is verified.

The performance of the controller (26) with feedback gains (31) is checked by simulation. The simulation is performed with various initial conditions (i.e., 10, 20, ⋯, 80 (deg)) to see the performance of controlling nonlinear system. Figure 3 shows the resulting response of the system.

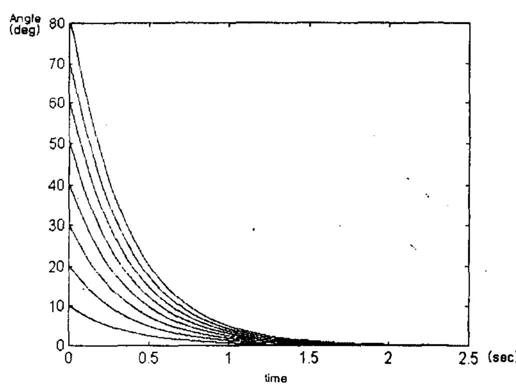

Fig. 3. Response of the example system with 8 initial conditions

Figure 3 shows that the performance specifications (28) are satisfied. Therefore, the performance of the proposed method is verified.

V. Concluding Remarks

A new design method for T-S controller is proposed. The method uses LMI approach to find the common symmetric positive definite matrix P and feedback gains K_i, $i=1, 2,\cdots,r$ numerically. The stability criterion of Wang *et al.* [3] is nonlinear MIs when P and K_i, $i=1, 2,\cdots,r$, are considered as matrix variables since P and K_i, $i=1, 2,\cdots,r$, are coupled. Therefore LMI approach can not be applied directly. The LMIs for stability criterion is derived from Wang *et al.*'s stability criterion by separating P and K_i, $i=1, 2,\cdots,r$, which are coupled. The desired performance is represented as r LMIs which place the closed-loop poles of r local subsystems within the desired region in s-plane. By solving stability LMIs and pole placement constraint LMIs simultaneously, the feedback gains which guarantee global asymptotic stability and satisfy desired performance can be determined.

The authors believe that it is the first systematic design method in fuzzy control field which guarantees global asymptotic stability and satisfies desired performance. The design method is verified by designing a T-S fuzzy controller for an inverted pendulum with a cart using the proposed method.

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