An Improved Method for Order Reduction of High Order Uncertain SISO Dynamic Systems by Affine Arithmetic

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Abstract: This article presents a refined algorithm using Modified Polynomial Differentiation (MPD) method through Affine Arithmetic (AA) to reduce the high order uncertain systems. This new algorithm is applicable for the reduction of Continuous SISO systems. Measurement errors due to variation in ambient conditions may result the system as an uncertain system unlike other methods in literature. This strategy, unlike previous ones found in the Iteration literature, can produce a reduced order model that is stable from a original high order uncertain system that is also stable. Applications of Affine Arithmetic steer clear of many of the drawbacks of Interval Arithmetic, including unbounded solutions in a number of important applications. Utilizing common numerical examples from interval literature, the proposed approach has been validated.

Keywords: Uncertain systems; Model Order Reduction; Affine Arithmetic; Modified Polynomial Differentiation Method.

1. INTRODUCTION

The Polynomial differentiation approach was first presented by Gutman et al. [2] to reduce the order of higher order fixed parameter systems. Here, differentiation is employed to lower a polynomial's order in order to guarantee model stability. The higher order transfer function's denominator and numerator are differentiated successively to create the denominator and numerator of the reduced order model. Lepschy and Viaro [3,4] derived the denominator of the simplified system using the approach [2]. The Maclaurin's expansion coefficients of the original system were matched to get the numerator.

For high-order systems, successive differentiation becomes a laborious operation. R. Prasad et al. [5-7] had integrated the approach suggested by Gutman et al. [2] with matching the temporal moments or/and Markov parameters via reciprocal transformation. The result was low order models with better response matching. Through the use of a Routh-type array structure, the Lucas methods [8,9] have demonstrated how the differentiation approach and the multipoint Taylor polynomial approximation are equivalent. However, in order to obtain the model, they too create lengthy Routh-type differentiation arrays, which makes the reduction process extremely difficult. Only the aforementioned methods are recommended for reducing the order of fixed systems w.r.t to the polynomial differentiation method. In the literature, there are a few methods for decreasing high-order interval systems.

Every mathematical issue where one wants assured enclosures to smooth functions could benefit from the usage of affine arithmetic. Affine arithmetic is one of several computational models that were proposed to overcome the problems of interval arithmetic. The correlation between computed and input quantities of first–order system is tracked by Affine arithmetic, which is automatically exploited in primitive operations. In many instances, affine arithmetic can generate interval estimates that are significantly superior than those generated using traditional interval arithmetic. Interval arithmetic has been used by earlier researchers to establish a mathematical model for the uncertain physical systems. In the worldwide literature, only a relatively small number of strategies are proposed to reduce the High order systems in general and systems with uncertainties in particular. From the prior techniques, it can be seen that many of them considered interval arithmetic to handle uncertain systems. When applied to a stable original high order system, interval arithmetic can occasionally result in an unstable model. Affine Arithmetic (AA) can be used to get around these restrictions. For a stable high order system, the stable reduced order model is generated via the methods outlined in the following section. The first K-time moments are likewise preserved using this method for the high order system in reduced order model. This method successfully matches the reduced order model's temporal response qualities with those of high order systems.

The author aimed to develop novel approaches for the model reduction involving high order interval systems in this research in order to circumvent some of the significant drawbacks and limitations of the order reduction techniques that have been discussed in the literature. These techniques are founded on the polynomial derivative approach.

2. PROBLEM FORMULATION

The past ten years have seen a significant increase in the efforts aimed at the model reduction of higher order interval systems. Some of the methods described in the literature have been studied, analysed, and suggestions have been made to enhance them in terms of computation and/or outcome.

The creation of a Routh type array for the interval based higher order polynomial's denominator D(s) is required by the Routh-Pade approximation method used by Bandyopadhyay et al. [10] in order to decrease the order of high order interval systems. The transfer function Dr(s) of the model reduced by order "r" has a denominator that is constructed from the Routh stability array of denominator from the original interval system. The coefficients of the numerator for the reduced order model's are obtained using both the coefficients of the reduced order model and coefficients of the original high order system's power series expansion.

The main problems with the aforementioned approach are that

i) The approach occasionally generates negative interval components since it is built on recursive algorithms, which leads to unstable lower order models.

ii) it requires formulating long Routh type interval arrays and

iii) Calculations are time-consuming because the reduced order interval model needs the solution of interval Pade equations to get the coefficients of the numerator.

The study proposes a novel technique [11] that creates stable reduced-order interval-models for stable high-order interval systems and always yields positive intervals, overcoming the restrictions.

The numerator polynomial and denominator polynomial coefficients of the higher order original interval system are used to evaluate the values of the interval and parameters in Bandyopadhyay [12] .'s - approximation by Routh technique. The reduced model by rth order is generated by keeping the first 'r' interval parameters, while the numerator of the reduced order model is derived by keeping the first 'r' time-moments of the original interval system.

This approach has a number of significant drawbacks, like

i) requires formulation of Routh type γ and δ - interval tables which involve much computational effort and

ii) as the method involves the recursive algorithms, it needs to find all the previous (r-1) reduced order models to generate r^{th} order reduced interval model hence the method becomes a laborious process.

The novel approach proposed by [11] does not call for the creation of tables to acquire lower order numerator and denominator polynomials. As a result, it is clear that the recommended technique is computationally straightforward and effective, requiring less calculations overall. The algorithms created for the suggested process [11] are not recursive, hence the rth order reduced models are derived directly in this study without the need to first discover the models with orders lower than 'r'.

The denominator from the reduced order interval model is obtained using the Routh array using the reciprocal of the denominator polynomial of the original high order interval system, up to (r+1) rows, according to Ismail et al"Pade .'s approximation method for the reduction of high order interval systems" [13]. The initial 't' interval time-moments and 'm' Markov's parameters from the reduced model are matched to those of the provided original interval system so that r = (t+m), and this yields the reduced order numerator polynomial.

The key issues with the aforementioned technique are that

i) it involves formation of long Routh arrays,

ii) it requires application of reciprocal transformations, and

iii) The Markov parameters and interval time moments must be calculated in advance.

Ismail et al"structured .'s linear uncertain systems reduction" technique According to al. [14], the basic interval system's reciprocal denominator and numerator polynomials are used to create Routh-like D-tables and N-tables. Last but not least, the model is created by expanding the D-table and N-table backward beginning from the bottom row using the values of and for (i=1,2,......,r), where the values of and for (i=2,3,......,r) are chosen to match the impulse energy from the original high order interval system.

The key drawbacks of the aforementioned technique are that

i) The transfer function of the original high order system has to be subjected to reciprocal transformations.

ii) the creation of two Routh-like tables, the D-table and the N-table, utilising the coefficients of the original system's denominator polynomial and both of its denominator and numerator polynomials, respectively.

iii) to check if the model fits the impulse energy from the original interval system, a trial-and-error approach is used. These restrictions undoubtedly increase the computational complexity and laboriousness of the reduction process.

In contrast, the suggested method [11] is created without the need to compute the original system's impulse energy beforehand. The computational complexity will therefore be significantly reduced by the suggested strategy.

The numerator and denominator from the polynomials of the low order model must be derived orderly for Ismail's order reduction technique, titled "On multipoint Pade approximation for Discrete Interval Systems" [15], to work and for the rth order reduced interval model to be a Pade approximant to the high order interval system for "2r" points. The approximation uses a variety of points as its expansion points, including actual, fictitious, complicated, and multiple points. The reduced order model's numerator and denominator polynomials are created like that of a Pade approximation for about "2r" points results.

The key drawbacks of the aforementioned technique are that

i) as the expansion point cannot ensure the stability, it may sometimes provide reduced unstable models for stable interval systems of high order.

ii) the initial interval system with high order must be stretched by around 2r points in order to get the reduced model with r^{th} order, which makes the process laborious and

iii) to requires evaluating the interval time moments beforehand.

On the other hand, the suggested method [16] consistently results in stable discrete models of low order for a stable original discrete system with high order. In order to get around the shortcomings and restrictions indicated above and/or to enhance the performance of certain current approaches, this article introduces novel techniques based on polynomial differentiation. In order to lower the order of linear continuous MIMO interval based systems [16] and discrete time interval systems [17], the suggested technique has been expanded.

3. REDUCTION PROCEDURE SUGGESTION

Assuming the following is the initial n^{th} order interval system:

$$G_n(s) = \frac{Q(s)}{P_n(s)}$$
$$= \frac{[Q_m^-, Q_m^+]s^m + [Q_{m-1}^-, Q_{m-1}^+]s^{m-1} + \ldots\ldots\ldots + [Q_1^-, Q_1^+]s + [Q_0^-, Q_0^+]}{[p_n^-, p_n^+]s^n + [p_{n-1}^-, p_{n-1}^+]s^{n-1} + \ldots\ldots\ldots + [p_1^-, p_1^+]s + [p_0^-, p_0^+]} \quad \ldots (1)$$

with m ≤ n

where, $[Q_i^-, Q_i^+]$ (i = 0,1,2, … , m) and $[P_i^-, P_i^+]$ (i = 0,1,2,….. ,n) are the interval coefficients of numerator and denominator interval polynomials respectively.

For the above original high order interval system, it is suggested to obtain a r^{th} order reduced model as provided below:

$$R_r(s) = \frac{q(s)}{p_r(s)} = \frac{[q_{r-1}^-, q_{r-1}^+]s^{r-1} + [q_{r-2}^-, q_{r-2}^+]s^{r-2} + \ldots\ldots + [q_1^-, q_1^+]s + [q_0^-, q_0^+]}{[p_r^-, p_r^+]s^r + [p_{r-1}^-, p_{r-1}^+]s^{r-1} + \ldots\ldots\ldots\ldots\ldots + [p_1^-, p_1^+]s + [p_0^-, p_0^+]} \quad \ldots(2)$$

with $[p_r^-, p_r^+] = [1,1]$ …(3)

Reduced Order Denominator $p_r(s)$:

For r = 1; $p_1(s) = [p_0^-, p_0^+] + [p_1^-, p_1^+]s$

For r = 2; $p_2(s) = [p_0^-, p_0^+] + [p_1^-, p_1^+]s + [p_2^-, p_2^+]s^2$

For r = 3; $p_3(s) = [p_0^-, p_0^+] + [p_1^-, p_1^+]s + [p_2^-, p_2^+]s^2 + [p_3^-, p_3^+]s^3$

For r = 4; $p_4(s) = [p_0^-, p_0^+] + [p_1^-, p_1^+]s + [p_2^-, p_2^+]s^2 + [p_3^-, p_3^+]s^3 + [p_4^-, p_4^+]s^4$

. . .

. . .

In general, $p_r(s) = [p_0^-, p_0^+] + [;p_1^-, p_1^+]s + \ldots\ldots\ldots + [p_r^-, p_r^+]s^r$ … (4)

Reduced order Numerator $q_r(s)$:

For r = 1; $q_1(s) = [q_0^-, q_0^+]$

For r =2; $q_2(s) = [q_0^-, q_0^+] + [q_1^-, q_1^+]s$

for r = 3; $q_3(s) = [q_0^-, q_0^+] + [q_1^-, q_1^+]s + [q_2^-, q_2^+]s^2$

. . .

In general, $q_r(s) = [q_0^-, q_0^+] + [q_1^-, q_1^+]s + ... + [q_{r-1}^-, q_{r-1}^+]s^{r-1}$ … (5)

The modified polynomial derivative technique is suggested, and it is shown that the models with reduced order for the stable higher order original interval system derived using this method meet the Kharitonov's stability criterion. The stability requirements are met when obtaining the interval coefficients from the numerator and denominator interval polynomials from the reduced order model. The following list includes the novel methods suggested to produce the numerator polynomials and denominator polynomials of the model of lower order:

Denominator, $d_r(s)$:

The following new procedures are suggested to produce the reduced model's low order denominator polynomials, $p_r(s)$ (r <= n):

For r = 1, $$d_1'(s) = \left(\frac{{}^{n-1}K_{n-1}}{{}^{n}K_{n-1}} \right)[A_1^-, A_1^+]s + [A_0^-, A_0^+] \quad \text{… (6)}$$

For r = 2,

$$d_2'(s) = \left(\frac{{}^{n-2}K_{n-2}}{{}^{n}K_{n-2}} \right)[A_2^-, A_2^+]s^2 + \left(\frac{{}^{n-1}K_{n-2}}{{}^{n}K_{n-2}} \right)[A_1^-, A_1^+]s + [A_0^-, A_0^+] \quad \text{… (7)}$$

… … ….

… … ….

and in general,

$$d_r'(s) = \left(\frac{{}^{n-r}K_{n-r}}{{}^{n}K_{n-r}} \right)[A_r^-, A_r^+]s^r + \sum_{j=1}^{r} \left(\frac{{}^{n-j+1}K_{n-r}}{{}^{n}K_{n-r}} \right)[A_{j-1}^-, A_{j-1}^+]s^{j-1} \quad \text{… (8)}$$

where, ${}^{P}K_Q = \dfrac{P!}{P!(P-Q)!}$ and ${}^{P}K_P = 1$.

The denominator by reduced order "r" is provided as follows after correct normalisation:

$$d_r(s) = \sum_{i=0}^{r} [a_i^-, a_i^+]s^r \; ; \; \text{ with } [a_r^-, a_r^+] = [1,1]. \quad \text{… (9)}$$

Numerator $q_r(s)$:

The suggested novel algorithms, which are described below, are used to produce the lower order numerator polynomials:

For $r = 1,$ $\quad q_1(s) = [q_0^-, q_0^+]$ … (10)

For $r = 2,$ $\quad q_2(s) = [q_1^-, q_1^+]s + [q_0^-, q_0^+]$

$$\text{For } r=3, \qquad q_3(s) = [q_2^-, q_2^+]\, s^2 + [q_1^-, q_1^+]\, s + [q_0^-, q_0^+]$$

and in general, $q_r(s) = [q_{r-1}^-, q_{r-1}^+]\, s^{r-1} + [q_{r-2}^-, q_{r-2}^+]\, s^{r-2} + [q_1^-, q_1^+]s + [q_0^-, q_0^+] \ldots$ (11)

where $[q_0^-, q_0^+] = c\ [p_0^-, p_0^+]$; $\qquad [q_{r-1}^-, q_{r-1}^+] = p[p_r^-, p_r^+]$ $\qquad$ *and*

for $i = 1,2,3,\ldots\ldots\ldots\ldots,(r-2)$

$$[q_i^-, q_i^+] = \left[\frac{[B_i^-, B_i^+]}{[A_0^-, A_0^+]}[a_0^-, a_0^+] + \frac{[B_0^-, B_0^+]}{[A_0^-, A_0^+]}\left\{[a_i^-, a_i^+] - \frac{[A_i^-, A_i^+]}{[A_0^-, A_0^+]}[a_0^-, a_0^+]\right\}\right.$$
$$\left. + \sum_{j=1}^{i-1}(-1)^j \left\{\frac{[A_j^-, A_j^+]}{[A_0^-, A_0^+]}[b_j^-, b_j^+] - \frac{[B_j^-, B_j]}{[B_0^-, B_0^+]}[a_j^-, a_j^+]\right\}\right] \ldots (12)$$

with 'c' = mean of $\frac{[\mathrm{B}_0^-, \mathrm{B}_0^+]}{[\mathrm{A}_0^-, \mathrm{A}_0^+]}$ and 'd' = mean of $\frac{[\mathrm{B}_\mathrm{m}^-, \mathrm{B}_\mathrm{m}^+]}{[\mathrm{A}_\mathrm{n}^-, \mathrm{A}_\mathrm{n}^+]}$.

4. NUMERICAL EXAMPLES

The findings are successfully confirmed, and typical numerical examples taken from literature are utilised to show superiority and efficacy of suggested novel approach.

Example 1:

Consider the following as an 8th order stable interval system:

$$\mathrm{G(s)} = \frac{\begin{gathered}[35,36.1]\ \mathrm{s}^7 + [1086,1118..6]\ \mathrm{s}^6 + [13285,13683]\ \mathrm{s}^5 + [80402,82814]\ \mathrm{s}^4 + \\ [238376,245527]\ \mathrm{s}^3 + [511812,522048]\ \mathrm{s}^2 + [482964,483001]\ \mathrm{s} + [194480,205002]\end{gathered}}{\begin{gathered}[1,1.1]\ \mathrm{s}^8 + [33,34]\ \mathrm{s}^7 + [437,445.5]\ \mathrm{s}^6 + [3017,3077]\ \mathrm{s}^5 + [11870,12107.5]\ \mathrm{s}^4 \\ + [27470,28019]\ \mathrm{s}^3 + [37492,38242]\ \mathrm{s}^2 + [28880,29457.5]\ \mathrm{s} + [9600,9792]\end{gathered}}$$

It is suggested to use the following procedure to generate a second order model for the initial interval system mentioned above:

$$R_2(s) = \frac{q(s)}{p_2(s)} = \frac{[q_1^-, q_1^+]\ s + [q_0^-, q_0^+]}{[p_2^-, p_2^+]\ s^2 + [p_1^-, p_1^+]\ s + [p_0^-, p_0^+]}\ \textit{with}\ [p_2^-, p_2^+] = [1,1]$$

Denominator, q_2(s):

By using the suggested technique, the following 2nd order reduced denominator is produced:

$$q_2'(s) = [1339,1365.8]s^2 + [7220,7364.4]s + [9600,9792]$$

The reduced model of second order is the result of adequate normalising.

$$q_2(s) = [1,1]s^2 + [5.2863,5.4995]s + [7.0289,7.3129]$$

Numerator, p(s):

$n(s) = [b_1^-, b_1^+]s + [b_0^-, b_0^+]$ where

$$[b_1^-, b_1^+] = [33.96, 33.96] \text{ and } [b_0^-, b_0^+] = [142.39, 153.12]$$

$$R_2(s) = \frac{[33.96, 33.96]\, s + [142.39, 153.12]}{[1,1]s^2 + [5.2863, 5.4995]s + [7.0289, 7.3129]}$$ (Proposed Method) (**Stable**)

The proposed 3rd order model for the above original system is given as:

$$R_3(s) = \frac{n(s)}{d_3(s)} = \frac{[b_2^-, b_2^+]\, s^2 + [b_1^-, b_1^+]\, s + [b_0^-, b_0^+]}{[a_3^-, a_3^+]\, s^3 + [a_2^-, a_2^+]\, s^2 + [a_1^-, a_1^+]\, s + [a_0^-, a_0^+]}$$

Denominator, d_3(s):

By using the suggested technique, the following 3rd order reduced denominator is produced:

$$d_3'(s) = [490.54, 500.34]\, s^3 + [4017, 4097.4]\, s^2 + [10830, 11046.6]\, s + [9600, 9792]$$

The third order reduced denominator after appropriate normalisation is

$$d_3(s) = [1,1]\, s^3 + [8.029, 8.353]\, s^2 + [21.645, 22.519]\, s + [19.187, 19.962]$$

Numerator, n(s):

$$n_3(s) = [b_2^-, b_2^+]s^2 + [b_1^-, b_1^+]s + [b_0^-, b_0^+]; \text{ with}$$

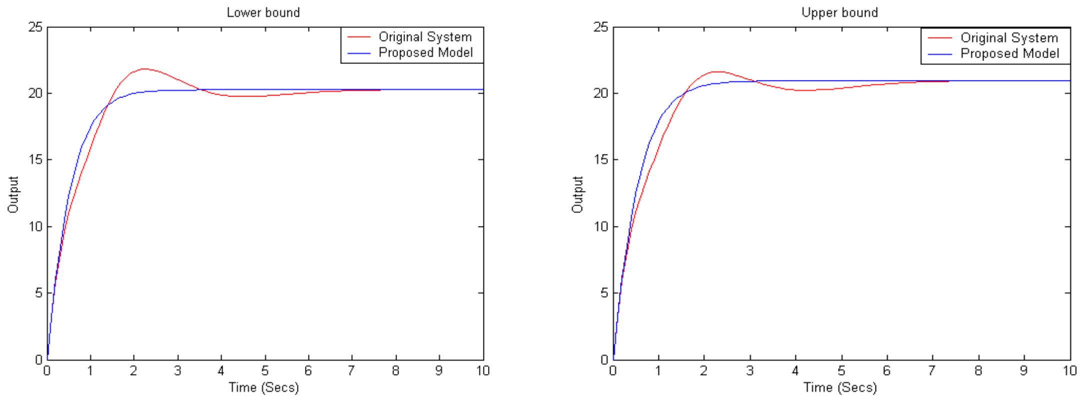
$$[b_2^-, b_2^+] = [33.96, 33.96];\ [b_1^-, b_1^+] = [159.15, 276.8] \text{ and}$$

$$[b_0^-, b_0^+] = [a_0^-, a_0^+] = [388.5, 417.42]$$

$$R_3(s) = \frac{[33.96, 33.96]\ s^2 + [159.15, 276.8]\ s + [388.5, 417.42]}{[1,1]\ s^3 + [8.029, 8.353]\ s^2 + [21.645, 22.519]\ s + [19.187, 19.962]}$$ (Stable Proposed Method)

The step responses of the original/first interval system are compared to those from the 2nd order reduced model produced from the suggested technique in Figures 1a and 1b.

As seen in figures. 1a and 1b, the suggested strategy creates a reduced order model that is stable and closely approximates the original interval system higher order.



(a) (b)

Fig. 1 Comparison of step responses

Comparison to other existing methods:

The reduced order models obtained from the proposed method are compared with some of the pre-existing methods available from the literature to determine superiority of the proposed method.

Example 2:

A stable interval system of fourth order is shown below: [10]

$$G(s)=\frac{[6,7]\,s^3+[26,28]\,s^2+[6,7]\,s+[20,22]}{[1.0,1.2]\,s^4+[3,3.5]\,s^3+[4,4.6]\,s^2+[2,2.4]\,s+[2,2.2]}$$

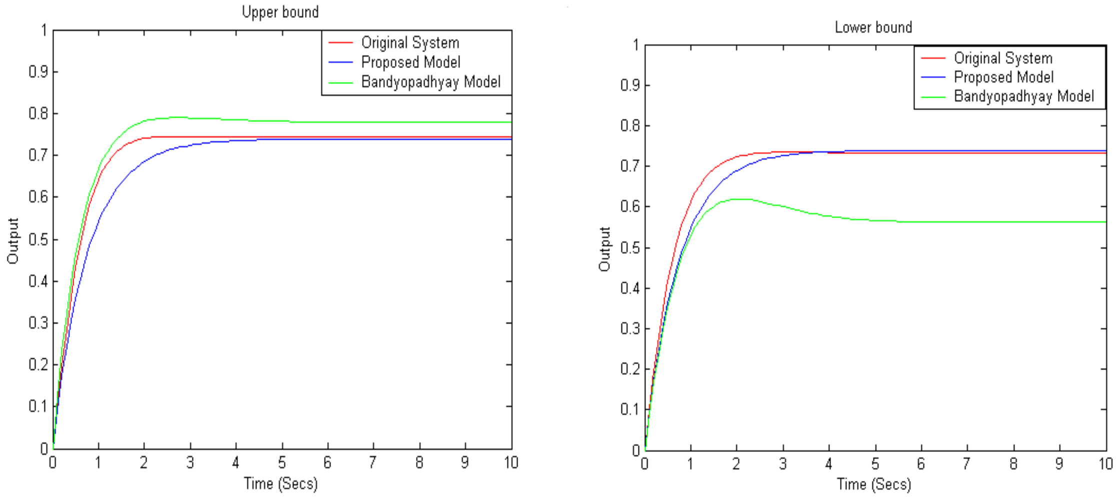
The suggested technique yields the 2nd order model for the aforementioned original system as shown below:

$$R_2(s)=\frac{[6,6]\,s+[26.2164,33.163]}{[1,1]\,s^2+[1.3043,1.8]\,s+[2.6086,3.2998]}$$ (Proposed Method) ***(Stable)***

The following is the 2nd order model as determined from the approach of Bandyopadhyay. [10]:

$$r_2(s)=\frac{[-88.39,62.01]\,s+[-82.764,28.237]}{[2.6,4.7]\,s^2+[-0.8052,2.36]\,s+[-7.524,2.567]}$$ **(*Unstable*)**

The model produced by the suggested technique is seen to be stable since it fulfils the Kharitonov's stability theorem, in contrast to the unstable model produced by Bandyopadhyay et alRouth-Pade .'s Approximation method [10].



(a) (b)

Fig.2: Comparison of the step responses.

CONCLUSION:

In this work, a new and better method for order reduction for uncertain systems has been proposed. By using the algorithm for reduction of SISO based systems, this method's adaptability may also be shown. It is clear that the new approach requires fewer calculations than earlier techniques while maintaining the stability for initial high order system in their lower order versions. This approach offers a near approximation for temporal response properties to the original High order system and their lower order counterparts because Affine Arithmetic is employed to manage the system's unknown parameters.

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