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A Study on Construction and Simulation of Agricultural Machinery System Control Model

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Abstract

In order to study the state-changing and running rules of agricultural machinery system, this paper establishes the control model of agricultural machinery system under the discrete-state space based on control theory, from the perspective of the complex systems and with reference to the actual conditions of agricultural production; conducts the qualitative analysis on the system model, builds the relevant simulation model of agricultural machinery system accordingly, and verifies the running of the simulation model. This control model can provide effective basis and reference for further quantitative studies on state evolution of agricultural machinery system.

Keywords: *agricultural machinery system; control model; discrete-state space; simulation model*

1. Introduction

Agricultural mechanization is an important part of agricultural development in China and the agricultural machinery system is the keynote and base for the development of agricultural mechanization. Agricultural machinery system means the integration of agricultural machinery and equipment which is mutually associated and influenced with each other [1]; agricultural machinery system can carry out the relevant agricultural production activities so as to achieve certain target of agricultural production [2].

Replacement of agricultural machinery is one of key issues to be studied in the development of agricultural mechanization and is an important part of agricultural machinery system. The replacement of for agricultural equipment group studied at home improves the deficiency of the unit replacement of agricultural machinery, but no adequate analysis is conducted for the whole agricultural machinery system associated internally [3]. Most of the overseas studies on the replacement of agricultural machinery focus on the replacement of agricultural machinery under the technical progress [4-5]; some scholars proposed the evolution equation model of agricultural machinery system based on aerodynamics, which analyzed the state evolution of agricultural machinery system [6], but such evolution equation lacks of studies on running and machinery aging structure of agricultural machinery system; the emphasis of studies on the replacement of agricultural machinery mostly involves exploration into the economic life and calculation method of optimal replacement period of agricultural machinery [7-12] and lack the consideration to the aging distribution of agricultural machinery and system running.

The agricultural machinery system control model is established for the purpose of further understanding and mastering the internal structural features and running rules of agricultural machinery system and with the significance of optimizing the decision-making for replacement of agricultural machinery, enhancing the technical and economic benefits of agricultural machinery system and promoting the progress and development of

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agricultural mechanization to some extent.

2. Construction of Agricultural Machinery System Control Model

Agricultural machinery system is mainly composed of different types of agricultural equipment that consists of different powered machinery and operating machinery necessary for agricultural production. Agricultural machinery system can be classified into several subsystems which are associated with each other. By different functions and models, agricultural machinery is classified into several categories in which each is a subsystem. Agricultural machinery in the same category has the same models and can play a substitutive role in practice of agricultural production. Between different categories of agricultural machinery, there will be certain association and mutual influence due to the working procedures of agricultural production.

In the agricultural machinery subsystem, the change of number and the distribution of aging of agricultural machinery are directly influenced by agricultural machinery scrapping rate, replacement rate and disturbance factors. Since the state change of agricultural machinery system results from the change of agricultural machinery subsystems, agricultural machinery subsystems are taken as the objects for further studies and analyses of the state rules of agricultural machinery system, considering the internal features and complex structure of agricultural machinery system.

According to the actual conditions of agricultural production, it is known that in agricultural machinery system, scrapping and replacement of agricultural machines directly influence the types and quantity of agricultural machinery and aging structure distribution of each category of agricultural machinery.

2.1. Modeling Assumptions

According to the running rule of agricultural machinery subsystem and with reference to the actual conditions of agricultural production, this paper proposes the following assumptions:

(1) Given that the agricultural machinery of the same function and model is in one category, *i.e.* , one subsystem of agricultural machinery system;

(2) Given that the agricultural machinery has the upper limit for aging and different agricultural machines have different upper limits for aging;

(3) Given that once exceeding its upper limit of aging, an agricultural machine shall be scrapped and will be no longer considered in the system;

(4) Given that in the agricultural machinery system, agricultural machines will be periodically scrapped or replaced as per minimum unit of years;

(5) Given that agricultural machines of the same function, model and aging have no unobservable difference;

(6) Given that the annual replacement fund for agricultural machines is limited as compared with the replacement demand of agricultural machines;

(7) Given that the environment for agricultural machinery system will not have any major change.

2.2. Modeling

Based on the assumptions in Section 2.1, above, the agricultural machinery system under study herein can be the agricultural machinery system of one farm, province, region or country. With the subsystem of one agricultural machinery system as the direct study object, the relevant agricultural machinery subsystem equation is established.

Introduce $x_r(t)$, indicating the number of agricultural machines with Year t as r years in one agricultural machinery system, where time t changes constantly; considering the periodical feature of agricultural machinery replacement and easy record of aging, $x_r(t)$ indicates the quantitative aggregation of all the agricultural machines with the aging up to r years but less than r+1 years in one subsystem.

Since all the agricultural machines have an upper limit for aging, set $r = 0,1,2,3,\cdots,m-1$, where, m value is the upper limit for aging of the agricultural machines in some category and the circumstance of $r+1 > m$ will not be taken into account.

Considering from t to t+1 years, the state distribution of the agricultural machines can be expressed as:

$$\begin{aligned} & x_{r+1}(t+1) = [1-\mu_r(t)] * x_r(t), \\ & r = 0,1,2,3,\cdots,m-1 \end{aligned} \tag{1}$$

Where, μ indicates the scrapping rate of agricultural machinery. From Formula (1), it is known that the state distribution equation of agricultural machinery is a recurrence equation, so a series of recurrence equations can be obtained accordingly, as shown in the following formula:

$$\begin{aligned} & x_1(t+1) = [1-\mu_0(t)] * x_0(t) \\ & x_2(t+1) = [1-\mu_1(t)] * x_1(t) \\ & x_3(t+1) = [1-\mu_2(t)] * x_2(t) \\ & \qquad\qquad \cdots\cdots \\ & x_{r+1}(t+1) = [1-\mu_r(t)] * x_r(t) \\ & \qquad\qquad \cdots\cdots \\ & x_m(t+1) = [1-\mu_{m-1}(t)] * x_{m-1}(t) \end{aligned} \tag{2}$$

From t to t+1 year, the equation of change for agricultural machinery replacement is as follows:

$$x_0(t+1) = u(t+1) * [1-\beta(t)] \tag{3}$$

$$u(t+1) = M_o(t) * \sum_{r=e}^{\mathrm{m}} x_r(t) \tag{4}$$

Where, β indicates the replacement limit rate, which is mainly subject to the impact of annual replacement fun; u indicates the replacement base, *i.e.*, the aggregation of agricultural machines to be replaced. Because agricultural machine beyond its economic life will result in certain economic losses in case of being further used, all the agricultural machines beyond economic life are generally taken as the base for replacement of agricultural machinery; Mo indicates the replacement mode, which is classified into three types: expand the scale, reduce the scale and maintain the scale; e is the given economic life of agricultural machinery.

$\beta^c(t)$ is set to indicate the replacement limit rate of No. c agricultural machinery subsystem at Year t due to the impact of fund in the agricultural machinery system, where, $c = 1,2,3,\cdots,N$; I is set as the total replacement fund, I_c as the fund allocated to each agricultural machinery subsystem.

p_c is set as the unit replacement price for Category-c agricultural machinery and

$x^c(t)$ as the number of Category-c agricultural machines for replacement in Year t, so:

$$L^c = x^c(t) * p_c \tag{5}$$

Where, L^c is the renovation fund actually required for Category-c agricultural machinery.

So the replacement limit rate is:

$$1 - \beta = \frac{I^c}{L^c} \tag{6}$$

In combination of Formulas (1) ~ (6), the general equation is obtained for one category of agricultural machinery subsystems:

$$X(t+1) = G(t)X(t) + H(t)X^u(t) + F(t+1) \tag{7}$$

Where, $X(t) = [x_0(t), x_1(t), x_2(t), \cdots, x_m(t)]^T$ indicates the quantitative distribution vector of all the agricultural machines in the agricultural machinery subsystem in Year t; $F(t) = [F_0(t) \quad F_1(t) \quad F_2(t) \quad \cdots \quad F_m(t)]^T$ is the disturbance factor vector of agricultural machines with different aging in Year t.The relevant coefficient matrixes G, H are as follows:

$$G(t) = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & 0 \\ 1-\mu_0(t) & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1-\mu_1(t) & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1-\mu_{m-1}(t) & 0 \end{bmatrix}, \quad H(t) = \begin{bmatrix} 0 & 0 & \cdots & M_{oe}(t) & \cdots & M_{o(m-1)}(t) & M_{om}(t) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & \cdots & -1 & 0 \end{bmatrix}$$

Where, $h(i, j) = -1, i = e+1 : m, j = e : m-1$.

Based on the assumption and Formula (7), as per control theory, it is known that the control system can be indicated with differential equations, transfer function or state-space expression; to establish the control model for agricultural machinery subsystems, agricultural machinery system under study is considered as discrete system and its subsystems also as discrete system; the discrete system is generally indicated with difference equation, *i.e.*, the relevant control model of agricultural machinery subsystems is established in the form of state-space expression.

The discrete state-space expression of control system is as follows:

$$\begin{cases} X(n+1) = AX(n) + BU(n) \\ Y(n) = CX(n) + DU(n) \end{cases} \tag{8}$$

According to the assumptions, the disturbance factor can be eliminated from the control equation. In Formula (8), variable n substitutes the original variable t, $A = G(n)$, $B = H(n)$, $C = eye(m+1)$, $D = 0$, and $X(n)$ is the state variable, $X^u(n)$ is the input variable, $Y(n)$ is the output variable, so the state-space expression for the control model of agricultural machinery subsystems is obtained as follows:

$$\begin{cases} X(n+1) = AX(n) + BX^u(n) \\ Y(n) = CX(n) \end{cases} \tag{9}$$

Where, parameters of the system matrix A involve the scrapping rate of agricultural machinery, relate to the aging of agricultural machinery and change along with the change of machinery aging, which can be obtained according to the statistics of historical data; the parameters in Control Matrix B are related with the mode for agricultural machinery renovation; different renovation modes have different impacts on the quantity and aging structure of agricultural machines, subject to the actual demand; Output Matrix C can be flexibly adjusted according to the purpose of system study; since the output equation for the control model of agricultural machinery subsystems established exclude variables, Direct Transfer Matrix D is a zero matrix.

3. System Analysis

3.1. System Running Analysis

With reference to the actual conditions of agricultural production, it is known that the major activities of subsystems in agricultural machinery system include:

(1) Participation in agricultural production;

(2) Substitution of other agricultural machines for production;

(3) Scrapping of agricultural machinery;

(4) Renovation of agricultural machinery;

(5) Idling of agricultural machinery;

(6) Maintenance of agricultural machinery.

The scrapping of agricultural machinery refers to two circumstances: one is that agricultural machines are scrapped before reaching the upper limit aging due to different faults and the scrapping rate is related to the aging of agricultural machines, which can be obtained by calculation as per actual conditions; the other is that agricultural machines are scrapped upon reaching the upper limit of aging, *i.e.*, the scrapping rate is 100% when agricultural machines reach the upper limit of aging.

The process of agricultural machinery renovation is: firstly, select the aggregation of agricultural machines to be renovated, which should include the agricultural machines up to the upper limit of aging for scrapping, agricultural machines not yet up to the upper limit of aging but up to the economic life and scrapped and agricultural machines not yet scrapped but up to the economic life; secondly, according to the constraint and limitation of such renovation conditions as renovation funds, screen out the aggregation of agricultural machines removable; then, select the appropriate renovation mode and delete from the system the renovated agricultural machines as well as add in the renovated agricultural machines for completing the whole process of agricultural machinery renovation.

The activities of agricultural machinery subsystems affect the type, quantity and aging structure distribution changes of agricultural machines in agricultural machinery system; scrapping of agricultural machinery will cause the quantity of agricultural machinery to decrease;renovation of agricultural machinery will cause the quantity of agricultural machinery to increase as well as keep the quantity of agricultural machinery unchanged or cause the quantity of agricultural machinery to decrease.

3.2. System Property Analysis

3.2.1. Observability Analysis: Observability of system state means the ability of the system output $Y(n)$ to reflect the state $X(n)$. Without direct contact with the input, Formula (10) can be simplified as follows:

$$\begin{cases} X(n+1) = GX(n) \\ X(0) = X_0 \\ Y(n) = CX(n) \end{cases} \tag{10}$$

From Formula (9) and (10), as for any given input $X^u(n)$, if it is possible to exclusively determine the initial state of the system $X(0)$ through output $Y(n)$ within the limited period, such state $X(0)$ is observable; if each state of the system is observable, the system is state-observable; otherwise, the system state is not completely observable. Therefore, the criterion for observability is that Matrix Q is a column full rank matrix.

$$Q = [C \quad CA \quad CA^2 \quad \cdots \quad CA^{m-1}]^T$$

From Formula (9) and Initial Condition $X(0) = X_0$, the following formula can be obtained:

$$X(n) = G^n X_0 + \sum_{i=0}^{n-1} G^{n-1-i} H X^u(i) \tag{11}$$

Where, input $X^u(i)$ is known, system state observability is equal to exclusively determining the initial state $X(0)$ through output, and whether the agricultural machinery system is completely observable is determined by the structure and output form of the system.

From Formula (10), $X(n)$ is solved as:

$$X(n) = G^n X_0 \tag{12}$$

So, from the output equation, it is obtained as follows:

$$Y(n) = CG^n X_0 \tag{13}$$

From Formula (13), it is known that the initial state X_0 is determined according to output $Y(n)$, subject to the nature of Coefficient CG^n. Based on the system theory, the adequate necessary condition for Formula (10) system state to be completely observable is that the following matrix meets column full rank matrix:

$$Q = \begin{bmatrix} C \\ CG \\ CG^2 \\ CG^3 \\ \vdots \\ CG^{m-2} \\ CG^{m-1} \end{bmatrix} \tag{14}$$

Where, C, G matrix is as follows:

$$C = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \tag{15}$$

$$G = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & 0 \\ 1-\mu_0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1-\mu_1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1-\mu_{m-1} & 0 \end{bmatrix} \tag{16}$$

C is the unit matrix of $(m+1)$ order; $A = G$ is the system matrix and parameters in G are related to the scrapping rate of agricultural machinery; and in combination with Formula (9) and (10) and Matrix (14), Matrix Q is obviously full row rank, so Formula (9) is system-observable.

3.2.2. Controllability Analysis: Controllability of system state reflects the control ability of $X^u(n)$ over state $X(n)$. If the movement of state resulting from any initial state at any initial moment can be affected by input and controlled to the spatial origin within the limited time, the system is controllable, or state is controllable; otherwise, the system is not completely state-controllable. Therefore, the criterion for controllability is that Matrix R is a row full rank matrix.

$$R = \begin{bmatrix} H & GH & G^2H & G^3H & \cdots & G^{m-1}H \end{bmatrix}$$

From Formula (11), it is known that the quality of G^nH decides the control of input over initial state and coefficient matrix H is as follows:

$$H = \begin{bmatrix} 0 & 0 & \cdots & M_{oe} & \cdots & M_{o(m-1)} & M_{om} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & \cdots & -1 & 0 \end{bmatrix} \tag{17}$$

According to Formula (9), $A = G$ is the system matrix, and parameters in G are related to the scrapping rate of agricultural machinery; $B = H$ is the control matrix, parameters in H are related to the renovation mode of agricultural machinery, and Matrix R is obviously a row full rank. Therefore, Formula (9) is system-controllable.

4. Actualization of Simulation

4.1. Establishment of Simulation Model

MATLAB software is applied to construct and actualize the simulation of agricultural machinery system control model, for which Discrete State-Space Module, Constant Module, Add Module, Manual Switch Module, Product Module, Display Module, and Scope Module in SIMULINK are used. According to Formula (9), the simulation model of agricultural machinery system is shown in Figure 1, below.

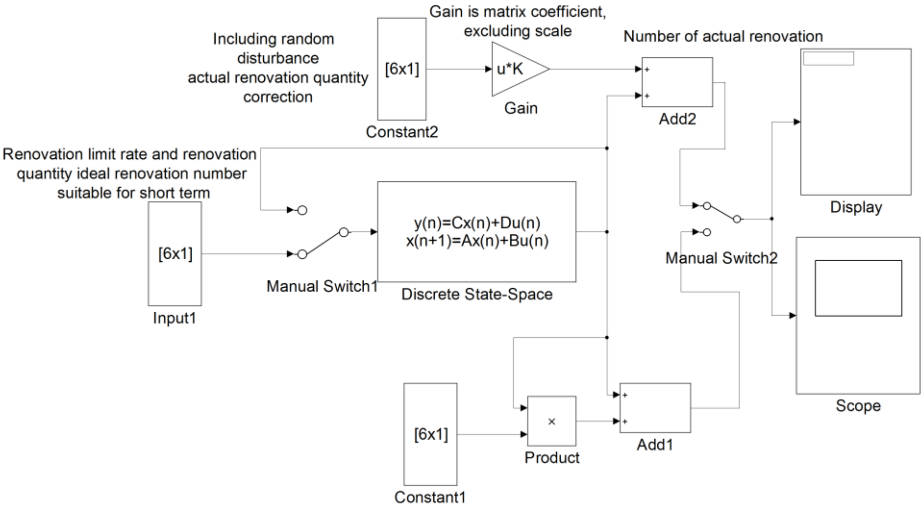
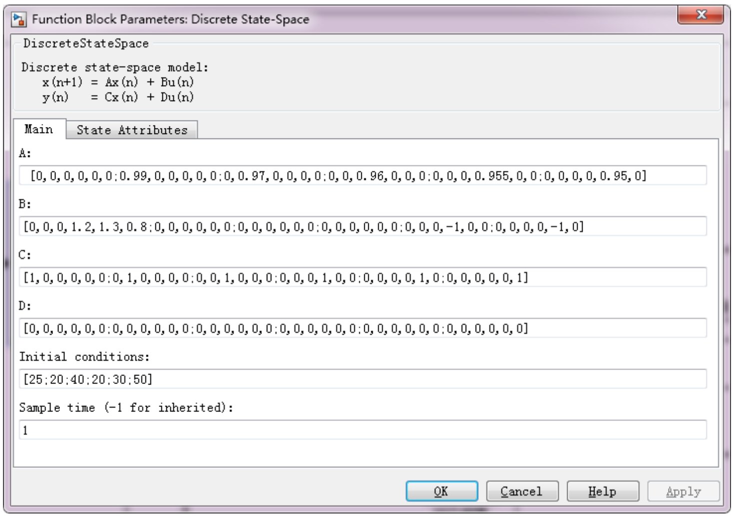


Figure 1. Simulation Model of Agricultural Machinery System

In Figure1, Discrete State-Space Module is the key module for actualization of simulation, and one Constant module is the input variable module of the system and another Constant module is renovation limit module and Manual Switch module is for adjusting the input variable. Since the control model is a discrete system model, variable-step is selected as the solving method of simulation. Display Model presents visually the numerical output results in the form of orderly numbers, while Scope Model presents output results in the form of line chart.

4.2. Running of Simulation Model

According to the simulation model in Section 4.1, bring in the given initial parameters and run the simulation model of agricultural machinery control system on SIMULINK platform, of which the input parameters of the key system module are as shown in Figure 2.



```
Discrete state-space model:
   x(n+1) = Ax(n) + Bu(n)
   y(n)   = Cx(n) + Du(n)
```

A:
[0,0,0,0,0,0;0.99,0,0,0,0,0;0,0.97,0,0,0,0;0,0,0.96,0,0,0;0,0,0,0.955,0,0;0,0,0,0,0.95,0]

B:
[0,0,0,1.2,1.3,0.8;0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,-1,0,0;0,0,0,0,-1,0]

C:
[1,0,0,0,0,0;0,1,0,0,0,0;0,0,1,0,0,0;0,0,0,1,0,0;0,0,0,0,1,0;0,0,0,0,0,1]

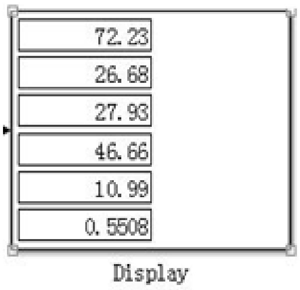
D:
[0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,0,0,0;0,0,0,0,0,0]

Initial conditions:
[25;20;40;20;30;50]

Sample time (-1 for inherited):
1

Figure 2. Input of Discrete State-Space Module

If the manual input is selected and the numerical value of the renovation limit module is also given, upon inputting the relevant parameters, click Run Simulation Model to show the relevant simulation solving results as in Figure 3 and Figure 4.



72.23
26.68
27.93
46.66
10.99
0.5508

Figure 3. Results of Numerical Output

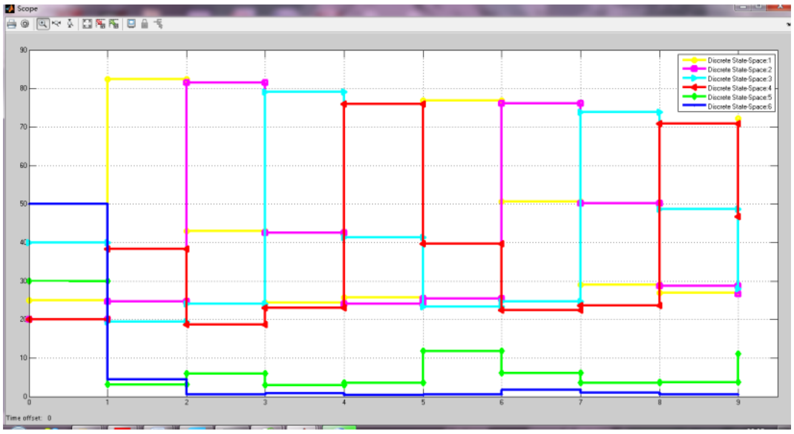


Figure 4. Results of Image Output

Figure 3, shows the visual results of numerical output and Figure 4, shows the results of image output, where Y-axis indicates the number of agricultural machines, X-axis indicates the time of simulation and different broken lines indicate the agricultural machines of different aging corresponding to one model. According to Figure 3, and Figure 4, aging structure distribution and quantitative distribution of agricultural machines in the agricultural machinery subsystems can be visually obtained when $n = 9$.

By changing the manual input variable of the simulation model, different results of control output can be obtained. According to the observable and controllable control model and simulation model of agricultural machinery subsystems established above, the control and simulation of the whole agricultural machinery system can be studies accordingly. By running the simulation model, the state change of agricultural machinery system can be quickly obtained, as verifies the effectiveness of agricultural machinery system control model established. With this simulation model, further studies can be carried out for types, quantity, aging structure distribution prediction and system state evolution of agricultural machines in agricultural machinery system.

5. Conclusions

The observable and controllable agricultural machinery system control model is established and is simulated with MATLAB software, based on control theory and complex system theory with reference to the actual conditions of agricultural production. The research provides an effective reference method and study basis for further studies on the internal contact, structural features and running rules of agricultural machinery system.

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