A Piece-Wise Linearization PID Control of Aero-engine Software Defined Control System

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Abstract. A scheme of piece-wise linearization PID control of aero-engine software defined control system based on wireless network is proposed in this paper. The characteristic of the system is that the PID controller is separated and distributed among the nodes of the wireless network, each node has the function of computing, memory and wireless communication, no core control unit in the system and the whole wireless network acts as a distributed PID controller. The linearization model and corresponding tuning parameters at different working points in flight envelope of the aero-engine are established offline using the memory resource of each node to make the node task parameters switch when the aero-engine working at different points. Finally, MATLAB/Simulink software tool is used to conduct the digital simulation analysis, the result shows that the proposed scheme achieves good dynamic and steady-state performance, and achieves good control effect.

1. Introduction

The aero-engine electronic control system undergoes analog electronic control, digital electronic control and distributed control[1][2]. In the above electronic control system, the components of the control system are connected by cables. During the flight, cables and connecters are prone to failure due to vibration and other factors, the thrust-weight ratio is reduced due to numerous cables and connecters in the system. In addition, the damage of the center control unit which covers the whole or main functions of the system has a great impact on the control system.

In the field of industrial control, with the development of wireless communication technology, Wireless Sensor Networks (WSN) and Wireless Networked Control System (WNCS) have appeared. WSN is a multi-sensor system, which is characterized by intelligent sensing nodes and shared communication links[3][4]. In WNCS, wireless network acts as a communication medium to undertake data communication tasks between nodes and has the characteristics of low cost, self-organization and easy maintenance[5][6]. [7] proposes the concept of EVM for industrial process control, the characteristic of which is to make use of the assignment and scheduling of the control tasks in nodes that the computing, communication, memory and energy are limited to complete complex control task.

Wireless sensor research for the harsh environment of aero-engine has achieved great results. For example, NASA Johnson Space Center[8], the University of Maine has conducted extensive research on passive wireless sensors in harsh environment. Environetix Technologies Corporation has developed a series of wireless sensors suitable for the harsh environment of aero-engine, of which the wireless temperature sensor EVHT-100 has been commercialized[9][10].
Linearization control of aero-engine is still a common control method, but the aero-engine is strongly nonlinear, it is difficult to guarantee the real-time requirement for online calculation of real-time linear model and tuning of controller parameters, for the offline calculation of linear model and tuning of controller parameters, with the improvement of the model accuracy of aero-engine, the number of aero-engine models and the corresponding controller parameters will be very large, this poses a high requirement for local memory of control system, and is a great challenge to the existing aero-engine control system.

The above research indicates that the aero-engine control based on wireless network is an important development direction of aero-engine control research in the future. In this paper, we proposed a aero-engine Software Defined Control System (SDCS) based on PID controller which is the simplest and most commonly used[11]. SDCS realizes a fully distributed controller within wireless network using linearization model of aero-engine at different working points in the flight envelope[12] to make the corresponding controller parameters switched. The control scheme can overcome the impact of the cables, connecters and core control unit in traditional electronic control system on aero-engine control system, and the powerful memory capacity of SDCS is suitable for high-precision aero-engine piecewise linearization control. The effectiveness of the scheme is analyzed by MATLAB/Simulink environment.

2. Architecture of Aero-engine SDCS

Figure 1 shows the overview of an aero-engine SDCS, which includes two parts: the Control Platform and the Support Platform. For the Control Platform, each node has the function of computing, memory and wireless communication, the PID controller is virtualized and dispersed in the wireless nodes in Figure 1, and the control system is a combination of wireless node tasks. The Support Platform is the manager of the control system (i.e. the whole wireless network), which mainly includes node resource monitoring, node scheduling and the management of node task mapping.

The wireless network based on the IEEE 802.11 protocol standard is used to build a Ad-Hoc network that is peer-to-peer and un-center. In order to simplify the research, this paper limits the scope of study to a small jet engine, and all nodes in the network can jump to each other.

![Figure 1. Overview of aero-engine SDCS.](image)

2.1. Control task virtualization based on MATLAB/Simulink

SDCS requires that control tasks be divided(i.e. virtualized) and then distributed among the nodes in wireless network. The process of task segmentation is called control task virtualization, and each segmented task is called Virtual Control Task (VCT).

![Figure 2. (a)Model of a PID controller; (b)Subsystem Block of Simulink software.](image)
The scheme of virtualization of the control task designed in this paper is based on MATLAB/Simulink, a PID controller Simulink model is shown in Figure 2(a). The Subsystem Block (as shown in Figure 2(b)) in Simulink is used to package the blocks that make up the controller, and each packaged subsystem is a VCT. For example, the Figure 3 is a virtualization scheme of the PID controller shown in Figure 2.

![Figure 3. VCTs from Figure 2(a).](image)

2.2. Introduction of Support Platform Architecture

The Support Platform architecture is shown in Figure 4. The Support Platform Manager (SPM) realizes all the functions of the Support Platform. Each node runs a Local Operating System (LOS) which executes Local Tasks (LT) of the node and VCT mapped to the node.

![Figure 4. Architecture of the Support Platform.](image)

3. Piece-wise Linearization operation of aero-engine SDCS

Linear control method is a mature and common method in aero-engine control, but the operation process of aero-engine is a complicated aerothermodynamics process. Within the full flight envelope, the aerothermodynamic process of the aero-engine varies with environment condition and working condition. The piece-wise linear model is required in the design of control system by using linear control law because aero-engine has strong nonlinearities, multimodality and high-order characteristics. For the SDCS scheme proposed in this paper, due to each node in the wireless network have capacity of memory, the whole control system can achieve powerful memory capacity to meet the requirement of aero-engine piecewise linear model accuracy improvement on the memory capacity of the control system. The implementation of piecewise linearization control scheme of aero-engine based on software defined control system is discussed in this section.

3.1. The operation analysis of Support Platform

In order to describe and schedule the whole wireless network and the control tasks, two data structures named SPM Description Table (SPMDT) and Nodes Control Table (NCT) are introduced. SPM gives the description of wireless network, VCT status and operating points of the aero-engine in flight envelope, including CPU utilization and memory usage of each node and communication status between nodes. NCT includes mapping relationship between VCT and network nodes, data transmission relationship between wireless network nodes, and the switching of VCT parameters of aero-engine at different working points.

The scope of SPM spans the entire wireless network and supports the following online operations: (1) Each node in the wireless network has a local backup of SPMDT and NCT, and keeps the SPMDT and NCT of the nodes in the wireless network consistent though periodic broadcast; (2) Each VCT is
mapped to 1 primary node and B backup nodes, the primary node and backup nodes can receive and process data synchronously, but the backup nodes do not send the process calculating data. (3) Switch all the parameters of VCT when working points in the aero-engine flight envelope changed.

During the operation of system, the following operating constraints should be satisfied:

(1) Each VCT is mapped to 1 primary node and B backup nodes

\[
\sum_{i=1}^{m} v_{i,j}^p = 1, \sum_{i=1}^{m} v_{i,j}^b = B, v_{i,j}^p + v_{i,j}^b \leq 1
\]

\[\forall i \in \{1,2,\cdots,m\}, j \in \{1,2,\cdots,n\}\]

(2) The number of all primary nodes is equal to the number of all VCTs exactly, the number of all backup nodes is great than or equal to the number of all VCTs

\[
\sum_{i=1}^{m} v_{i,j}^p = 1, \sum_{i=1}^{m} v_{i,j}^b = B, v_{i,j}^p + v_{i,j}^b \leq 1
\]

\[\forall i \in \{1,2,\cdots,m\}, j \in \{1,2,\cdots,n\}\]

(3) The IP address and MAC address in the network have a one-to-one mapping relationship

\[
\sum_{i} ip_i^l = 1, \forall i \in \{1,2,\cdots,m\}
\]

Where, the decision variables in the above constraints are:

(1) \(v_{i,j}^p\), the assignment variable of the primary node of VCT\(_i\), where \(i \in \{1,2,\cdots,m\}, j \in \{1,2,\cdots,n\}\)

\[v_{i,j}^p = \begin{cases} 1, & \text{node}_i \text{ is the primary node of VCT}_j \\ 0, & \text{else} \end{cases}\]

(2) \(v_{i,j}^b\), the assignment variable of backup node of VCT\(_i\), where \(i \in \{1,2,\cdots,m\}, j \in \{1,2,\cdots,n\}\)

\[v_{i,j}^b = \begin{cases} 1, & \text{node}_i \text{ is the backup node of VCT}_j \\ 0, & \text{else} \end{cases}\]

(3) \(ip_i^l\), the mapping variable of IP address, where \(i \in \{1,2,\cdots,n\}, j \in \{1,2,\cdots,a\}\), \(\text{IPADD} = \{ipadd_1, ipadd_2, \cdots, ipadd_a\}\) is the set of all IP addresses

\[ip_i^l = \begin{cases} 1, & \text{ipadd}_j \text{ is mapped to node}_i \\ 0, & \text{else} \end{cases}\]

3.2. VCT parameters switching

Computer memory technology has developed rapidly in these years, more than 100GB high-speed FLASH chips can be carried in a few square centimeters. There are many wireless nodes in the aero-engine SDCS, and the memory capacity of the whole control system is equal to the sum of all the nodes’ memory capacity in wireless network.
A set of nodes in the system can be used to store the parameters of controller at different working points in aero-engine flight envelope, which is called Parameter Nodes. Each node executing VCTs contains the working points of aero-engine at the present and local backup of controller parameters at nearby working points.

The working points of aero-engine flight envelope will be numbered. Assume that the aero-engine in flight envelope is divided into \( v \) working points, \( WP = \{wp_1, wp_2, \cdots, wp_v\} \) is a set of all working points in flight envelope, \( PAR = \{par_1, par_2, \cdots, par_v\} \) is a set of controller parameters at \( v \) working points after the aero-engine is piece-wise linearized, where \( par_i \) is a set of controller parameters at working point \( wp_i \) of aero-engine. In addition, assume that \( wp_i \) is the current working point of aero-engine, \( LPAV = U(par_i, \delta) \) is a set of local backup of controller parameters of all VCT nodes, where \( U(par_i, \delta) \) is the area with radius \( \delta \) of the element \( par_i \) in the set \( PAR \). With the change of the working point of aero-engine, VCT nodes apply for the controller parameters of corresponding working point from the parameter node, and discard the controller parameters that do not belong to \( U(wp_i, \delta) \) working point.

During the switching of VCT parameters above, the parameter set \( LPAV \) of local controller for the primary and backup nodes of all VCTs is dynamically adjusted as the aero-engine operating at different working points in flight envelope. When the working state of aero-engine is switching between the adjacent working point, the VCT nodes obtain the corresponding controller parameters directly from the local and update the parameter set of local controller by using the idle time of the nodes to reduce the time consumption of the switching of the controller parameters and ensure that the local storage resource of VCT nodes is sufficient.

In addition to the constraints of the section 3.1, the system also needs to meet the constraint below during the operation:

(4) the range of the local controller parameters is not exceeding the neighborhood with center of the current working point and radius of \( \delta \)

\[
\sum_{j} \text{Imp}_i^j \leq 2\delta + 1, j - i \leq \delta, i, j \in \{1, 2, \cdots, v\}
\]

where the decision variable \( \text{Imp}_i^j \) is

\[
\text{Imp}_i^j = \begin{cases} 1, & \text{parameters of } wp_j \text{ belongs to } U(par_i, \delta) \\ 0, & \text{else} \end{cases}
\]

4. Simulation analysis

In order to verify the effectiveness of the scheme, a analysis of digital simulation is made by MATLAB/Simulink software tool in this section. The piecewise linearization of a twin-shaft turbofan aero-engine at zero height and zero Mach number conditions from [13] is taken as the research object, and 5 working points running on the flight envelope of aero-engine are adopted for the purpose of simplifying the study. The PID controller and its virtualization plan are shown in Figure (2) and Figure (3).

The transfer function model of aero-engine is:

\[
G_{AE} = \frac{K(Tzs + 1)}{(Tp1s + 1)(Tp2s + 1)}
\]

Table 1 shows the model parameters at 5 working points in the flight envelope, where WP denotes the working point.
Table 1. Mode parameters of 5 working points in flight envelope.

| Working Points | 1  | 2  | 3  | 4  | 5  |
|----------------|----|----|----|----|----|
| $K$            | 0.0454 | 0.0472 | 0.0475 | 0.0476 | 0.0476 |
| $T_{p1}$       | 0.2156 | 0.2205 | 0.2190 | 0.2082 | 0.1717 |
| $T_{p2}$       | 0.1947 | 0.1860 | 0.1625 | 0.2072 | 0.1021 |
| $T_z$          | 0.2684 | 0.2305 | 0.2448 | 0.2726 | 0.1410 |
| $T_{z}$        | 0.2684 | 0.2305 | 0.2448 | 0.2726 | 0.1410 |

Given the system input as a Step input, the aero-engine is sequentially switched from the working point 1 to the working point 5, the linear model of aero-engine at 5 working points is obtained from the parameters in Table 1. Assume that the switching time of aero-engine at 5 working points is 5s, 10s, 15s and 20s respectively, since the system has to judge the current working point, the switching of VCT parameters lags behind that of working points of aero-engine. In this simulation, the lag time is set as 2 sampling periods, and the system response is shown in Figure 5. It can be seen from the figure that the switching of VCT parameters caused by the change with working point of aero-engine has little impact on the control system, the system maintains good dynamic tracking performance and steady state performance.

![Figure 5. System response when parameters of VCT switched in Step input](image)

![Figure 6. System response when parameters of VCT switched in a series of different Step and Ramp inputs](image)
Given the system input as a series of different Step and Ramp input, other conditions are consistent with that in Figure 5, the system response diagram is shown in Figure 6. It can be seen from the figure that the switching of VCT parameters caused by the change with working point of aero-engine has little impact on the control system, the system maintains good dynamic tracking performance and steady state performance.

It can be concluded from the above two simulation results that the proposed scheme achieves good dynamic and steady state performance in the piecewise linearization of aero-engine control, which shows the effectiveness of the proposed control scheme.

5. Conclusion

Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

In this paper, a concept of aero-engine SDCS based on wireless network is proposed. The virtualization scheme of PID controller which is the commonly used is introduced, the virtualized PID controller is distributed in wireless network and a fully distributed controller based on wireless network is realized. Aero-engine has strong nonlinear characteristics, in this paper, a controller parameters switching scheme is design by using the linearized model of aero-engine at different working points in flight envelope. This control scheme makes full use of the powerful memory function of SDCS.

According to the piece-wise linearization control scheme of aero-engine proposed in this paper, the digital simulation analysis is carried out. The simulation results show that the control scheme proposed in this paper achieves good control effect when the aero-engine works at different working points in the flight envelope, and the VCT parameter switching has little effect on the output response of the control system. Therefore, the scheme proposed in this paper is suitable for the subsection linearization control of aero-engine flight envelope, and reduces the impact of cables, connectors and core control unit on aero-engine control system at the same time.

6. References

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