Stability Analysis of PID Control of Aero-engine Software Defined Control System under Nodes Faults

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Abstract. A distributed aero-engine PID controller implementation scheme based on nocenter and peer to peer wireless network is proposed in this paper. The basic method is to make the PID controller virtualized and then distribute them in the nodes of the wireless network, the control task of the system is the synthesis of node tasks of multiple wireless network, and there is no special controller node in the system. In order to deal with the potential faults of nodes in the wireless network, tasks have the ability to migrate among nodes. Based on the analysis of complex frequency domain theory, task migration has less impact on the system response. Finally, the influence of task migration on the system is simulated and analyzed in the MATLAB/Simulink environment, simulation results are consistent with the theoretical analysis, the availability of the designed control system is proved.

1. Introduction
At present, the aero-engine control system is mainly based on the electronic control connected by cables[1][2]. There is a central control unit in the control system, all or main functions of the system are concentrated in the core unit. The damage of the core unit has a great influence on the system. In addition, the cables and connectors used in large quantities increase the failure probability of the control system, and reduce the thrust-to-weight ratio of the aero-engine at the same time.
With the development of low-cost sensing, computing and wireless communication technologies, Wireless Sensor Networks (WSN) have emerged[3][4], it is composed of several sensors, which take intelligent sensor nodes and shared communication links as the main topological features. Inspired by the WSN, Wireless Networked Control System (WNCS) appears in the control field[5]. WNCS has the characteristics of low cost, self-organization and easy maintain. In WNCS, wireless network is mainly used as communication medium and only takes on the task of data communication among the nodes in the wireless network[6]. In [7], a preliminary concept of EVM is proposed for industrial process control, the characteristics of EVM is to use the assignment and scheduling of control tasks in nodes with limited resources such as computing, communication and memory to complete relatively complex control task.
At present, research of aero-engine wireless sensor has achieved certain results, for example, NASA Johnson Space Center introduced the research status of passive wireless sensors in aero-engines and rocket-engines at the Report of Passive Wireless Sensor Technology 2012 Workshop Plan[8]. Environetix has developed a full suite of wireless sensors including high-temperature sensors, pressure sensors, vibration sensors and strain sensors for taking measurements in harsh and extreme environments with the supporting of the US Air Force and other organizations, and the wireless high-temperature sensor EVHT-100 has been commercialized and was available for customized
installation[9]. The above research shows that the control scheme based on wireless network is the
development direction of future aero-engine control system. The aero-engine Software Defined
Control System SDCS control system was proposed based on the development of the above mentioned
related supporting technologies.
Aiming at the challenge of modern aero-engine control system, based on the development of wireless
communication technology, computer technology, memory technology, and other supporting
technologies, this paper proposes the concept of SDCS, which is a fully distributed control system
based on IEEE802.11 protocol standard wireless network.

2. Architecture of Aero-engine SDCS
Figure 1 is overview of a aero-engine SDCS on a turbine engine, where WT denotes the wireless
temperature sensor, WP denotes the wireless press sensor, WA denotes the wireless actuator, \( \Xi \)
denotes nodes in wireless network, \( \triangle \) denotes the node have the abilities of wireless communication.
The SDCS consists of the Support Platform and the Control Platform, every node in the Control
Platform has the abilities of computation, memory and wireless communication, virtualized control
tasks are distributed in the wireless nodes, the whole wireless network forms complete controller to
complete the control function of the system; the Support Platform manages the control system, mainly
including the monitoring and analysis of nodes and control tasks, and task migration among the
wireless nodes.

Figure 1. Overview of a SDCS on a turbine engine.

2.1. Virtualization of PID controller for the Control Platform based on MATLAB/Simulink
The Control Platform requires that control tasks be distributed in nodes of the wireless networks, and
the overall control tasks of the system need to be divided into multiple sub-tasks. The division of
the control task is named control task virtualization, and each sub-task is named Virtual Control Task
(VCT).

Figure 2. Simulink model of a closed-loop PID controller.
As shown in Figure 2, it is the Simulink Model of the PID controller, the closed-loop PID controller
consists of several Simulink Blocks, each VCT is a Simulink Block or a combination of Simulink
Blocks, each Block or combination of Blocks can be encapsulated as a subsystem, each subsystem is a
VCT. An example of implementation of virtualization of PID controller is shown in Figure 3. The
function model of each VCT can be generated by using the Real-Time Workshop, it is compiled under
node platform to generate executable code of node platform.
Figure 3. Virtualization of controller in Figure 2.

2.2. Architecture of the Support Platform

Figure 4 is the architecture of the Support Platform, the function of the Support Platform is realized by the Support Platform Manager (SPM), the scope of the SPM span the entire wireless network, every node of the wireless network runs a Local Operating System (LOS), LOS executes Local Task (LT) and VCT assigned to the node, SPM realized the mapping relationship between VCT and nodes in the wireless network, and monitors the local resources (CPU, memory, etc.). In addition, SPM also complete the assignment and migration of VCT, and manages the entire network.

Figure 4. Architecture of the Support Platform.

3. Support Platform handle & node fault analysis

3.1. Support Platform handle

The operation of the Support Platform is described in this section. The set $SVCT = \{VCT_1, VCT_2, \cdots, VCT_n\}$ denotes set of all VCTs, the set $NODE = \{node_1, node_2, \cdots, node_m\}$ denotes set of all physical nodes in the wireless network, each VCT is assigned to $B + 1$ nodes, one of which is the primary node and the other $B$ node(s) is(are) the backup node(s). When the primary node of $VCT_i$ is at fault, the corresponding backup node is selected as the new primary node according to the ascending order rule of the IP address. When a backup node of $VCT_i$ is at fault, the corresponding idle node (the node does not execute any VCT) is selected as the new backup node according to the ascending order rule of the IP address. The state data is periodically exchanged among the primary node and the backup node and broadcast to the whole wireless network for node status monitoring.

The following decision variables is introduced to describe the operating process:

1. Primary node assignment variables $v_{ij}^p$, where $i \in \{1, 2, \cdots, m\}, j \in \{1, 2, \cdots, n\}$

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

2. Backup node assignment variables $v_{ij}^b$, where $i \in \{1, 2, \cdots, m\}, j \in \{1, 2, \cdots, n\}$

$$v_{ij}^b = \begin{cases} 1, & \text{node}_i \text{ is the backup node of VCT}_j \\ 0, & \text{else} \end{cases}$$
(3) IP address mapping variables $\text{ip}_j^i$, where $i \in \{1, 2, \cdots, m\}$, $j \in \{1, 2, \cdots, a\}$, the set $\text{IPADD} = \{\text{ipadd}_1, \text{ipadd}_2, \cdots, \text{ipadd}_a\}$ denotes all IP address

$$
\text{ip}_j^i = \begin{cases} 
1, & \text{if ipadd}_j \text{ have been mapped to node}_i \\
0, & \text{else}
\end{cases}
$$

During the running of the system, the following operating constraints must be satisfied:

(1) Every VCT have 1 primary node and B backup node(s), $\forall i \in \{1, 2, \cdots, m\}, j \in \{1, 2, \cdots, n\}$

$$
\begin{align*}
\sum_{i=1}^{m} v_{ij}^p &= 1 \\
\sum_{i=1}^{m} v_{ij}^b &= B \\
v_{ij}^p + v_{ij}^b &\leq 1
\end{align*}
$$

(2) The number of all primary nodes is exactly equal to the number of all VCTs, and the number of all backup nodes is greater than or equal to the number of all VCTs, $\forall i \in \{1, 2, \cdots, m\}, j \in \{1, 2, \cdots, n\}$

$$
\begin{align*}
\sum_{i=1}^{m} \sum_{j=1}^{n} v_{ij}^p &= n \\
\sum_{i=1}^{m} \sum_{j=1}^{n} v_{ij}^b &\geq n
\end{align*}
$$

(3) The IP address and MAC address have one-to-one mapping relationship, $\forall i \in \{1, 2, \cdots, m\}$

$$
\sum_{j} \text{ip}_j^i = 1
$$

3.2. Node fault analysis

When a node fault causes a VCT migration, the output of the VCT is 0 during the migration, which can be regarded as adding a square wave disturbance to the VCT's output when the migration action occurs. The width of the square wave is the duration of the migration action, the amplitude of the square wave is the same as the amplitude of the output of the VCT when the migration occurs, and the direction is opposite, i.e., disturbance $d(t) = -R \cdot \epsilon(t - t_2) + R \cdot \epsilon(t - t_1)$, where $\epsilon(t)$ is the Step Function, R is the amplitude, $t_2 - t_1$ is the duration of the migration action, and $t_2 > t_1$.

In this section, we mainly discuss the migration of VCT$_2$ and VCT$_3$ in Figure 3. The disturbance transfer function of the system is:

$$
Y(s) = \frac{G_{AE}(s)}{D(s) \left(1 + G_{PP}(s)G_{AE}(s) + G_I(s)G_{AE}(s)\right)}
$$

where $G_{AE}(s)$ is the aero-engine model, $G_{PP}(s)$ is the model of VCT$_2$ and $G_I(s)$ is the model of VCT$_3$.

From the disturbance transfer function, the impact of migration on system response mainly depends on the amplitude R, the greater the amplitude R, the greater the fluctuation of system response during task migration.

The steady-state error of the system under the disturbance is:

$$
e_{ss} = \lim_{s \to 0} \frac{sD(s)}{1 + G_{PP}(s)G_{AE}(s) + G_I(s)G_{AE}(s)}
$$
when the disturbance is Step \( r(t) = R \cdot \varepsilon(t - t_i) \), where \( R \) is the amplitude, \( t_i \) is the Step time, and the stead-state error of the system under this disturbance is:

\[
e_{ss} = \frac{R}{1 + \lim_{s \to 0}[G_{PD}(s)G_{AE}(s) + G_I(s)G_{AE}(s)]}
\]

Considering the disturbance \( d(t) \) as a superposition of two Step signals with opposite amplitudes. For the transfer function model of PID controller, the order of the numerator is two and the order of the denominator is one, the order of the numerator is greater than the denominator, it is easy to conclude that the stead-state error of the system under disturbance input \( d(t) \) is 0.

4. Simulation analysis

In order to verify the effectiveness of this scheme, this section is based on MATLAB/Simulink software tool for digital simulation analysis. In this simulation, the fuel-high-pressure rotor speed linear model of a twin-shaft turbofan aero-engine at zero height and zero Mach condition[10] is used as the plant model. The controller and virtualization scheme are shown in Figure 2 and Figure 3.

![Figure 5. System response under Step input](image)

The system response under Step input is shown in Figure 5, it shows that the system response has good stead-state characteristics and dynamic tracking performance. The scheme designed in this paper meets the requirements of the control system.

![Figure 6. Output of \( VCT_2 \) when \( VCT_2 \) is migrated at \( t = 3s \).](image)
Figure 7. Output of VCT$_3$ when VCT$_3$ is migrated at $t = 3s$.

Figure 6 is the output of VCT$_2$ when VCT$_2$ is migrated at $t = 3s$ and there is no migration of VCT$_2$. Figure 7 is the output of VCT$_3$ when VCT$_3$ is migrated at $t = 3s$ and there is no migration of VCT$_3$. It can be concluded that when migration happened, the output of VCT$_2$ is smaller than the output of VCT$_3$. From the perspective of disturbance, it can be seen that the amplitude of square wave disturbance when migration of VCT$_2$ occurs is smaller than that of VCT$_3$.

Figure 8. System response when VCT$_2$ is migrated at $t = 3s$.

Figure 9. System response when VCT$_3$ is migrated at $t = 3s$.

Figure 8 is the system response when VCT$_2$ is migrated at $t = 3s$ and there is no migration of VCT$_2$, and Figure 9 is the system response when VCT$_3$ is migrated at $t = 3s$ and there is no migration of
VCT₂. From Figure 8 and Figure 9, we can conclude that when VCT₂ and VCT₃ is migrated at same time separately, the impact of the migration on system response is different. The migration of VCT₃ has greater impact on system response than that of VCT₂. From the simulation results in Figure 6 and Figure 7, the difference of the system response is mainly due to the difference of the amplitude of the equivalent perturbation of the migration of VCT₂ and VCT₃.

From Figure 6 to Figure 9, it can be concluded that when VCT₁ is migrated, the greater the output of VCT₁ at the time of migration (it can be seen as the larger the amplitude of the equivalent disturbance is), the greater the impact of migration on system response, this is consistent with the theoretical analysis above, which shows that the analysis of the impact of VCT migration on system response is correct.

Different from the existence of the core control unit hot backup scheme, the controller of the control scheme proposed in this paper is distributed. Compared with the scheme with the core control unit, when the controller node fails and performs backup switching or task migration, the proposed scheme has less impact on system control performance, and risk caused by node fault is reduced due to the distributed structure of the controller.

5. Conclusion
This paper introduces a distributed aero-engine control system based on wireless network, and presents a virtualization scheme of PID controller based on MATLAB/Simulink software, the controller in the scheme is distributed. VCT(s) can be migrated between nodes to cope with the potential faults of nodes, and the impact of migration of VCT(s) on system response is analyzed. Finally, the digital simulation analysis is carried out. The simulation results show that the control system designed in this paper has good control performance, the impact of migration of different VCT on the system are simulated and compared, and the simulation results are consist with the analysis in this paper. It can be obtained that in the distributed control scheme proposed in this paper, while the control task are distributed in the wireless network, the risks brought by the node fault(s) to the control system is also distributed in the wireless network.

6. References
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