Wireless strain synchronization acquisition method based on Kalman Filter

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Abstract. For distributed wireless sensor networks, the time synchronization mechanism is the core part and the key to realize the coordination and processing of tasks between nodes. In this paper, an algorithm based on kalman filter is developed the wireless strain of synchronous acquisition system, through the coordinator fixed time interval by a synchronous message, when each node receives the synchronous message to mark its timer timestamp clock information of nodes, then the node according to the records of the clock information periodically call kalman filtering algorithm is used to estimate the next cycle of its own real clock and standard clock deviation coordinator, in the next cycle, real-time compensation is made by adjusting the overflow count value of node timer to achieve high synchronization accuracy. The sensor nodes in the system have high strain sampling accuracy and meet the requirements of general engineering applications.

1. Introduction

Wireless sensor network does not need the support of fixed base station, and has unique advantages such as fast expansion and strong damage resistance. Moreover, the distributed monitoring network constituted by wireless sensor network can greatly reduce the number of wired leads of the device, which has great advantages compared with the traditional wired acquisition and monitoring method [1]. As a specific application of wireless sensor technology, wireless strain acquisition system has been put into use in many fields [2]. Among them, due to its mature technology, convenient networking, high data transmission rate, and large number of nodes that can be accommodated, WIFI technology is increasingly used in a variety of occasions that require more data transmission [3] [4]. In many large engineering monitoring systems, in order to diagnose the integrity and health of the structure, it is generally necessary to conduct cross-regional collection, and the system will then conduct data fusion with massive collection data to judge the overall condition of the structure under test. In structure monitoring, the commonly used method of data fusion is modal analysis, and modal analysis requires the data collected by nodes to be processed and analyzed by sequencing on time sequence, which requires the adoption of a high-precision time synchronization mechanism to collect data, so as to obtain accurate synchronization of signal phase and potential. If the collected data appears chaotic in timing, modal analysis will lose its significance for data processing and prediction and even cause major disasters. Therefore, the time synchronization between data acquisition nodes plays a pivotal role in the whole system and is its core component [5] [6].
2. The Design of Wireless Strain Sensor Network

2.1. Overall system design
The strain acquisition system is composed of an upper computer, a coordinator and several nodes, as shown in Fig 1. The upper computer software is responsible for issuing control instructions, including start acquisition instruction, stop acquisition instruction, strain circuit bridge switch instruction, etc., and receiving the data uploaded by each node, which can be processed and displayed in real time. The coordinator is responsible for receiving the control instructions issued by the upper computer software, conducting unified coordination and management of the nodes under its control through broadcasting, and transmitting the data uploaded by the nodes to the upper computer. The node collects and uploads data in response to the control instructions of the upper computer software.

![Figure 1. Block diagram of strain acquisition system](image)

2.2. The node module
The block diagram of node module is shown in Fig 2, which is composed of power supply module, WIFI module, main control chip STM32F103, AD module ADS1274 and strain signal acquisition and conditioning circuit. After the system power supply, the strain signal is transmitted to the AD module through the signal acquisition and adjustment circuit. After the AD module completes the signal transformation, the converted result is read in by the MCU STM32 chip through SPI. STM32 completes the data packaging, and then sends it to the node WIFI module through the serial port. WIFI module is pre-configured with IP address, port number, working mode and other parameters. The node WIFI module works in STA mode, and the WIFI module working in AP mode on the connection coordinator will be searched after power on.

![Figure 2. Block diagram of node modules](image)

2.3. Coordinator module
The block diagram of coordinator module is shown in Fig 3 which is composed of power supply module, WIFI module and high-performance STM32F767 main control chip. The main control chip
STM32F767 connects with the coordinator WIFI module through serial port, receives the data uploaded by the node and forwards it to the upper computer through WIFI. After the WIFI module of the coordinator is powered on, it works in AP mode, selects a wireless channel with good communication quality according to the surrounding environment, and waits for the node WIFI module to be connected to complete the construction of data transmission network.

3. Time Synchronization Algorithm Based on Kalman Filter

The local clock of the sensor node is realized by its crystal oscillator. When a pulse from the crystal oscillator is received, the clock register inside the node is incremented. The accuracy of the crystal clock will be reduced if the crystal oscillator is of low cost and simple construction. There are many factors that can cause clock drift in real life, and they can be roughly divided into two categories: the first is the short-term environmental influences, such as temperature, humidity and power supply voltage; The second type is the slow long-term influence, such as the aging of crystal vibration, which can continuously affect the parameters of crystal vibration.

Most of the time synchronization algorithms that have been applied to wireless sensor networks are based on two different technologies: the first is based on pulse coupling; The second is based on message transfer technology. The pulse-coupled time synchronization scheme USES the waveform of the physical layer to transmit clock information, and the wireless signal pulses interact with each other in the nodes to simulate the biological system, which can automatically synchronize its periodic activities. In the time synchronization scheme based on message transmission, periodic information with timestamps is exchanged between nodes, which can effectively define the clock offset between nodes. Because the synchronization algorithm based on information interaction is easy to implement, and due to the long-term efforts of a large number of researchers, there have been many mature synchronization theories based on information interaction, among which RBS algorithm is the most representative one.

The sender of information in RBS algorithm periodically sends Reference Broadcast to the receiver of information in the wireless sensor network through Broadcast at the physical layer. The receivers of the information in the wireless sensor network first record the time of receiving the reference broadcast on their respective local clocks, and then exchange the recording time of each other. In this way, the receivers of the information can know the offset of the clocks between each other. After calculating the mean value of these clock offsets, the network nodes can adjust the local clocks to improve the precision of time synchronization between nodes effectively. However, for the wireless sensor network using RBS time synchronization algorithm, its algorithm complexity is high. For WSN with N nodes, at least N(N-1)/2 pieces of information need to be exchanged between nodes to complete synchronization. Moreover, frequent information interaction between nodes will cause channel congestion, thus reducing the efficiency of data transmission.

This system is based on RBS algorithm to design and implement the process of node synchronization. First cluster nodes in wireless sensor network is the coordinator through the WIFI
module receives the PC instruction and to reduce the node forwarding, by receiving node corresponding response command to confirm whether their jurisdiction and to reduce the network nodes is successful, then the coordinator on the basis of their own MCU clock clock, fixed interval period T to broadcast synchronization information to reduce the node, the node MCU timer enable itself every time receives the synchronous message immediately record the local clock timestamp that own timer count and the number of enter the interrupt, The node timer clock interval T0 relative to the coordinator standard clock interval T is calculated by two adjacent timestamps. Assuming that the node timer timing cycle is T2, when the node receives the time synchronization message in packet n (current packet) and packet n-1 (previous packet), the timer count value and the number of interrupts entered are respectively RVn,RCn and RVn−1,RCn−1, so T0 can be solved according to the following formula:

\[
T_0 = T_2 * (R_C_n - R_C_{n-1}) + R_V_n + (T_2 - R_V_{n-1})
\]  

(1)

Taking T0 as the measured value of this node clock, the kalman filtering algorithm is called to estimate the real clock T1 of the node itself within the next standard clock T (the initial estimate is standard clock interval T).

Kalman filtering is an algorithm for optimal estimation of system state using linear system state equation and through the input and output observation data of the system. Since the observed data includes the influence of noise and interference in the system, the optimal estimation can also be regarded as the filtering process. Kalman filtering is mainly realized by the system state equation and the system observation equation, and the state equation is mainly the relation between the state vector of a certain moment and the next moment. In this system, the coordinator MCU adopts the equal interval to send clock synchronization signal, and the node under its control receives the synchronization signal. The node true clock interval state equation of time point is:

\[
X_n = AX_{n-1} + BU_n + W_n
\]  

(2)

In the formula, \(X_n\) represents the system state vector at time n, while A represents the state transition matrix. In this system, the crystal oscillator clock offset is a slow linear process, and the clock drift rate within a certain time interval can be regarded as a constant, which can be calculated by the least square method. \(U_n\) is the control quantity of the system at time n, because the equal interval is adopted for the clock, there is no system input control variable. B to zero; \(W_n\) is process noise.

The measurement equation is mainly the relation between the measurement vector and the state vector at the same time:

\[
Y_n = HX_n + V_n
\]  

(3)

In this formula: \(Y_n\) represents the measurement vector at time n; H represents the measurement matrix, and the measured value is only the node clock count, so H = [1,0]; \(V_n\) represents measurement noise. The process noise and measurement noise of the system are considered as Gaussian white noise. The iterative calculation process of Kalman filter is as follows:

\[
X_{n,n-1} = AX_{n-1,n-1}
\]  

(4)

\[
P_{n,n-1} = AP_{n-1,n-1}A^T + Q
\]  

(5)

\[
Kg = P_{n,n-1}H^T (HP_{n,n-1}H^T + R)^{-1}
\]  

(6)

\[
X_{n,n} = X_{n,n-1} + Kg(Y_n - HX_{n,n-1})
\]  

(7)

\[
P_{n,n} = (I - KgH)P_{n,n-1}
\]  

(8)
In this formula: $X_{n,n-1}$ is the result of state prediction using historical data. $X_{n-1,n-1}$ is the optimal result of the previous state; $X_{n,n}$ is the final result of Kalman filter output. $U_n$ is the control quantity of the current moment state. If there is no control quantity, it can be zero. The control quantity in this design is zero. $Q$ is the covariance of system process noise $W_n$; $R$ is the covariance of measurement noise $V$; $K$ is the Kalman gain. Due to the results of the filter in the system by the current state of observed value and the historical state prediction decision together, so the observed value and predicted value of the weight directly affects the reliability of the system output, these parameters vary with environmental conditions and, in the practical engineering application often need to adjust the process noise covariance and measurement noise covariance value to get a better filtering effect.

Node in the process of clock synchronization calculation, after receiving the coordinator to send synchronous information, node MCU application $X_{n,n-1}$ predicted value (that is, the last time the result of the kalman filter) and itself clock $T_0$ relative to the standard clock interval $T$, calculate the nodes’ standard next time interval $T_{\text{offset}}$ of the node’s clock relative to the standard clock in the next period.

$$T_{\text{offset}} = T_1 - T$$  \hspace{1cm} (9)

Suppose node timer overflow interrupt is triggered $N_c$ times in the interval $T_1$, its expression is

$$N_c = \frac{T_1}{T_2}$$  \hspace{1cm} (10)

Then the clock compensation factor $V_{ccf}$ of the node is expressed as

$$V_{ccf} = \frac{N_c}{T_{\text{offset}}}$$  \hspace{1cm} (11)

Since the drift cannot be divisible, the fractional part of clock compensation factor $V_{ccf}$ needs to be processed in order to achieve better compensation effect. Let the clock decimal compensation factor be $V_{ccd}$, and its expression be

$$V_{ccd} = \frac{1}{10^{*\frac{1}{10}*V_{ccd}} - \frac{1}{10^{*\frac{N_c}{T_{\text{offset}}}}}} - 1$$  \hspace{1cm} (12)

In the next cycle, each node receives the coordinator of the synchronous information recorded after the timer the clock information, call the formula (1) to find the real clock interval $T_0$ node, the current cycle $T_0$ as measuring values, in combination with historical forecast calls kalman filter algorithm and the real clock interval of the next cycle node, and then call formula (9) - (12) and the clock compensation factor. After the beginning of the next cycle, whenever the node timer triggers $V_{ccf}$ or $V_{ccd}$ times of interruption, the node clock shall be compensated, that is, the counting period of the node timer shall be modified to achieve the goal of node clock synchronization. Since kalman filter algorithm only needs to be saved the last time the result of a call for this call to estimate input, take up little system memory, low algorithm complexity, and volatility after convergence is small, the synchronization process is also only for a single one-way communication can be done, to achieve a precise at the same time also do not take up too many system resources, the wireless strain measurement system can be the main resource for high-speed data acquisition and processing.

4. The system test
The coordinator and two nodes are selected for synchronization test. After the system is powered on,
the upper computer sends the network access confirmation instruction, and starts the synchronization process after receiving the confirmation reply from the two nodes. In the experiment, the coordinator sends synchronization information to the node under its jurisdiction at a fixed time interval of 30 seconds, and the node timer timing cycle is 25 microseconds. The node MCU is used to pull up and pull down one IO pin level every 1ms, and the oscilloscope is used to measure the IO ports of the two nodes every 5 minutes. The synchronization error is shown in Fig 4. The maximum synchronization error between the two nodes is 143 microseconds, the minimum synchronization error is 15 microseconds, and the average error is 74.5 microseconds, which can effectively compensate the node clock offset.

Figure 4. Synchronization error within 2 hours between two nodes

The strain acquisition accuracy of the strain acquisition node was tested, and the standard strain simulator XL2106A was used to simulate the strain input, and the collected strain signals were sent to LABVIEW software of the upper computer and displayed in real time through the waveform interface. See Fig 5 (a) ~ (c) show the waveforms output when the simulated strain input is 20µε, 500µε, and 2000µε, respectively. It can be seen from the figure that the strain measurement error is small and the overall error of the system is less than 2%. Fig 5(d) and Fig 5(e) show the process of the simulated strain input shift from 1000µε to 2000µε and from 1000µε to 500µε. It can be seen that the system response switch process is less than half second.
Fig 5. Strain measurement waveform figure
5. Conclusions
In this paper, a wireless strain synchronization acquisition system based on kalman filter time synchronization algorithm is designed and implemented. The system is composed of upper computer, coordinator and strain acquisition node, and the data transmission network is formed by WIFI technology. The system has low complexity, high time synchronization precision and high strain acquisition precision, which meets the general engineering application.

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