Ultra-low-power wireless anchor load monitoring system based on internet of things technology

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Abstract. Ground anchoring is a popular method to stabilize the slope. It is essential for stability evaluation to measure the tension value of anchor from installed load cell. In this paper, a wireless anchor load measuring system is proposed for continuously on-site slope stability monitoring. Each anchor load cell is connected to a MCU-based acquisition unit and become a wireless IoT end-device. This system is scalable so the sensor deployment will be much more flexible than that in conventional data acquisition system. The excitation circuit, signal amplification and analog-to-digital conversion are completed by a small-size device next to the anchor so that very low-noise result can be obtained. Each measurement consumes less than 10mA·s so this device can be drive only by a 55mm*70mm*40mm solar power module. Verified by almost 3-year’s on-site test, it is confirmed the proposed monitoring system can continuously capture and send one measurement per minute to the cloud server without any other electric power. The experimental and on-site test results show the practicability of proposed system and its reliability of long-term measurement. It has very high application potential on real-time slope stability monitoring by collecting and analyzing the load values of all installed anchors.

1. Introduction
Ground anchoring is a popular method to maintain the stability of slope. After construction, the residual tension load of the anchor should be continuously monitored for evaluating the stability of slope [1]. The traditional approach is sending people to the site regularly for measurement by using a load meter. However, it is not easy to perform because the load cells are usually hard to reach without the assistance of large machines. It is especially difficult to measure in severe weather condition, even though the information at this time is the most useful. Generally a data logger is connected to load cells nearby to store more measurements in a period of time for further process. It could be useful to get more data for afterward structural health analysis but cannot achieve real-time monitoring.

Recently with the rapid evolution of processors and communication technologies, IoT (Internet of Things) and WSN (Wireless Sensor Network) provide a new signal acquisition and process method for structural health monitoring [2, 3]. The signal of sensors installed in the field can be captured, processed, converted and transmitted back to remote server wirelessly. Hill et al. proposed an open-source-based sensor network system for structural health monitoring [4]. Kurata et al. deployed 14
wireless sensors on a bridge to capture acceleration response caused by a truck moving, the result shows very good agreement with that is captured by traditional method [5]. Tennyson et al. applied FBG (Fiber Bragg Grating) technology to measure the strain on civil engineering structures [6]. Backer et al. deployed strain gauges on large post-tensioned concrete beams of a railway support structure to confirm the applicability of laboratory-used resistive foil strain gauges on a real structure [7]. Whelan et al. applied an adaptive real-time wireless sensor network to monitor the strain of a highway bridge with resistive foil strain gauges [8]. Liu et al. verified a wireless strain sensor network is suitable for structural health monitoring through the experimental and theoretical value comparison [9].

Based on the above literature, IoT and WSN technology could be a very useful tool for developing a structural health monitoring system. However, it is very essential to reduce the power consumption as much as possible while applied to on-site structure health monitoring. In this paper, a solar-powered wireless anchor load monitoring system is proposed. With built-in excitation and signal conditioning circuit, it can be easily connected to the conventional load cells and transform the signal to wireless data packet out within a small-sized module. The on-site monitoring result will be used to verify the practicability and reliability of the proposed system for real-time slope stability monitoring.

2. Composition of anchor load monitoring system

To simplify the installation process on construction site, a wireless distributed system is developed in this paper as shown in figure 1. Each distributed smart node is connected to a conventional load cell for signal capturing. It can excite the bridge circuit inside load cell, amplify differential analog signal and then convert into digital data independently. All the distributed smart nodes are connected with a gateway in star topology to form a Zigbee-based wireless ad hoc network. The gateway is a central connection point of the LAN (Local Area Network) and also a router of the monitoring system to WAN (Wide Area Network). It collects digitized data from all the distributed nodes, transforms into network packet and sends to cloud server via 4G network. For remote configuration function, it receives parameters from the remote server and sends to the specified nodes. The distributed smart node features ultra-low-power consumption characteristics so that it can operate all the time with only one tiny solar power module. In addition, the elimination of signal and power line layout can effectively reduce the complexity of on-site installation.

In traditional application, the anchor load is measured by a handheld reader so the operator has to reach the load cell which is usually located high above ground. It is so manpower consuming and is therefore only suitable for periodic inspection. The conventional data logger can capture and save the value periodically in storage memory for further analysis but it lacks of real-time monitoring function. Some data acquisition system can achieve real-time monitoring when combining an on-site computer or sending data to remote server through a wireless module. However, it is power consuming and not suitable for harsh weather condition. Besides, the signal line will introduce environmental
electromagnetic noise to seriously affect the received signal because the load cells are usually far from the data acquisition device.

To overcome above mentioned problems, an ultra-low-power wireless distributed smart node was developed in this research to be installed close to load cells for load value measurement. It is mainly composed of a power control module, a microcontroller, a communication module and most importantly a load cell conditioning circuit, as shown in figure 2. The power control module converts solar energy into electrical energy and store it in a capacitor bank. It also contains several ultra-low dropout regulators to provide constant-voltage power for each component and to shutdown, if needed, for power conservation. The communication module is composed with a switch regulator and a Zigbee transceiver which is controlled by a microcontroller through a UART (Universal Asynchronous Receiver Transmitter) interface. This is a duplex module which transmits data to the gateway and also receives commands from it. The load cell conditioning circuit plays a role like a conventional load reader to excite the bridge circuit, amplify the differential signal and convert the analog signal into digital one. It is controlled by the microcontroller through a SPI (Serial Peripheral Interface) interface. To make the node smart, a mixed-signal microcontroller takes the whole necessary task on power control, signal capturing and data communication. The firmware inside is precisely designed to make the node ultra-low-power and stable.

2.1. Load cell conditioning circuit

From the electrical circuit point of view, the load cell is essentially a Wheatstone bridge circuit, as shown in figure 3. The differential voltage output between S+ and S- is usually as small as millivolts so that the condition circuit has to be as close to the load cell as possible to prevent electromagnetic noise interference and signal attenuation. In this research, the load cell conditioning circuit is designed small enough to be installed next to the load cell. Besides, the excitation voltage is keeping as low as 2.5V to reduce power consumption and also the gauge self-heating effect.

![Figure 2. Composition of distributed smart node.](image)

![Figure 3. Configuration of load cell conditioning circuit.](image)

This circuit is power by a voltage regulator which is controlled by a microcontroller to achieve optimized power usage. A low-drift, dual-output voltage reference is integrated to provide a stable voltage $V_{REF} = 2.5V$ to excite the bridge circuit and also be the rail-to-rail reference voltage for ADC (analog-to-digital) converter. A second highly-accurate voltage $V_{REF}/2$ can be used to bias the amplified bipolar signals which will be send to the ADC. Different from traditional design, the excitation voltage is much lower because the distance between the load cell and the conditioning circuit is much shorter than traditional one. The attenuation of the excitation voltage and the differential signal from bridge circuit become ignorable owing to a very short connection cable. In addition, it can still keep high signal-to-noise ratio on received signals even exited by a relative low exciting voltage because much less electromagnetic noise will be introduced by the connection cable.

It has so much benefit while the connection cable is short enough to allow a low operation voltage in the conditioning circuit. The excitation voltage can be generate by a voltage reference which is...
much more accurate and stable than traditional voltage regulator. For a 12V traditional conditioning circuit connected to a 120Ω bridge circuit, the supply current is as high as 100 mA so that it can only adopt a voltage regulator to excite the circuit. In addition, the energy consumption of the proposed 2.5V system is about 1/23 that of a 12V system which will greatly reduce the self-heating effect on the strain gauges.

An instrumentation amplifier with rail-to-rail output is used to amplify the small differential signal. To simplify the circuit, it is set in single supply operation mode and the output reference of the voltage reference VREF/2 is used to offset the output signal to a precise mid-supply level. The other output reference is connected to the reference input of an ADC converter so that the bipolar signals can be completely captured. Through the SPI interface, the microcontroller can control the converting process of the ADC converter and get the digital load value of the load cell.

2.2. Communication protocol
To reduce the wireless packet length, a communication protocol that can handle the streaming data was designed. As shown in figure 4(a), a sensor data is mainly composed with one ID byte and several non-ID bytes. The highest bit must be 0 in ID byte and 1 in non-ID byte so that each sensor data can be divided out in a continuous data steaming. The ID byte is uniqueness in a monitoring system for sensor identification. The non-ID byte could contain other information such as sensor type, sensor value, node voltage, etc. The length of non-ID bytes is variable and all data can be re-distributed in the form as shown in figure 4(b).

In proposed monitoring system, the sensor value captured by the smart node will be transmitted wirelessly to the gateway. All the latest data will be accumulated in a memory buffer of the gateway as shown in figure 5(a). The gateway will send the accumulated sensor data to sever periodically through 4G or Ethernet. Each smart node will send a segment of sensor data to the gateway according to the parameter configuration so that the gateway will receive the data segment separately at different time. As shown in figure 5(b), the gateway will search for an ID byte as the beginning point and search for next ID byte as the separating point to extract a complete sensor data. If it is a new node the data segment will be appended to the end of stack, otherwise it will replace the associated data segment in the stack.

![Figure 4](image-url) (a) Sensor data structure (b) Non-ID Byte re-distribution.

![Figure 5](image-url) (a) Sensor data accumulation in gateway (b) Data processing flow chart.
The protocol is simple and efficient especially for smart structural health monitoring. With the ID byte and Non-ID byte design, the gateway can easily separate sensor data segment from a continuous data streaming. The new type sensor can be defined with any number bytes of information and the gateway can still handle the sensor data streaming without any firmware upgrade. It makes the proposed monitoring system more flexible on changing the type or number of sensors.

2.3. Power saving strategy

For structural health monitoring applications, wiring a powerline to each sensor is pricey and troublesome. Especially in the lighting strike area, the whole system could be destroyed in no time. A self-contained wireless smart node supplied by solar power would be a very useful device. In this paper, the strategy for power saving of the smart node is as follows.

For load cell conditioning circuit, instrumentation amplifiers and ADCs that consume less than 1 mA in working condition are easily found in commercial components. It is the bridge circuit in load cell consumes most power in the load cell conditioning circuit. As shown in figure 3, the exciting current $I_{EXC}$ is:

$$I_{EXC} = V_{EXC} \left( \frac{1}{R_1 + R_2} + \frac{1}{R_3 + R_4} \right)$$

(1)

In traditional load value reader, the exciting voltage $V_{EXC}$ could be as high as 12V. If applied to a common used 350Ω bridge circuit, the exciting current is about 34 mA so the power consumption is about 0.4W. A linear regulator is often used to provide low-noise exciting current. However, the output voltage will still be affected by temperature and non-negligible self-heating effect is caused by high current passing through strain gauges that will make the measurement result unstable.

In proposed monitoring system, the exciting voltage could be as low as 2.5V without obvious noise interference because of very short connection cable between the load cell and conditioning circuit. The exciting current is down to 7 mA and the power consumption is only 0.018W. The self-heating effect is almost negligible, and more importantly, it can be measured without waiting for the heat balance after power-on. To minimize the power consumption, the smart node switches on the voltage regulator to supply the load cell conditioning circuit only for less than 1ms in each measurement.

The current of the Zigbee module for data transmission is 29 mA which is relative large in proposed system. Fortunately, this module takes only 0.15 s to get ready for transmission after power-on and less than 0.1 s to transmit packet out. The firmware of MCU needs to be precisely designed to control the measuring procedure to minimize the power consumption and prevent unnecessary interference of data acquisition from wireless transmission. To achieve the function as described above, the power of wireless module is turned on right after the load value measurement and conversion is completed. Besides, the power supply of the wireless module will last 0.2 s after packet sending for parameters receiving from the gateway so the smart node can be configured by remote server.

With the power saving strategy, the smart node consumes only 10 mA·s per measurement including the wireless data exchange. At other times, the load cell conditioning circuit and the communication module will be powered down while the microcontroller will enter power-saving mode. During this period, only a timer driven by a low-frequency oscillator is active for next measurement trigger so that the smart node consumes as little as 1 µA. Therefore, it consumes only 1526 mA·s per day for 10 minutes periodical measurement. If it is powered by a conventional 3.6Ah lithium battery (17 mm in diameter, 51 mm in height), the measurement could last for more than 6 years without battery replacement. Otherwise, it could also be powered by a tiny solar module (55mm*70mm*40mm) and could be functioning lifetime long.
3. Application of anchor load monitoring system

In mid-May 2016, an anchor load monitoring system proposed in this paper was installed in a forest recreation area in central Taiwan for real-time monitoring the stabilization of a slope. As shown in figure 6(a), there is a river below this slope whose foundation will be scoured during rainy season. Several pre-tensioned ground anchors were installed to stabilize the slope. At this installation site, mains electricity is hard to reach so the solar-power module was used to supply the wireless distributed smart node connected to the load cell at the end of the ground anchor as shown in figure 6(b). The distributed smart nodes measure load value and send converted data wirelessly back to the server via a gateway every minute. The real-time load values and historical data will be shown on a web page as shown in figure 6(c). Moreover the monitoring program can send a warning message to the manager when the monitored value exceeds the set safe range.

![Figure 6.](image)

Each load cell has its own electrical characteristic because electrical resistance of the strain gauges in the bridge circuit is not identical even they comes from the same brand of the same specifications. Small variation of composed resistor will cause the bias of output voltage of the bridge circuit. Calibration test was conducted on each load cell with the smart node to get the relationship between the force and the output voltage as shown in figure 7.
In Taiwan, because January is the dry season, there will be no heavy rain at the installation site. As shown in figure 8(a), the load value of three sensors is almost unchanged in whole month except little periodical variation caused by temperature effect. Figure 8(b) shows the load value in a week. Sensor 01 and Sensor 03 are installed in the place where the sun shines so the sensor value shows a cyclic change of one day simultaneously. Whereas Sensor 02 is under the shadow so the temperature effect is not so obviously.

In July 2016, a small area of slope under the installed site collapsed which was caused by days of torrential rain. As shown in figure 9, the load value began to drop around noon on July 8. The measured force suddenly dropped from 46 tons to 40 tons in one day and finally kept around 38 tons about one week later. The whole process had been completely recorded by the proposed monitoring system.

4. Conclusions
In this paper, an ultra-low-power wireless anchor load monitoring system was proposed and deployed to monitoring the load value of ground anchors in an existing slope. With the ultra-low-power design
of the distributed smart node, the value of anchor load can be captured and sent to the server wirelessly with a very small solar module instead of mains electricity. Moreover, the cable between the load cell and signal capturing device is very short so that it can dramatically reduce the electromagnetic noise interference and signal attenuation. Till now, this system has been transmitting data to remote server every minute for three years. It shows the long-term stability of the system for on-site structural health monitoring. More importantly, the ability of proposed system for real-time monitoring of the anchor load can be verified by the collapse event in June 2016. The proposed system has very high application potential on real-time slope stability monitoring by collecting and analyzing the load values of all installed anchors.

![Figure 9. History data of collapse zone.](image)

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