TenSense: Sensor Node for the Remote Tension Measurement of a Bolted Joint

Michail Sidorov
Department of Computer Science and Engineering
Toyohashi University of Technology
Toyohashi, Japan
mike@usl.cs.tut.ac.jp

Phan Viet Nhut
Department of Architecture and Civil Engineering
Toyohashi University of Technology
Toyohashi, Japan
p175510@edu.tut.ac.jp

Atsushi Okubo
Toyo Metal Co., Ltd.
Toyohashi, Japan
a-okubo@toyometal.co.jp

Yukihiro Matsumoto
Department of Architecture and Civil Engineering
Toyohashi University of Technology
Toyohashi, Japan
y-matsum@ace.tut.ac.jp

Ren Ohmura
Department of Computer Science and Engineering
Toyohashi University of Technology
Toyohashi, Japan
ren@tut.jp

***Abstract* — This paper presents an overview of a sensor node designed to measure the tension of a bolted joint for the purpose of unattended structural health monitoring. The electronic circuits are embedded inside a custom designed stainless steel washer. LoRa is used for wireless communication and data transfer between the sensor node and the base station. The proposed design eliminates the necessity of using specialized bolts with mechanical modifications to monitor tension making it an easy add-on to current and future mechanical structures. Design of the prototype is discussed and evaluated by means of simulation to confirm the proper functionality and adherence to the set requirements.**

Keywords — Fastener Tension Monitoring, Structural Health Monitoring, Industrial Internet of Things, LoRa, Smart Metering

I. Introduction

Bolts are widespread in the construction industry for making an easy and fast connection between different pieces or material. The fastening procedure works by clamping two or more objects together using tension created by the bolt. This method is easy and convenient, however, problems occur when the tension loosens due to different kinds of stress imposed on the fastener, e.g. vibration, shock, thermal expansion, etc. For applications like bridges, wind turbines, etc., it is critical to monitor this tension in order to know the general structural health and prevent failure. Currently scheduled inspections of bolted joints are performed or a certain basis to avoid failures. However, they can be costly, time consuming, or inconvenient to perform in case of limited access to the structure. It is also possible for the fault to be unnoticed until critical damage to the bolted joint becomes apparent. To combat this problem the best solution is to use remote monitoring. Numerous designs are proposed to monitor the tension of the fastener. However, most of them require either some mechanical modifications to the bolt itself, which is a deviation from a set standard [1-2]; are suited only for visual inspection [3]; not suited for remote monitoring at all [2–5]; or require the design to be split into two separate parts [6–9]. Thus, in order to combat these limitations we propose TenSense – a smart sensor node, with a novel washer design, capable of monitoring the tension of a bolted joint remotely with the integration of an Industrial Internet of Things (IIoT) network. Full system overview is presented. However, the design of the base station is not in its scope. Our vision is to use the TenSense node on big sized structures, e.g. bridges, wind turbines, etc. Fig.1. These structures are sometimes placed in remote locations or are hard to get to in order to do inspections. Thus, a simple and practical solution is necessary. A set of requirements was made for the prototype, these are listed as follows:

- Sensor node has to have a small footprint.
- Tension sensing mechanism integration should require no bolt modifications to conform to a set standard.
- Sensor node has to be targeted at unattended and remote monitoring via integration with IIoT.
- Ensure an operational life time of the sensor node greater than 5 years with daily transmission of 1-2 times.
- Use a low power and long range transmission protocol for communication to prolog battery life.
- Include the possibility to reconfigure the node via OTA updates. A feature that is needed to comply with IIoT.

Hence, the motivation for this project is to create a sensor node that fulfills the requirements and functions stated above.

II. Approach

Compared to all of the described products available on the market our novel approach to monitor the fasteners tension eliminates the need of any modifications to the bolt itself as the

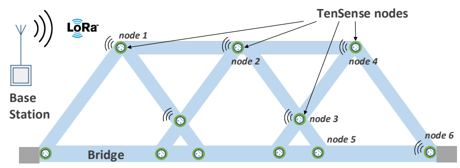

Fig. 1. TenSense application on a Girder Bridge

whole design is incorporated into the structure of a custom designed TenSense washer. Since large sized bolts are sold already with an integrated washer, we make no modifications to the set. Our TenSense washer is manufactured using stainless steel, has a circular shape and is adapted for use with M30 bolt type. The structure inside is split into six sections allowing to house the electronics, Fig 3. Thus, it can be considered as an all-in-one tension monitoring system.

III. Mechanical System Design and Implementation

The most critical requirement for this part of the TenSense washer is not to lose its primary function - to behave like a washer and not deform after the pretension load is applied. Thus, the load-carrying capacity of the TenSense washer was investigated by means of finite element analysis (FEA) using LUSAS software package. A half model was designed, since the structure is symmetrical, and a pretension load of 200 kN was assigned to the top part of a standard washer (the one that comes as a set with the bolt). A solid washer structure, without any cut outs, was then compared to a TenSense. The results can be seen in Fig. 2 on the left (L). In a solid washer an even stress distribution is observed, with some localized stress points that exceed 325 MPa mainly due to the impact conditions specified in FEA model. Same analysis was done for the TenSense washer, Fig. 2 on the right (R). We can observe a number of concentrated local points with the stress over 325 MPa due to the same reason mentioned before. The general distribution is below 270 MPa and is less than the yield strength of 310 MPa for grade 301 stainless steel. Thus, we can conclude that the six hollow sections in a TenSense washer do not impact the main mechanical function – being a washer.

IV. Electronics Sysytem Design and Implementation

A. Communication Protocol Choice

For a device primarily dedicated to be used for IIoT choosing the correct communication standard is application dependent. IIoT is a subset of IoT targeted for use in the industrial area and has to meet higher operational standards in terms of security, reliability, serviceability, etc. Protocols can be split into several major groups – very short, short and long range. Two former groups are not in our interest, since our TenSense node has to transmit over the distance of at least 1 km. This leaves us with cellular IoT protocols e.g. LTE-M, NB-IoT, and LPWAN e.g. SigFox, LoRa and RPMA. Many previous research papers compared different protocols in terms of coverage, transmission speed, etc. [10-12]. However, this is heavily design and working environment dependent. We chose the most efficient one based on the modules transmission (TX) range, sleep current consumption, footprint, running costs. Modules supporting cellular protocols are at clear disadvantage since they require a SIM card and consume high amount of current during TX. Thus, we turn to LPWAN. SigFox and RPMA have proprietary stacks

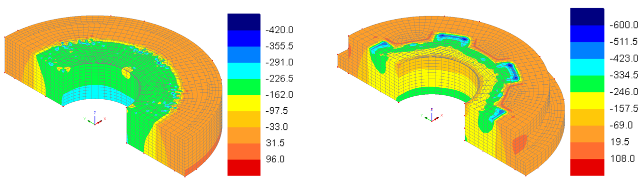

Fig. 2. Stress distribution in a solid washer (L) and TenSense washer (R)

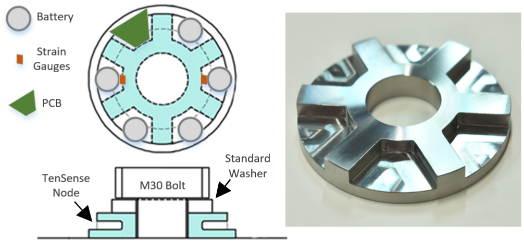

Fig. 3. Left side: Representation of the designed washer together with electronics component placement. Right side: TenSense washer

and modules consume a larger amount of current during TX according to [13-14]. Thus, LoRa was chosen. Murata offers the best solution that fits our needs out of all examined modules [15–18]. It has an integrated host controller and the smallest footprint. Furthermore, it supports LoRaWAN Class A, which would enable us to send MAC commands and reconfigure the settings of the node, e.g. change channel, SF factor, etc.

B. Tension measurement technique

Since there are many ways to measure tension we use the most practical one by utilizing bonded metallic strain gauges. Strain gauges are constructed in a way that allows them change their electrical resistance in proportion to the amount of strain applied. For the purpose of measurement they are configured in a Wheatstone bridge. In a perfectly balanced configuration, the output of the bridge will theoretically be equal to 0 mV. Practically, due to tolerances there will be some voltage at the output. This is dealt with in software providing some offset value to calibrate the initial reading to zero. The output voltage of the bridge is extremely low, hence it needs to be amplified. Typical configuration to drive the Wheatstone bridge consists of a voltage source and an operational amplifier to amplify the output signal. However, a one chip solution is used in our design.

C. Main TenSense node design

Fig. 4 shows a simplified block diagram of the full design. Main module consists of a Murata LoRaWAN module. Strain Gauge block contains strain gauges configured in a Wheatstone bridge. Design allows to monitor the values from two different bridges, with the strain gauges positioned on different sides of the washer, Fig. 3. The analog output from the former block is conditioned using an HX711 chip and fed into the main module. To minimize the power consumption a power gating technique is used. The HX711 and consequently the Strain Gauge block is completely disconnected from the power rail until it is needed again. An early stage prototype is shown in Fig. 5. The whole electronics assembly is covered by stainless steel making the antenna placement a critical issue. Using a chip antenna would be an ideal solution for a space restricted application. However, it is not applicable here. The surrounding stainless steel would load the antenna degrading its performance. External antenna can be used as a solution, however, it can be damaged if handled improperly. Thus the custom one was designed for integration into the structure of a TenSense node, Fig. 6. The design and evaluation was done using CST Microwave Studio 2017. Simulation results show that the center frequency of the antenna is 923.2 Mhz, with the VSWR value of 1.096 and the bandwidth equal to 7.5 MHz, where VSWR value is below 1.5, Fig. 6.

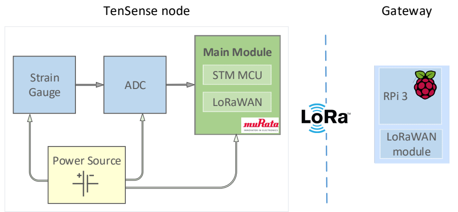

Fig. 4. Block diagram of the TenSense node

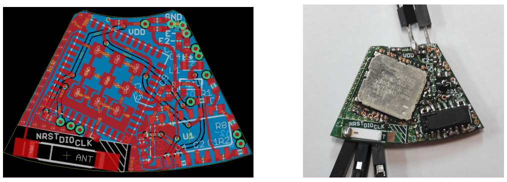

Fig. 5. PCB design and assembled board of an early TenSense node

Radiated efficiency is estimated to be 75.5 %.

D. Battery life estimation

Battery life was estimated using the current consumption numbers taken from the datasheets, a concrete TX scenario and a preliminary energy budget consisting of 5 CR1625 Lithium batteries with a capacity of 85 mAh each. TenSense node has 3 distinct operational modes: ON, Sleep and TX. Thus, the average daily current draw can be calculated from the following formula: $I_{Daily} = I_{ONmode} + I_{TX\ mode} + I_{sleep\ mode}$

I_{ONmode} is the amount of current consumed during tension measurement, $I_{TX\ mode}$ is the current consumed during TX time and $I_{sleep\ mode}$ is the current consumed during sleep sequence. As an extreme case 20 dBm power TX mode was used, with a current consumption of 128 mA. TX time is set to 1 second and tension measurement time is 3 seconds. Thus, we get the following:

$$I_{ONmode} = (3.2 + 1.5) * \frac{3}{3600} = \ 0.0039\ mA$$

$$I_{TX\ mode} = 128 * \frac{1}{3600} = \ 0.035(5)\ mA$$

$$I_{sleep\ mode} = (0.00086 + 0.0002) * \frac{3596}{3600} = 0.00106\ mA$$

The daily consumption is then equal to 0.06434 mA and yearly consumption is 24.48 mA. Theoretically, if we transmit 5 times per day the battery life will be 5 years, if we limit it to a single transmission the expectancy rises to 18 years. Practically, we need to account for battery self-discharge and other factors that will inherently limit its lifetime. Using a lower power transmission mode will also help. Furthermore, since the batteries are capable of providing only a limited constant current it is feasible to use a supercapacitor to buffer the energy needs during short periods of high current demands.

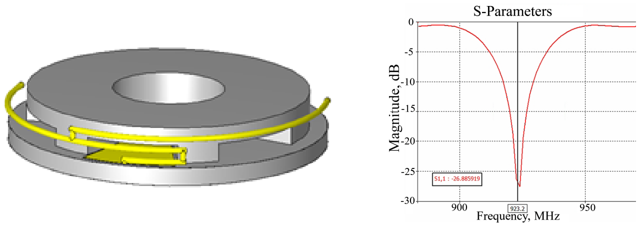

Fig. 6. Left: Antenna placement. Right: Performance at resonant frequency

V. Software Design

Software design is straight forward. Most of the time the TenSense node spends in sleep mode. Thus, it needs to know when to wake up. Real time clock (RTC) will help to keep the track of time and tell the main MCU when to wake up to take the measurements. Murata module would allow to receive the data, so it is possible to reconfigure the TX time and period to suit the scenario. Thus, the repetitive sequence consists of taking a measurement, transmitting it to the base station and entering the sleep mode until RTC wakes up the system to repeat the same sequence again. Fig. 7 shows the simplified main loop.

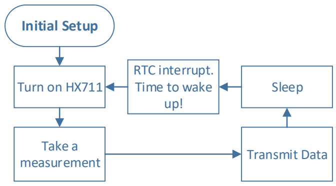

Fig. 7. Software flowchart

Conclusion

This paper presented a novel approach to measure the tension of a bolted joint remotely with all of the electronics integrated inside the custom designed washer. Numerous adjustments can be made to the design in order to improve performance figures and the design will be polished further.

Demo Exhibition

Tentatively we aim to present a poster, outlining the use cases of the TenSense node and a working prototype with a washer structure made out of material that allows to measure strain with a low force applied to it. Data would be visualized on the PC.

References

[1] S. Mekid and U. Baroudi, "Fastener Tension Monitoring System," 8,893,557 B2, 2014.

[2] H. Ohta and T. Sumigawa, "Bolt with function of measuring strain," 7,293,466 B2, 2007.

[3] G. Y. Lin, P. H. Ngo, T. F. Kennedy, and P. W. Fink, "RFID Torque Sensing Tag System For Fasteners," 9,483,674 B1, 2016.

[4] BoltSafe, "BoltSafe Sensor CMS." BoltSafe Sensor Continuous Monitoring System datasheet, Version 2.0.

[5] BoltSafe, "BoltSafe Sensor PMS." BoltSafe Sensor Periodic Monitoring System datasheet, Version 2.0.

[6] J. D. Smith and S. G. Pothier, "Load Sensing System Including RFID Tagged Fasteners," 7,412,898 B1, 2008.

[7] S. Mekid and B. Abdelhafid, "Bolt Tension Monitoring System," 8,596,134 B1, 2013.

[8] U. Baroudi and S. Mekid, "Bolt Tension Monitoring System," 8,448,520 B1, 2013.

[9] S. Mekid, B. Abdelhafid, and U. Baroudi, "Smart Lid for Smart Bolts and Probes," 8,540,468 B2, 2013.

[10] Y. Song, J. Lin, M. Tang, and S. Dong, "An Internet of Energy Things Based on Wireless LPWAN," *Engineering*, 2017.

[11] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, 2018.

[12] S. Al-Sarawi, M. Anbar, K. Alieyan, and M. Alzubaidi, "Internet of Things (IoT) communication protocols: Review," in *2017 8th International Conference on Information Technology (ICIT)*, 2017.

[13] WISOL, "Sigfox / Sub-1GHz." WSSFM10R1AT datasheet, 2018.

[14] UBlox, "NANO-S100 RPMA module." NANO-S100 datasheet, 2017.

[15] Microchip, "Low-Power Long Range LoRa® Technology Transceiver Module." RN2903 datasheet, 2018.

[16] Murata, "LoRa Module Data Sheet." CMWX1ZZABZ-TEMP datasheet, 2016.

[17] USI, "WM-SG-SM-42 LoRa Module." USI LoRa Datsheet, 2017.

[18] HOPERF Electronics, "RFM95/96/97/98(W) - Low Power Long Range Transceiver Module." RFM95/96/97/98(W) datasheet, 2017.