# Beidou NPS Applied to Monitor the Structure Safety Health of Bridge

Riqiang Chen, Shaoding Li, and Zhibin Xu

***Abstract*—**Based on the specific situation of bridge structure status in China and the technical advantage of Beidou navigation positioning system (NPS) in all-weather, real-time synchronization and large range, a system to monitor the structure safety health of bridge is installed on the Fensha cable-stayed bridge located on the north west of Beijing, China. The system consists of a updated Beidou base station, three measuring station as well as some traditional sensors. The data from major pier and major span are collected dynamically by the stations and sensors, converted to unique TCP/IP communication protocol, transmitted to a remote monitoring center to be stored, processed, analyzed, and displayed on a screen.

***Keywords*—**Beidou NPS, bridge health, base station, measuring station.

## I. Introduction

As rapid development of Chinese economy, dramatic change is happening on the speed and number on extra-large bridge construction. However it is facing the specific situation for enterprises to construct the bridges comparing to the leading countries in the field:

1) For long period of time, the quantity is paid much more attention than the quality in bridge construction area so that real life cycle of the bridges is lower than their design standard.
2) Because the cars are increasing year by year, the number of cars is over the design capacity of infrastructure like bridges.
3) In order to get good benefit, there are the huge number of overloading cars passing bridge every day, therefore the loss on the bridge structure is increased quickly.
4) The investment on bridge maintenance is much lower than on the construction, the many bridges are under overloading operation.

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TABLE I
THE NUMBER OF UNSAFE BRIDGES IN CHINA IN TEN YEARS

| Order | Years | Unsafe Bridge NO.(ten thousand) |
|---|---|---|
| 1 | 2001 | 1.01 |
| 2 | 2002 | 1.08 |
| 3 | 2003 | 1.04 |
| 4 | 2004 | 1.33 |
| 5 | 2005 | 1.46 |
| 6 | 2006 | 6.31 |
| 7 | 2007 | 9.86 |
| 8 | 2008 | 9.78 |
| 9 | 2009 | 9.57 |
| 10 | 2010 | 9.35 |

Therefore health monitoring system for bridge structure safe has been rapidly developed recent years. It is combined with the modern sensor, network and communication technologies to sure the normal operation of bridges in life cycle. There are the following disadvantages by the traditional displacement sensors, accelerometers, and laser interferometer etc in the system:

1) In bad weather, laser will be unable to work well; zero shift in traditional sensors will be caused.
2) The horizontal and vertical displacement can not be measured in the same point.
3) It is difficult to obtain big displacement over meters, but happen so often for the extra-large bridge with flexible structure.
4) The life of traditional sensors is so short, only two or three years, even shorter, that they can't be satisfied with the monitoring of long-life bridges.

Beidou navigation positioning system (NPS) can compensate for the faults of traditional sensors. Beidou NPS with 24/7 mode can obtain 3-dimension and larger parameters at a point simultaneously.

In this paper, Beidou NPS system will be applied to monitor the structure safe health of bridge. It will include new signal receivers and antenna to process data from Beidou system. The system is being installed on the Fengsha bridge (Fig. 3) located on the north west of Beijing, China in order to monitor the status of bridge in settlement of the main pier, vertical displacement of main span, and the displacement of bridge deck. At the same time, the traditional immunity sensors are installed to evaluate the results of Beiduo system.

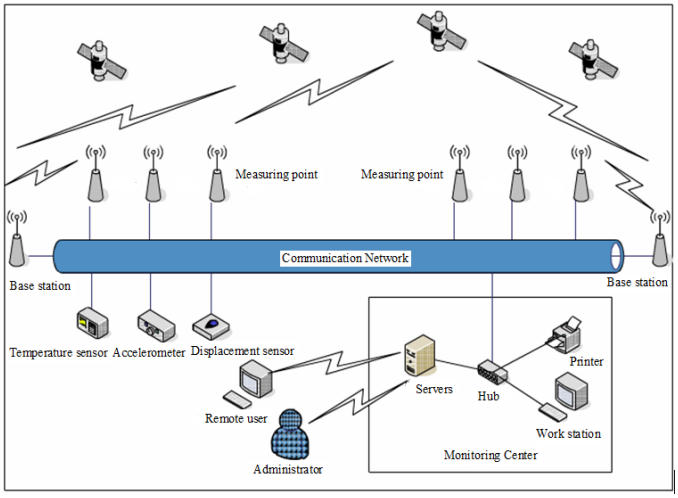


Fig. 1 Beidou NPS system architecture for monitoring bridge health

## II. System Architecture

The Beidou NPS to monitor the bridge health [1], [2], [4]-[8] is composedof the parts:

*Base Station*

Base station (BS) or called as Reference is installed at the place with stable foundation and open view near the bridge. It is responsible for the reception and transformation of satellite data in real time, then the data as standard is calculated either by Real Time Kinematic (RTK) or by post processing RTK.

*Communication Network*

The communication among the measuring station and local computer on the bridge adapt outdoor fiber cable; there are the number of he communication modes between the computer and remote monitoring center: 3G/4G, GPRS, wireless bridge network and Internet.

*Measuring Station*

Measuring station (MS) or called as measuring point on the bridge is responsible for the reception from the satellites, then either direct RTK calculation with the data from the BS or data transmission to the remote center for post processing.

*Monitoring Center*

Monitoring Center (MC) will manage all the data from both BS and MS, including the data store, calculation mining, analysis, statistics and display.

## III. System Design

The Fengsan bridge is the first cable-stayed bridge constructed by the method of pier-top swivel in Asia (Fig. 3) [3]. To verify its design, Beidou NPS system, as well as traditional sensors is used to monitor the status of bridge structure in 24/7.

*Sensing Network*

There are a base station and three measuring stations in the system, one of them is to monitor the settlement of the main pier and the horizontal and longitudinal displacements of

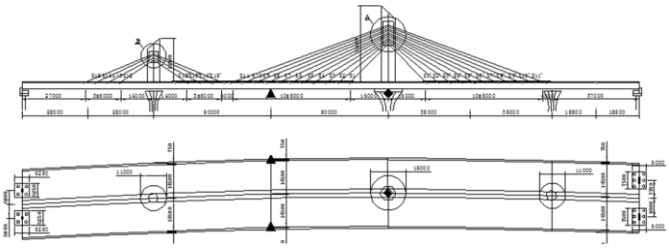

Fig. 2 Beidou measuring station distribution on bridge

bridge plane; other two are for the vertical displacements of main span.

*Parameters*

1) Settlement of the main pier: by calculating vertical difference between two continuous coordinates through post-process RTK algorithm, change trend will be obtained to approve if the main pier is stable.
2) Displacement of bridge plane: like the settlement computation of main pie the difference in both horizontal and longitudinal coordinates between two successive points is obtained by post-process RTK algorithm.
3) Immunity of main span: The vertical coordinate of 1/2 position of the main span is calculated by RTK in real time to compare with the results from traditional sensor at the same point. Its amplitude and recovery trend will be one of key sings and indicators for the fracture safety and overall stiffness of the bridge.
4) Environment temperature: temperature of both bridge surface and inside of box girders is very important for the system to identify weather the change of monitoring values is affected by bridge structure or environment.

*Intelligent Modules*

The intelligent modules are designed and implemented to complete the signal collection, transmission, management and analysis.

1) Data collection: an intelligent module can identify the different kinds of sensors with RS485/232/422, or TCP/IP protocols and get their data.
2) Transmission: data formats from multiple-protocol sensors are converted to unique TCP/IP before transmission through network.

Fig. 3 Fengsha bridge and Beidou base station location


Fig. 4 Beidou receiver

3) Integration platform: it can store, process, analyze and display data from sensors in a system.
4) Remote parameter setting: by Java Web Service, the system can set parameters up by web pages.

## IV. Implementation procedure

### *Beiduo Receiver*

An updated high-precision Beidou receiver has been designed and manufactured to monitor bridge structure health (Fig. 4).

### *Base and Measuring Station Location*

The location of both base and measuring stations should satisfy with conditions:

1) Small effect on electromagnetic interface and multi-path near antennas.
2) Satellite elevation angle over 10 degrees without shelter.
3) Provide station with uninterrupted power supply.
4) With lighting protection

In according to the basic requirements of bridge monitoring, the multi-path effect can be solved by the selection of the antenna with flow choke ring.

To have good view as many satellite as it can, the base station is installed on top of a building (red point) near the bridge (Fig. 4). Measuring stations will be located on the bridge deck (Fig. 2). In the beginning, the data of static observation is collected in 24 hours, then some professional software like TEQC is used to analyze the ratio of cycle slip signal-to-noise ratio, and multi-path effect and to evaluate their quality, particularly the quality of L2 observation data in experience. Based on the results of analysis and assessment, the location of both base and measure stations is adjusted properly to obtain the optimal state.

### *Communication System*

1) To reduce the loss during RF signal transmission process, the cable with good conduction performance is chosen. If possible, the receivers will be placed as close to their antennas as they can. If necessary, the low noise amplifiers will be added.
2) Data communication bandwidth for both base and measuring stations should be greater than 2M, transmission delay is less than 0.5s, Usage rate is higher than 95% and error rate is lower than $10^{-8}$
3) Data communication bandwidth for the monitoring center is larger than 2M, Usage rate is higher than 98% and error rate is lower than $10^{-9}$
4) Communication network: local computer on bridge connect to both base and measuring stations with fiber cables; the computer is connected to the monitoring center with 3G/4G, GPRS or fiber cable

TABLE II
BEIDOU RECEIVER TECHNIC PROPERTIES

| Property | Name | Parameter |
|---|---|---|
| Channel | Beidou | B1 12, B2 12 |
| | GPS | L1 C/A 12, L1P(Y) 12, L2P(Y) 12 |
| *RTK* | Base line (<30km) | 8 mm + 1ppm(H),15 mm + 1ppm(V) |
| | Network | 3 mm + 0.5ppm(H), 5 mm +0.5ppm(V) |
| | Pseudo code accuracy | <15cm |
| | Carrier phase accuracy | <15mm |
| | Sensitivity | -133dBm |
| | Timing accuracy | <50ns |
| | Positioning at first time | <60s |
| | Reacquisition time of lock loss | <1s |
| | Collection frequency | 1Hz |
| | USB support for external storage device | >10GB |
| | Weight | 500g |

TABLE III
BEIDOU INTERFACE PROPERTIEES

| Property | Name | Parameter |
|---|---|---|
| Power | Interface | 9 pin Lemo connector |
| | Voltage | 9-28V overvoltage protection |
| *Timing* | Interface | BNC connector |
| | Frequency | 10 MHz |
| | Electrical level | 3.3V±10% (VPP, 50Ω load |
| *Data* | UART interface 1 | 1, 9 lines, RS232 (DB9) |
| | UART interface 2 | 1, 3 lines, RS232 |
| | USB interface | 1 |
| | Enthnet | 1, 10M/100M, RJ45 |
| *Display* | LCD | 2 lines |
| | Indicator lamp | 4 (red and green) |
| *Environment* | Working Temperature | -40℃~+80℃ |
| | Water/dust proof | IP67 |
| | Shockproof | Anti natural drop 1.5 meters |

TABLE IV
HG-G0YH4201 ANTENNA PROPERTIEES

| Order | Property Name | Parameter |
|---|---|---|
| 1 | *Phase center stability* | <1mm |
| 2 | Working channel | GPS LI/L2、BDS B1/B2、GLONASS L1/L2 |
| 3 | Standing-wave Ratio(SWR) | ≤1.5:1 |
| 4 | Polarization | Right-hand circular polarization |
| 5 | Gain | 43dB |
| 6 | Work temperature | -45℃~+85℃ |
| 7 | Work humidity | 95% |
| 8 | Impedance | 50Ω |

### *Protection Procedure*

1) A surge protection module is added to between power and receiver in order to the effect on the receiver from

unstable power

2) The lighting protection module is installed between any station and the serial port of the computer.
3) The grounding device connected to the cabinet of the computer.
4) Safety protection facilities such as protection fence, cement pier and so on must be installed to prevent vandalism.

## V. Key Technology

*Cycle Slip Detection and Repair*

The precision of cycle slip will play an important role in high-precision monitoring of bridge structure deformation, therefore the cycle slip in original measurement must be detected and repaired at the first. There are many approaches to improve the precision of the cycle slip, such as High Order Difference (HOD)method, Ionosphere Residual Error (IRE) method, Pseudorange with Carrier Phase (PCP) and so on. However those methods have the faults of their own, respectively. The HOD can detect the larger slip only, and is suitable for the observation data of carrier phase at higher sample rate; the IRE can be applied the receivers with dual frequency, detect the small slip only, and have the multi-value problem when the slip is calculated[6]-[8].

In the principle, the all kinds of the methods to detect and to repair the cycle slip are the use of carrier phase observation from a continuous and smooth sequence without the cycle slip, therefore, the Chebyshev polynomial fitting algorithm with robust and the difference method of carrier phase between two adjacent epochs with dual frequency are used to detect and to repair the cycle slip.

*Fuzzy Degree Determination*

Due to the terrain limitation and environment influence, it is a key technology how to determine the fuzzy degree between base and measuring stations in bridge structure deformation monitoring. At the first, its ambiguity is determined using the long wavelength obtained by the line combination of wide lane, then, L1 integer fuzzy ambiguity is isolated by either the linear combination without the ionosphere or the linear relationship between the ambiguity of L1 and L2.

## VI. System Features

1. The records from a number of sensors on bridges are transmitted to the unique platform by the intelligent data-acquisition intelligent module. It makes the application easier to maintain and saves lots of money because it is prevented from the multi-devices to handle the data from various sensors.
2. Through web-service technology, the status and configuration of any sensor can be changed or controlled remotely so that fees for operators to maintain the device on the bridges can be reduced dramatically clustering has been great improvement for a number of users to access the system at the same time.
3. Clustering architecture has satisfied with the mass of data storage, parallel processing, and disaster recovery.
4. There are kinds of modes to show the real-time records such as lists, 2D graphs, and 3D renderings. Historical records can be shown in histogram and lists,
5. The history data can be loaded to any computer to print statistical reports or for bridge experts to analyze the structure safety of the bridge by software in real time.
6. Multi-level of pre-alarm threshold can be setup and modified on web page flexibly
7. Both application server and DB server can be updated and increased without the stop of the data acquisition in the cloud computing center.
8. The permission and role of a user can be controlled depending upon the user's job properties.

## VII. Conclusion

To verify the design of Fengsha bridge, the first pier-top swivel in Asia, the advanced Beidou NPS system is used to monitor the structure safy status of the bridge. The system includes a base and three measuring stations as well as traditional sensors to get information of the settlement of main pier, vertical displacement of 1/2 position of main span and so on. There are some key challenges to be exploited in this project, such as cycle slip detectiona and repair, fuzzy degree determination, the RF signal loss of transmission, multi-path effect, and the selection of stations. In fact, it is a successful attempt to use Beidou technology to monitor the dynamic parameter by RTK and static one by post-processing RTK.

To decrease the price and apllication range of Beidou system, an updated receiver with multiple antennas and higher frequence like 10Hz or 20Hz is being designed and developed.

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