DEVELOPMENT OF A GENERAL MONITORING PROGRAM FOR BRIDGE STAYS AND HANGERS IN WALLONIA, BELGIUM

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Abstract

The present paper reports on the design, implementation and preliminary testing of an accurate and non-intrusive axial force monitoring system for cables with a small bending stiffness anchored to possibly flexible supports. Wireless sensors are used to measure accelerations at selected points along the cables. Vibration measurements are acquired on a daily basis and processed to get estimates of the natural frequencies of vibration of the cable that feed up a numerical algorithm for the axial force identification.

INTRODUCTION

The Walloon Public Service department is responsible for the supervision of many cable-stayed and tied-arched bridges. To follow the variation of their condition over time, the axial forces inside their stays and hangers have been monitored for many years [1-4]. This process has already allowed detecting degradation issues in a few cables, in particular in Lanaye Bridge (see Fig. 1-(a)), where the tension in a stay decreased to 70% of its initial value from 1986 to 2003. Similarly, between 2001 and 2020, the axial force in another stay diminished by 21% (see Fig. 1-(b)). After expertise (see Fig. 1-(c)), it appeared that these cables were both weakened by stress corrosion cracking. This phenomenon is in fact a worldwide subject of concern even though the steel strands and rods are manufactured, installed and protected with increasing care [4-6].

In Wallonia, the determination of the tension in each cable of interest is currently based on sparse on-site evaluations of their natural frequencies, which are extracted from acceleration signals measured with wired sensors. For the moment, data are actually acquired at best once a year because the intervention of a skilled worker is still required, but they could be collected much more frequently in a remote way thanks to appropriate sensors and communication devices since cables are particularly prone to vibrate in ambient conditions. The Walloon Public Service department has thus decided to create and to install a new monitoring system on the cable supported bridges that belong to their road network.

Preliminary studies have shown that the natural frequencies of Walloon cables are not affected by sag-extensibility effects but well by bending stiffness effects. In addition, their extremities are somewhat slightly flexible in translation but also in between the ideal cases of hinges and clamps in rotation. A new algorithm has therefore been developed to tackle the identification of axial forces in such structural elements based on their natural frequencies. As the modal shapes are not necessary, the telemetry solution can hence rely on a simple network with only one sensor per cable.

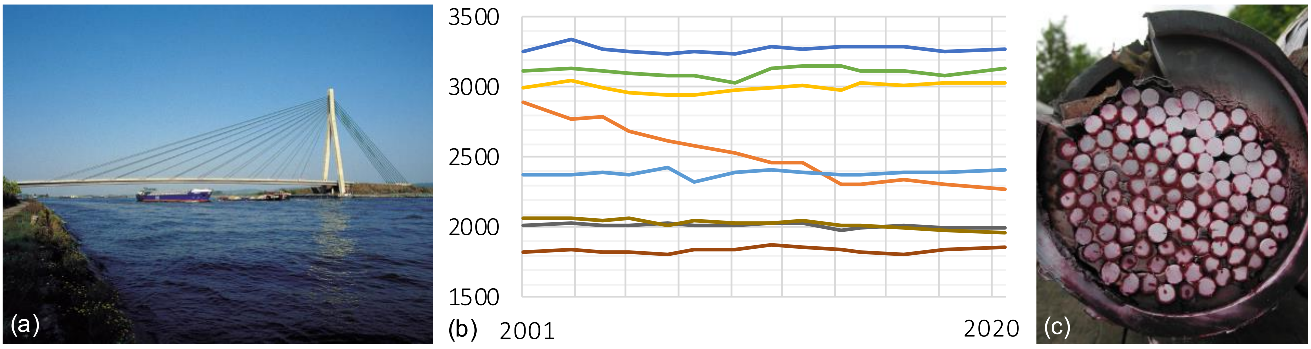

Figure 1 – (a) Lanaye Bridge, (b) variation of the axial forces in kN over time, (c) cross section of a damaged stay

IDENTIFICATION ALGORITHM

When the structural element at hand behaves like a taut string, its natural frequencies are integer multiples of the fundamental one

$$\omega_0 = \frac{1}{\ell}\sqrt{\frac{H}{\mu}} \tag{1}$$

and the axial force H can therefore be obtained by reversing this relationship, provided the length ℓ and the lineic mass μ are known. Unfortunately, the use of the taut string model gives correct results if and only if bending stiffness effects are negligible in the actual cable [4].

To address the identification problem, the first step consists in the selection, the analysis and the understanding of a parametrized model which is general enough to reproduce with sufficient accuracy the dynamical behavior of the different configurations that are encountered in the instrumented cables. The structural model chosen in accordance with this principle is shown in Figure 2.

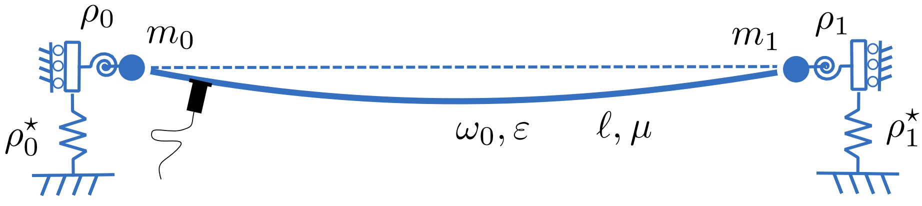

Figure 2 – Structural model, see [7] for a thorough description of the parameters

Considering the possible smallness of the dimensionless parameter

$$\varepsilon = \sqrt{\frac{EI}{H\ell^2}} \tag{2}$$

which translates the importance of bending stiffness effects, perturbation methods have allowed to derive an asymptotic expression for the first few natural frequencies of this structural element as follows

$$f_n = \frac{\omega_0}{2}\left(n + np\varepsilon + n\left(\frac{\pi^2 n^2}{2} + p^2\right)\varepsilon^2\right) + \text{ord}\left(\varepsilon^3\right) \tag{3}$$

where $p = 2 + \rho_r - 1/\rho_t$ with $\rho_r = \rho_0 + \rho_1$ and $1/\rho_t = 1/\rho_0^\star + 1/\rho_1^\star$ [7].

This formula helped to understand that it is useless to try to identify the rotational stiffnesses of the anchorages if the bending stiffness is extremely low, for instance. Similarly, for obvious symmetry reasons, it is impossible to detect separately parameters related to the left or to the right end, since the natural frequencies remain unchanged when the cable is flipped over.

Then, hinging on these findings, the second step focuses on the definition of a scheme that allows to determine the parameters of the cable based on its measured natural frequencies.

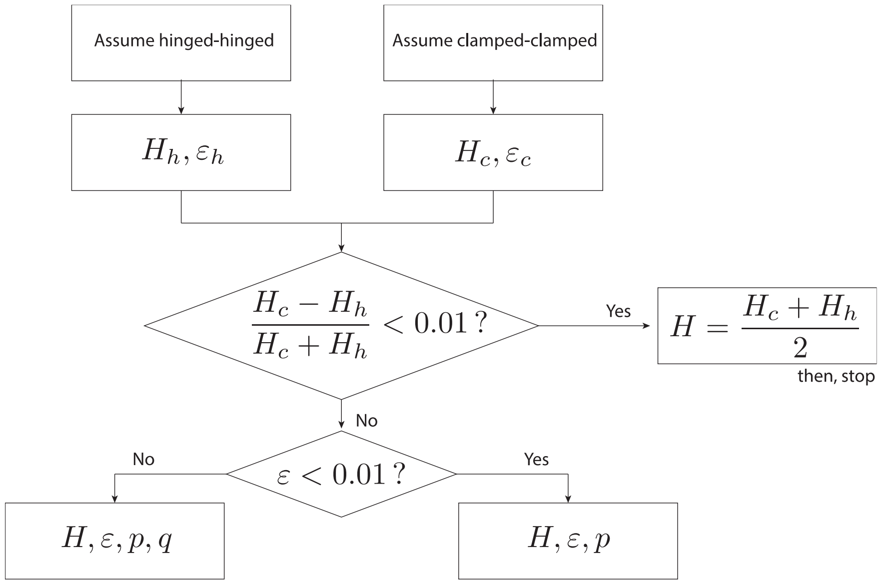

Figure 3 – Identification algorithm

The algorithm that was finally developed is presented in Figure 3 and additional details can be found in [7]. The approach is unified, in the sense that the mechanical cable model used is unique, whether the cable is long, short, trapped with flexible supports or not, translational and/or rotational. Based on the accumulated data, the procedure automatically adapts the number of parameters to be identified.

MONITORING SYSTEM

On the one hand, the identification algorithm thus takes the natural frequencies of a cable as inputs and delivers estimates for its axial force, its bending stiffness and, in some cases, also one or two parameters related to the translational and rotational restraints provided by its anchorages.

On the other hand, a complete monitoring system has been assembled as shown on Figure 4. The solution comprises three parts (from left to right in figure 4). First, wireless nodes measure the accelerations of each instrumented stay. Then, the central station computes the tension of each stay, using the algorithm defined in the previous section, and dispatches the results to an online server. Finally, a web application can be used to display the results.

Acquisition Setup

Concerning acceleration measurements, the use of wireless sensors has been preferred because it appeared to have many advantages. First, it does not require pulling wires along the whole bridge to link the sensors with the central station. Second, it allows the sensors to be easily placed far enough from the bridge deck to prevent vandalism issues. Third, it avoids adding mechanical weak points to the network, such as wires which are in addition complicated to repair or to replace.

A customized power supply system of four D-size batteries has also been designed to provide the capacity for the tri-axis accelerometers[1] to record five-minute long signals, four times a day, for ten years, at least. The sensor and battery assemblies have then been placed inside IP66 rated, waterproof and UV-resistant casings whose internal structure has been 3D printed. They also contain a temperature sensor with an accuracy of 0.25°C, an antenna and the electronics that are necessary to communicate with a central processing, control and relay station.

Each cable is equipped with such a box. It is attached by means of two U-shaped metallic plates which can adjust to any element provided its diameter is within a given range. In order to ensure that the natural frequencies of the cables are well distinct from those of this acquisition system, it has been tested on a shaker. Globally, it resonates at very high frequencies, that are hardly ever excited when dealing with ambient vibrations.

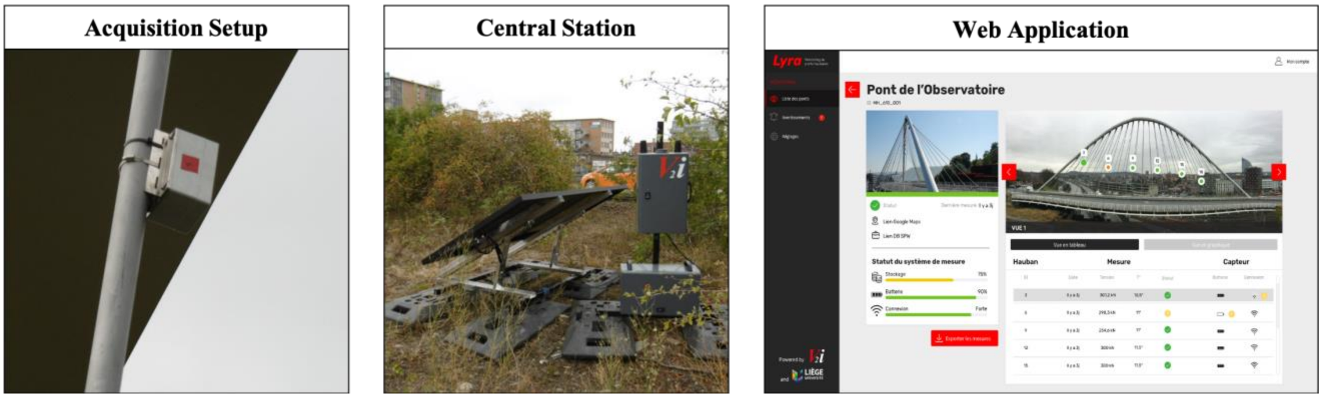

Figure 4 – Monitoring system

Central Station

The central station has three main functions. First, it controls the acquisition system. Several strategies are implemented to minimize the risk of collision or loss of packages. For instance, the station activates the sensors one after the other according to a specified schedule. A quality index is associated to the time series depending on their signal-to-noise ratio and the stability of the wireless connection. It allows to determine confidence levels for the subsequent identification of tensions or to directly discard some measurements. The sensors are also able to keep a part of the signal on their internal memory during a few seconds to transmit it correctly even though the connection with the station is intermittent.

Second, the station processes the acceleration measurements it receives by using the "crystal clear" version of the Stochastic Subspace Identification (SSI) method in order to compute the natural frequencies of the cables that correspond to stabilized poles [8-9]. It thus provides inputs for the identification algorithm to be used.

Third, the station acts as a relay by uploading and organizing raw data received from the acceleration and the temperature sensors but also the tension estimates and information about the remaining capacity of the batteries on an online server and on its own on-site database.

In addition, some parameters are embedded inside the memory of the station and can be modified either by direct access, either via the cloud. Typically, it encompasses the length and the lineic mass of the cables that are necessary for the axial force identification. Apart from that, the sampling frequency, the duration of acceleration measurements, their timing and the SSI parameters are defined there as well.

[1] LORD G-LINK-200-OEM-8G tri-axis accelerometer from MicroStrain, measurement range of ±2g

Web Application

Last but not least, a web application dedicated to the monitoring of axial forces in the stays and the hangers of cable supported bridges has been developed. It allows to visualize the variation of the tension in each cable by means of tables or graphs and it sends automatic warnings if an issue is detected on the central station (e.g. a power loss) or if the tension in an instrumented cable is outside specified limits.

MONITORING RESULTS

Figure 5, Figure 6 and Figure 7 gather the results that have been obtained during one month on the Wandre Bridge, the Observatory Bridge and the Harchies Bridge respectively. For each figure, the top left illustration corresponds to a picture of the bridge, the top right graph shows the axial forces identified over time in kN while the bottom left and the bottom right graphs represent the histograms of the bending stiffness parameters and of the axial forces.

In overall, the dispersion of the results is limited. Axial forces are just a little more scattered when the bending stiffness parameter is greater than 0,1 because it cannot be considered much smaller than one in this case, see black colored data in Figure 7. It is worth to notice here that temperature might influence the results as well. The purpose of the continuous monitoring is also to acknowledge the effects of temperature by referring to data accumulated in similar weather conditions. The scatter in the identified tensions is thus partly explained by the environmental variables. After detrending, the residual variances are decreased by a factor 5 or more, which contributes to increase the detectability of the proposed methods.

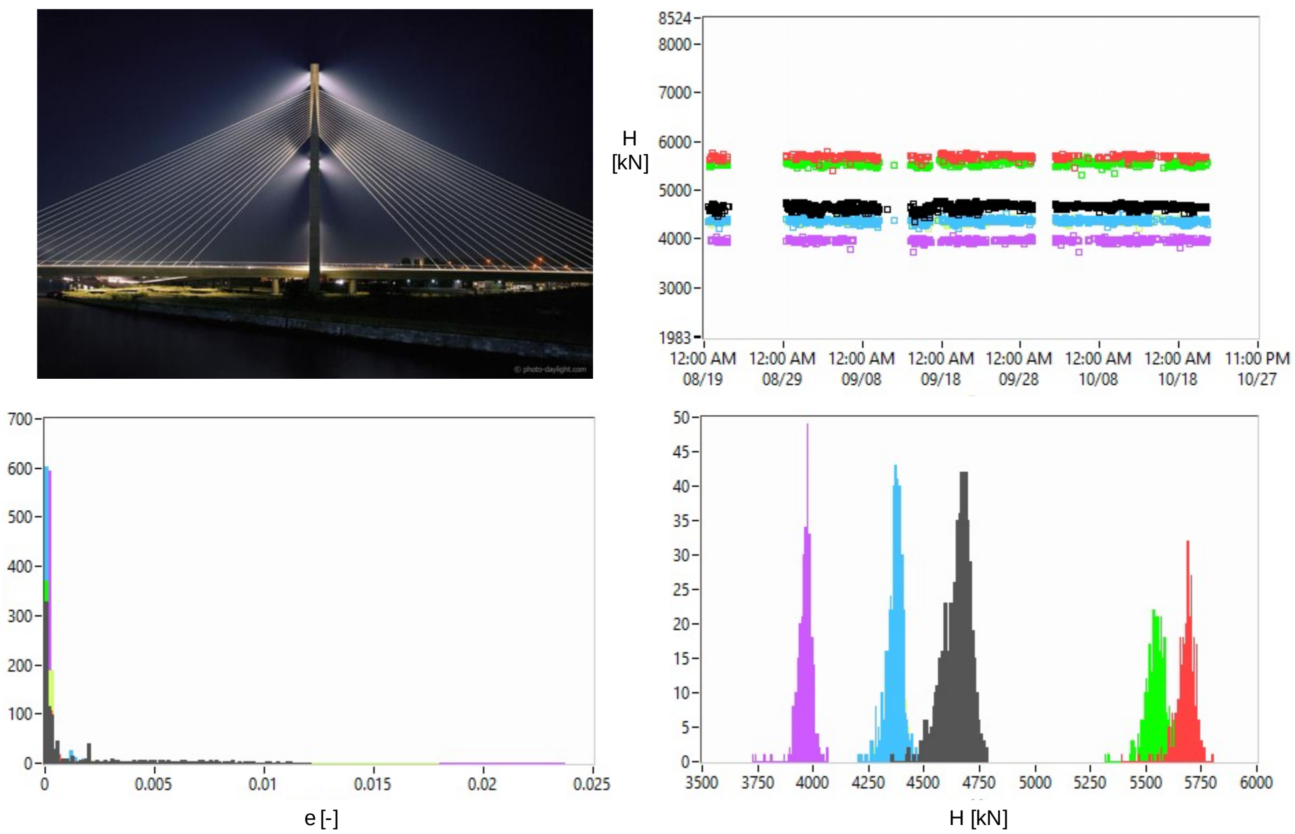

Figure 5 – Results obtained on Wandre Bridge (picture from Jean-Luc Deru)

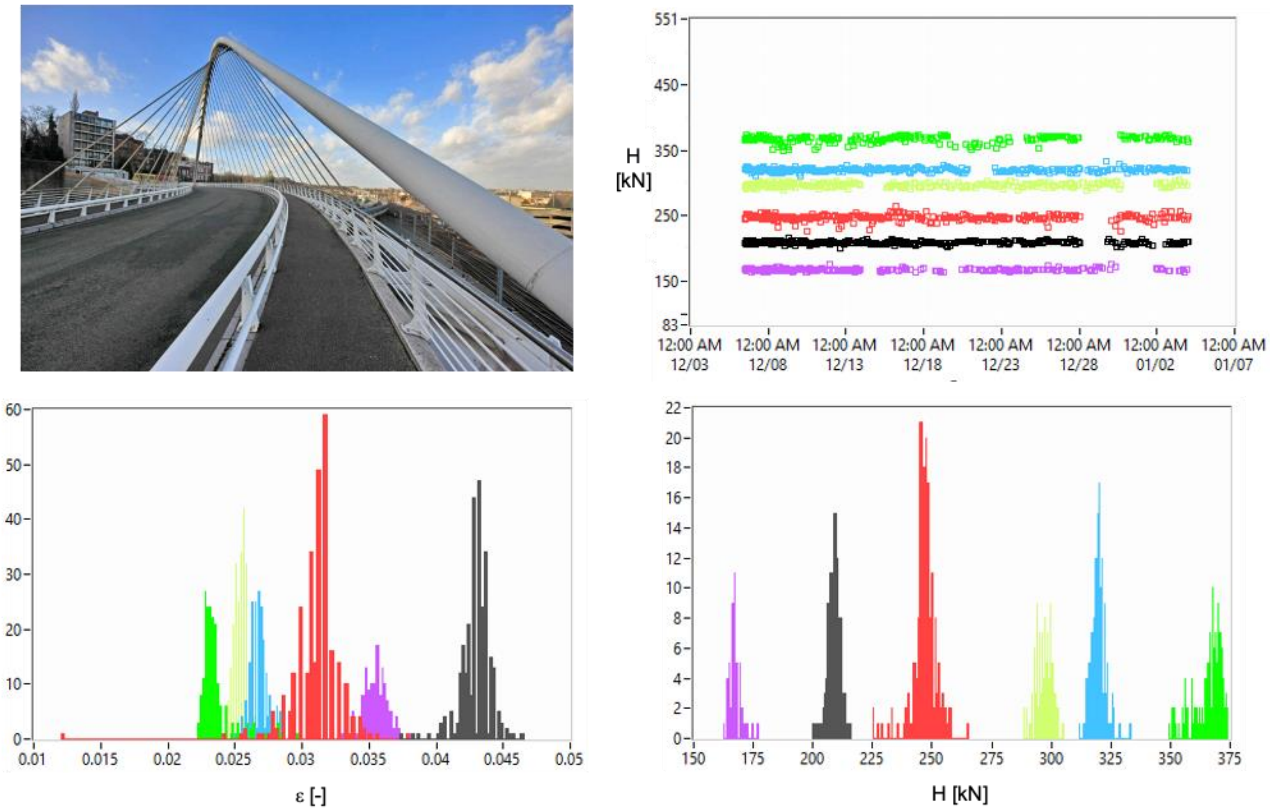

Figure 6 – Results obtained on the Observatory Bridge (picture from Dominique Houcmant)

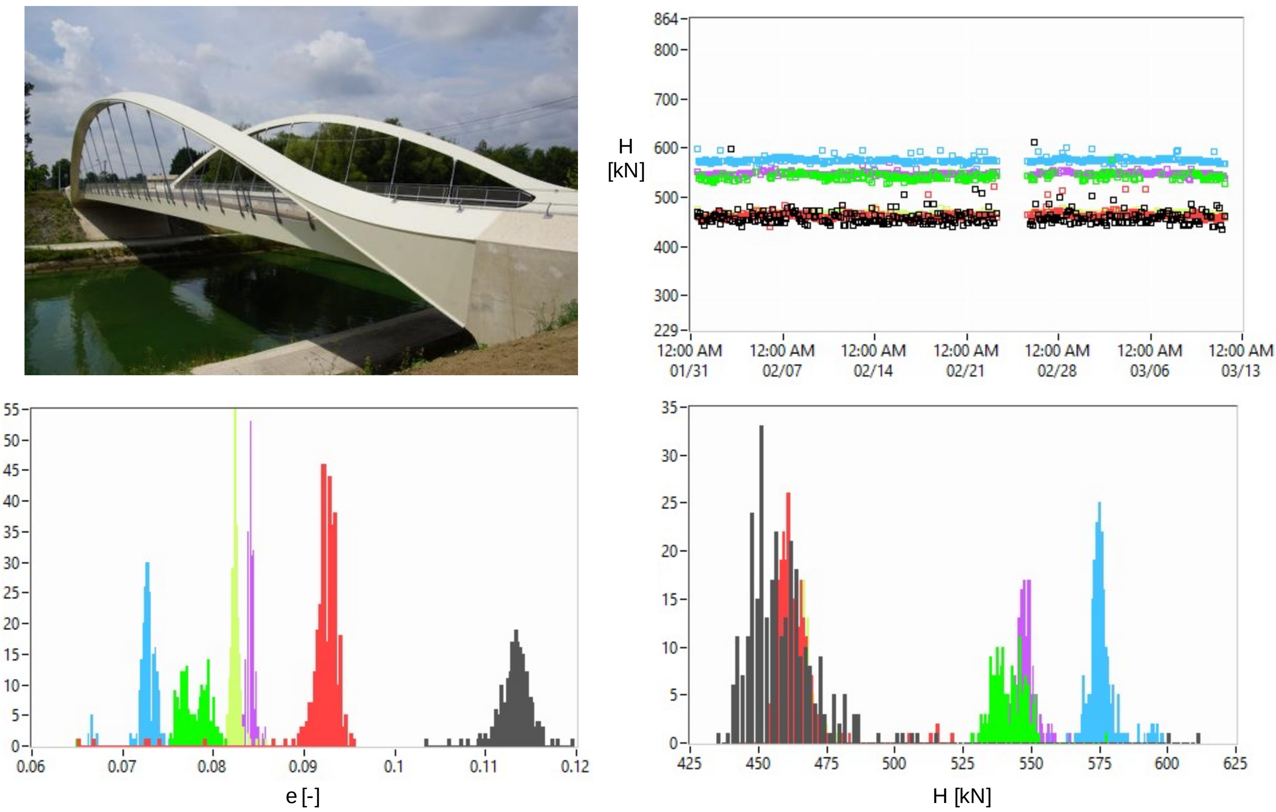

Figure 7 – Results obtained on Harchies Bridge (picture from Nicolas Janberg)

CONCLUSIONS

The paper has briefly summarized an integrated monitoring system that has been developed over the last two years. The proposed solution hinges on cutting edge solutions for each of the three components: an ad hoc model and identification technique based on the specificities of the considered problems, the deployment of sensitive wireless sensors and the implementation of a modern data transmission system which automatically populates a cloud database and allows real-time visualization.

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