An Ultrasound Monitoring System For Concrete Structures

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ABSTRACT

The research project "Ultrasonic Net for Concrete Monitoring (UNeCOM)" aims at developing a methodology for an embedded ultrasonic network for the condition assessment of infrastructure constructions.
Civil engineering structures made of concrete, which are located in tectonically active regions or undergo special loading conditions, may require continuous monitoring. It is important to assess the condition of the building and its stability to recognise and classify the effect of a seismic event or evolving damage at early stages before failure occurs.
Embedded ultrasonic sensors offer the possibility to detect changes in the material and degradation mechanisms from inside the structure in areas which are difficult or impossible to inspect otherwise.
In contrast to conventional ultrasonic testing methods, where the concrete surfaces are scanned with ultrasound probes, this new approach uses sensors, which are embedded into concrete, eliminating the effect of variable coupling conditions between sensors and concrete. This method allows an integral detection of changes in the concrete structure, for example due to seismic activities, to detect mechanical impacts, as well as degradation of the material due to overloading. Such methods have great relevance especially for the monitoring of constructions like power plants, bridges, offshore structures and other structures with high technical safety requirements. The sensor network can be controlled remotely through the internet which is also being used for data transfer.
The embedded sensor network is designed to monitor structural damage and concrete degradation globally with high sensitivity.

Introduction

This paper describes a monitoring concept, based on the use of a network of embedded ultrasound sensors, which was developed within the project UNeCOM (Ultrasonic Net for Concrete Monitoring). A sensor network was set up at a continuous beam bridge with a reinforced concrete deck in the Izmir area of Turkey.

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The sensors are described in detail and their range and directional characteristics are presented as well as the method of installation. An introduction to the data collection concept and the software used to control the installation is given.

The test site in Izmir has been selected as a case study since Turkey is situated on a very active earthquake zone. Earthquakes with relatively big magnitudes already happened in different parts of Turkey and they are expected to happen at any time in the near future. It is very helpful to have information about the usability of the transportation infrastructure to react with short emergency response times in disaster areas. Ideally, earthquake-resistant construction should be designed to have a regular configuration so that the behavior is simple to conceptualize and analyze, and so that inelastic energy dissipation is promoted in a large number of readily identified yielding components.

It is very important to assess the condition of the structure. Most of the loadings and other influences result in cracks in the structural elements of the bridge structure which affect their durability. There are other reasons such as settlement of the bridge piers, failure of ground (such as slopes or retaining walls) that damage the structure. Once the structure lost its durability, it may not serve under design-loads and a sudden loading such as an earthquake may cause the structure to collapse.

Case study

From the bridges in the Izmir area one was chosen for the case study with obvious degradation. The damages are due to ASR (alkali-silica-reaction) because of the aggregates used in this region. There are many cracks observed visually, however, the inner structure is not known and it is one task to estimate the damage level in these structures. The construction year of the selected bridge for this case study is 1986 and it is situated close to the airport of Izmir. It is a continuous beam bridge with a reinforced concrete deck of 47 cm thickness. No post-tensioning is used in this structure. Major traffic of this area has to pass below or over the structure and this makes the bridge an important traffic network node. A first renovation with cement grout and Carbon fibre reinforcement panels was carried out at some of the

Figure 1. Izmir – Aydin Bridge, Turkey.

bridge piers. Due to the ongoing ASR deterioration, the bridge has to be renovated or replaced in the near future. Figure 1 shows signs of ASR deterioration as well as cracks in the asphalt layer on the top. According to the information received from the bridge authorities, the deterioration is developing fast. It was decided to monitor the bridge deck for several reasons: safety of the installation, homogeneity of the area being monitored and fast ongoing deterioration.

Embedded sensors

Ultrasonic waves interact with the medium while travelling through it. As a mechanical wave, the mechanical properties of the medium influence the ultrasound. This effect can be very small and may not be easily found in the typical measurement results, e.g. travel time or attenuation. But any changes in the material will manifest itself in typically very small variations of the signal measured before and after the change. Only embedded sensors with non-varying coupling to the medium qualify for such measurements, otherwise the change in coupling would by far exceed the signal from the material change.

The ultrasonic sensors developed for the project need to be able to work for a long time when embedded into concrete. They must allow a distance of some meters between sensors. Laboratory tests were conducted to estimate the maximal distance, as well as the directivity characteristics of the transducers.

Figure 2 shows such a sensor as developed by the project partner ACSYS. The sensor is of cylindrical shape, with a hollow body which is used as a cable canal, allowing up to five transducers to be installed in one borehole.The frequency range of the emitted ultrasound is 60 kHz to 70 kHz. Each transducer can serve as transmitter and receiver.

Laboratory tests, described in detail in [1], proved that the embedded sensors have no preferred direction of emission (Fig. 3), ensuring a 360° uniform ultrasonic coverage in the

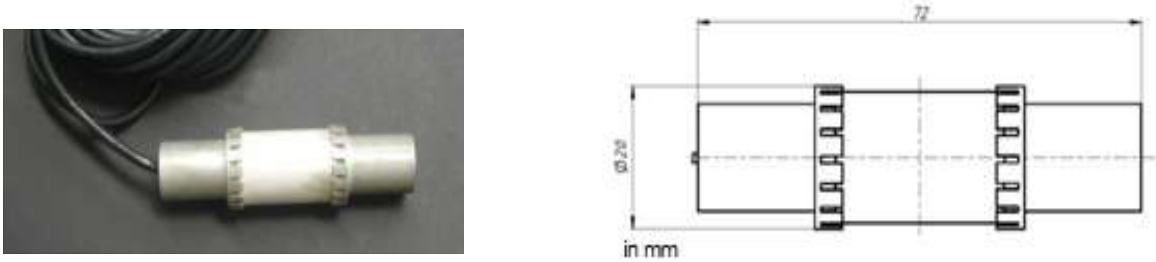

Figure 2. Photo and sketch of the ultrasonic sensor.

plane parallel and perpendicular to the symmetry axis of the sensors. For those tests a sensor each was embedded into two cylindrical concrete specimens. The sensors were aligned vertically and horizontally to the plane of measurements. The excitation of the surface is measured with a laser vibrometer at the height of the sensor.

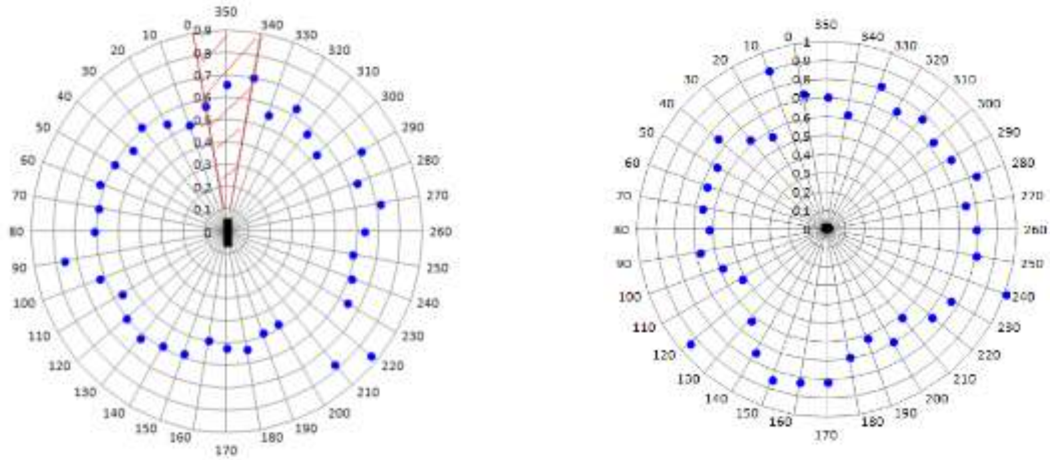

Figure 3. Directional characteristics of the sensor parallel (left) and perpendicular (right) to its symmetry axis. No representative amplitudes could be taken between 340° and 360°, because of the position of the sensors cable.

The range of the sensors is needed to approximate the maximum allowable distance between them and therefore the size of the covered area. To estimate the range, specimens were constructed to evaluate the attenuation of amplitudes in concrete depending on the aggregate size (AS), reinforcement (reinf.) and method of embedding (Fig.4). The lowest attenuation is found in the sensors embedded after construction (mortar). The reason is most likely the grouting mortar used to fill the space between sensor and surrounding concrete. The volume of the swelling mortar increases up to 2 % during curing [2], giving excellent contact. The lowest attenuation between pre-installed sensors was found in the specimen with 16 mm aggregate size.

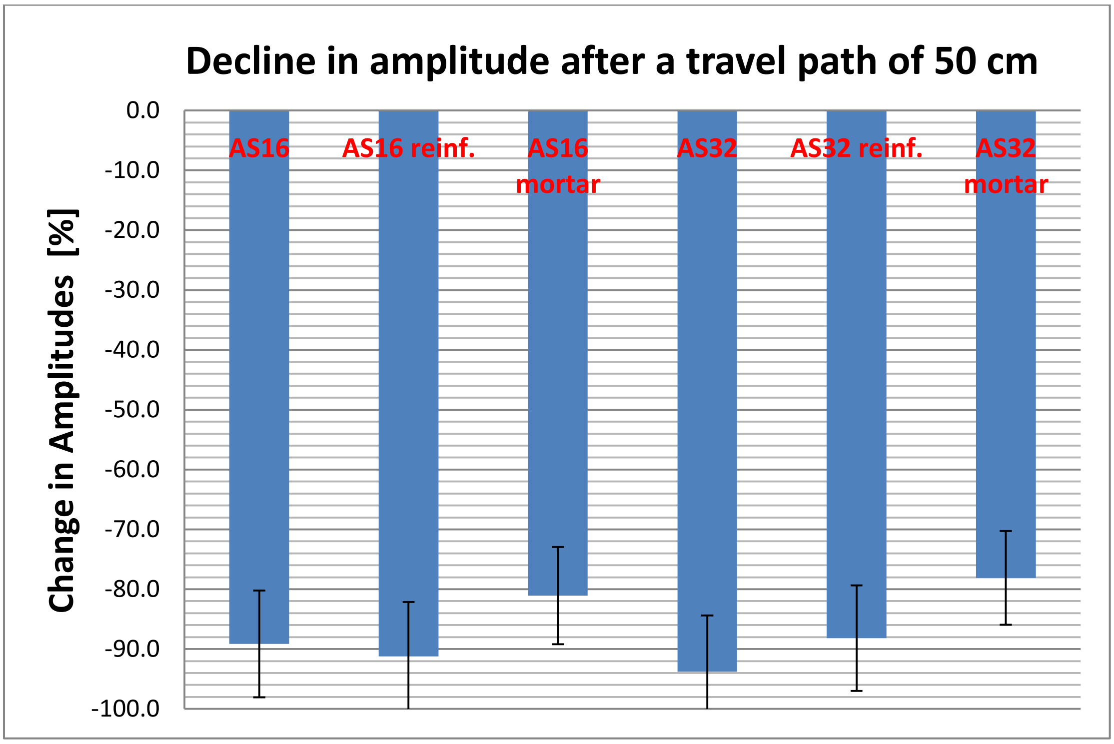

Figure 4. Attenuation of signal amplitudes depending on aggregate size, reinforcement and different methods of embedding the sensors.

After figuring the attenuation of the signal over a given path, the maximum distance can be evaluated depending on the Signal-to-Noise-Ratio (SNR) [1]. Under laboratory conditions and respecting a SNR of two, the approximate allowable range is therefore 3.6 m. Based on the experiences with embedding the sensors for the attenuation experiments, methods were developed to install them into a real structure.

Sensor installation

The installation of ultrasonic sensors into concrete is made through boreholes. The installation in vertical boreholes overhead is non-trivial. Depending on the depth of the boreholes there are different methods which can be used. In any case it is recommended to use the mortar as grouting in order to optimize the contact between sensors and the surrounding concrete.
To position the sensors within the boreholes and to guide the cables, PVC tubes were used. After positioning, the mortar is injected around the sensor/PVC tube construct in a scheme as sketched in Figure 5, left.
In the Izmir – Aydin Bridge the sensors are placed in an arrangement which spans two planes parallel to the underside of the bridge deck. Based on results from laboratory experiments two sensors each could be placed in eight boreholes at depth of 10 cm and 21 cm (Fig. 5, right).

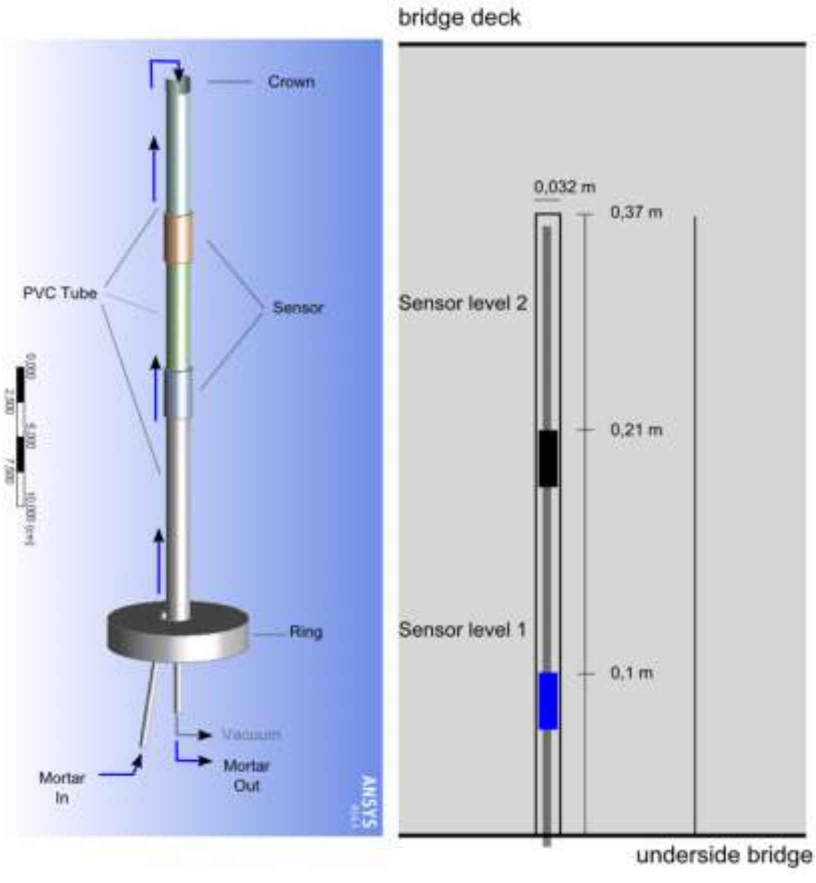

Figure 5. left: Sketch of the mortar injection into the borehole. Right: Two levels of sensors in depths of 10 cm and 21 cm.

The arrangement supports the monitoring of material changes in a near surface plane and one deeper in the structure. The boreholes are spaced 2.3 m and 3 m from each other, allowing distances between transmitters and receivers between 2.3 m and 7.5 m (Fig. 6).

Figure 6. Installed monitoring system at Izmir – Aydin Bridge, Turkey, with boreholes and data acquisition nodes.

Analysis of ultrasonic signals

After the installation is complete and the sensors transmit and receive signals sufficiently (Fig. 7), the next step has to be taken: the evaluation of the signals. With the aim to access actual changes in the concrete condition, different influencing factors to the ultrasonic signal need to be understood. Regularly recorded parameters will be the change in temperature and moisture.

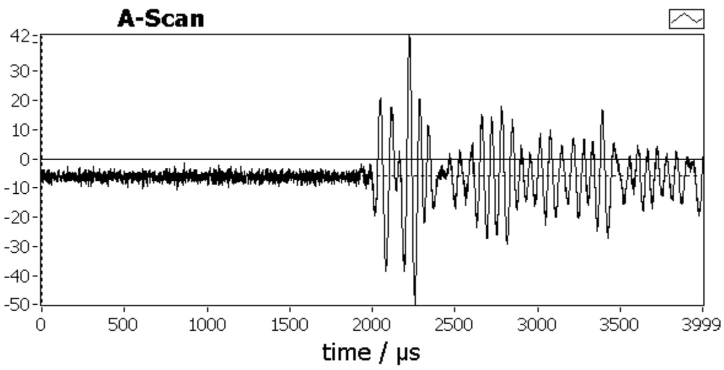

Figure 7. Signal between a transmitter and receiver 5.6 m apart.

Laboratory experiments show a decrease of the ultrasonic velocity by almost 4 % during a temperature rise of 50 °C [3]. Literature such as [4] and [5] describe an increase of ultrasonic velocity with the increase of moisture in concrete.

Both changes in environmental conditions lead to a decreased correlation between two subsequent signals. The correlation between a reference signal and another one of the same transmitter/receiver combination, but taken at a different time, is an easily implementable evaluation technique. It is used to analyze the signals gathered from the network. To differentiate between natural temperature and humidity variations and real changes in the material is subject of ongoing research.

Monitoring concept

The monitoring concept developed for the UNeCOM project is intended for the automated collection of data to monitor the condition of reinforced concrete structures. It had to be stable and simple to use. The principle of operation is based on the method of end-to-end ultrasonic testing of an object with a distributed ultrasonic array. Operation of elements of the array, data collection, time synchronization and electric power is provided by the same physical cable. Data acquisition is conducted independently, without participation of the operator by a predetermined algorithm which can be remotely programmed via the internet (Fig. 8). Arbitrary transmitter receiver combinations, amplification of the signals, as well as the time interval of measurements can thus be configured.

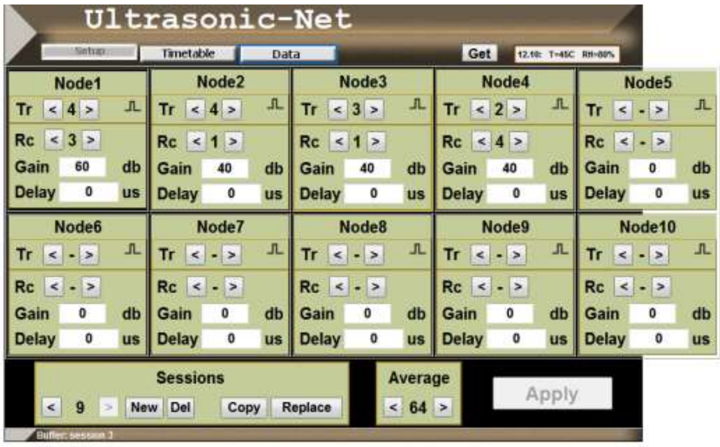

Figure 8. Web based configuration panel to set transmitter /receiver combinations and the signals amplification.

Figure 9 depicts the monitoring concept as a sketch. The network installation consists of a variable number of measuring modules connected to four ultrasonic sensors each. No more than four modules are connected to a network switch supporting “Power over Ethernet”. The measuring modules trigger the measurements and retrieve the data. Data include information about the activity of the nodes, the present environmental conditions (temperature, moisture) and of course the ultrasonic signals. The signals are saved based on a time stamp. The data format is 16 bit. The measuring modules itself are configured and controlled by the main computer onsite, which has access to the internet network and is being controlled with the web based interface (Fig. 8).

The project partners can access the data from the main server. The aim is to develop an algorithm to analyze and evaluate the signals automatically and to warn the user when the signals are to dissimilar, indicating a change in the material.

Summary

A new sensor concept for monitoring concrete structures has been developed and installed in a bridge in Turkey. Ultrasonic sensors are embedded in the bridge superstructure to monitor the material changes in a volume spanning over an area of 3 m x 6 m. The sensors are pair wise installed in boreholes, one sensor close to the surface and one deeper in the slab. All sensors act as transmitter and receiver, a full data set consists of 224 transmission signals. The difference between two subsequent signals from each transmitter/receiver pair is analyzed using the correlation technique.

Acoustic waves are mechanical waves and interact strongly with concrete, which is an inhomogeneous material, causing multiple scattering for the ultrasonic wave. The correlation coefficient from two measurements is taken as a signal for the material change. It was confirmed in laboratory studies that temperature, moisture, stress and cracking influence the ultrasonic signal and are registered by this technique.

The sensor network was successfully installed in a bridge in Turkey and can be remotely controlled through internet access. Data is being collected at pre-determined variable intervals. Presently the system is being evaluated and optimal settings for the measurement process are derived. Environmental and traffic induced loading of the bridge needs to be evaluated from the data. The influence of progressing ASR damage in the bridge is going to be researched in the future.

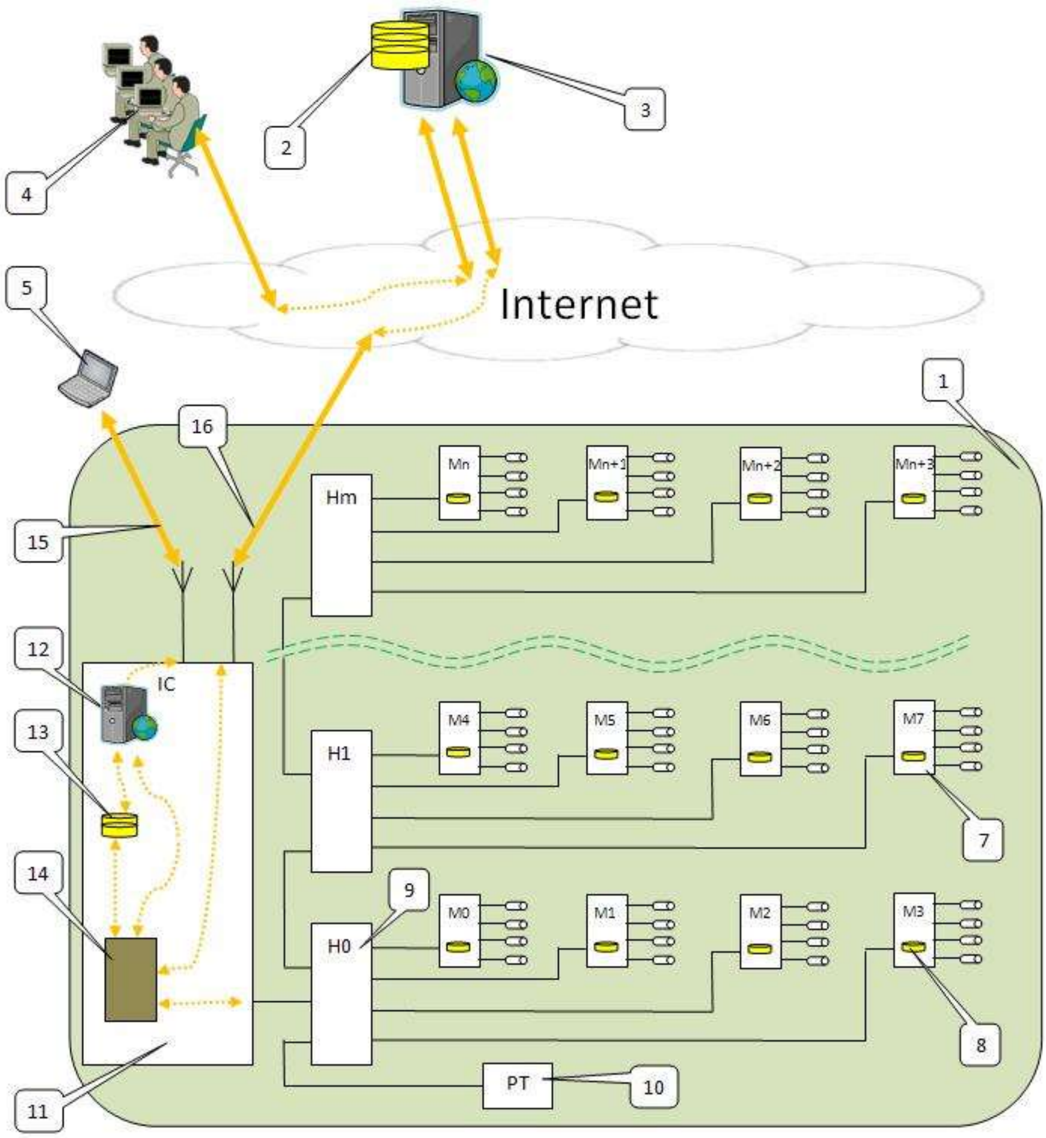

Figure 9. Monitoring concept: 1 - inspected object, 2 - main data storage, 3 - web server, 4 – operator, 5 – laptop with web browser for operating, 6 - ultrasonic sensors, 7 - one of (M0-Mn+3) measuring modules, 8 – data storage integrated in each measuring module, 9 - one of (H0-Hm) net commutator, 10 - environmental sensor, 11 - main computer (NLP X1000), 12 - web server integrated in main computer, 13 - data storage integrated in main computer, 14 - software module comprised of the main computer for configuring, managing and controlling the measurement modules, 15 - WiFi, 16 - 3G/GPRS.

Acknowledgements

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