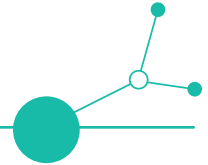


D.1. 2.1: REPORT OF STATE-OF- THE-ART OF BRIDGE MONITORING IN CENTRAL EUROPE

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1. Intro

The main goal of the D.1.2.1 report is to present the state-of-the-art bridge monitoring and maintenance systems in Central Europe by analyzing the strengths and weaknesses of different methods.

Also included in this report is a description of the monitoring systems used, the field of application and the technologies, data collection methods and an overview of some projects.

2. Overview of bridges - Italy

The Italian road network is huge, and its management is very complex. There are about one and a half million kilometres of roads whose management is fragmented. The responsibility for the road network is divided between the State, Regions, Provinces and Municipalities, and numerous concessionaires.

The Italian road network also has very special characteristics. Italy has a geographical and orographic conformation that is unique in the world: from North to South, Italy is about 1,200 kilometres long and just 200 kilometres wide, if we exclude the Alps. Suppose we add to this the mountain ranges of the Alps and the Apennines, which cross the territory transversely and longitudinally, and a network of waterways distributed capillary. In that case, it is easy to understand how many viaducts, bridges and tunnels are essential to connect the peninsula.

The Italian motorway network is managed partly by the State and private entities. It has an extension of 7,016 km with 12,045 bridges, viaducts, and overpasses.

SINA S.p.A. is the engineering company of the ASTM Group, the second largest private operator in Italy, which manages approximately 1,423 km of network, equal to approximately 20% of the national motorway network.

The Group's motorways have a total of 2920 infrastructural structures, with a span greater than 6m, including 1643 viaducts, 722 overbridges, 500 underpasses and 55 hydrological channels, distributed as presented in Table 1.

Table 1 ASTM total number of motorway's civil structures

Motorway		Total number of structures (span >6m)	Viaducts	Overbridges	Underpass	Hydrological channels	Structures with post-tensioned cables	Fragile structures (conjugated ashlars)
A21 Torino-Piacenza	SATAP	308	119	152	32	5	188	123
A6 Torino-Savona	ADF	356	216	81	55	4	67	0
A12 Sestri Levante-Livorno	SALT	384	272	62	49	1	200	0
A10 Savona-Ventimiglia	ADF	296	214	32	38	12	150	0
A15 Parma-La Spezia	SALT	220	172	40	7	1	164	0



Motorway		Total number of structures (span >6m)	Viaducts	Overbridges	Underpass	Hydrological channels	Structures with post-tensioned cables	Fragile structures (conjugated ashlar)
A21 Piacenza-Brescia	AP	170	79	64	25	2	60	0
A33 Asti-Cuneo	SATAP	89	28	26	35	0	20	6
A4 Torino-Milano	SATAP	319	165	100	35	19	20	0
A5 Quincinetto-Aosta	SAV	234	129	14	91	0	100	0
A5 Torino Quincinetto + tang. Torino	ATIVA	314	89	114	111	0	100	0
A32 Torino Bardonecchia	SITAF	181	148	9	19	5	106	51
A58 Tangenziale esterna Milano	TEM	49	12	28	3	6	0	0
Total		2920	1643	722	500	55	1175	180

3. The most typical bridges in Slovenia

Slovenia has around 39,000 km of public roads, which include state and municipal roads. State roads are further divided into motorways, expressways, main and regional roads. Slovenian Infrastructure Agency (DRSI) is responsible for roughly 5,942 km of main and regional roads. At the same time, Slovenian Motorway Company (DARS) manages, maintains and plans the development of motorways and expressways in a total length of 625 km. These stakeholders are responsible for the management of all the assets, including bridges. Among the various bridge types, the most typical bridge on Slovenian roads and highways is the **reinforced-concrete slab bridge**, representing a substantial 40% of the total bridges in the country. This dominant bridge type exhibits an average age of 37 years old, has a single spans of 1 with an average span length of 11 meters. Second and third most typical bridges in Slovenia are reinforced concrete girder and prestressed concrete slab, constituting 15% and 13 % of the Slovenia's bridge network, respectively. Interested reader is referred to Deliverable D.1.3.1 [ref], where are more detailed analysis of bridge types is given.

4. Types of monitoring systems

The monitoring systems mainly used on the structures under management vary greatly depending on the type of work. The main common objective is to acquire all the parameters related to the sensors positioned on the deck, piers and abutments, performing a joint statistical analysis of the values detected directly from sensors with low acquisition frequency (e.g. deformations, temperatures, displacements, inclinations, weather conditions, forces, etc.) and values obtained indirectly through the periodic execution of experimental dynamic analysis (e.g. Operational Modal Analysis OMA) acquired with high acquisition frequency (e.g. accelerations and velocities).



In addition, the safety controls implemented in the structural monitoring system typically involve two phases:

- A long-term one, with controls aimed at assessing the loss of capacity of the work over time, as a consequence of the normal degradation of the structures.
- one of short duration, with checks aimed at verifying the possible occurrence of anomalies, as a consequence of exceptional events (e.g. subsidence of soils, seismic actions, exceptional loads, etc.).

As mentioned, the aim of a monitoring system for a bridge is the continuous evaluation of the safety of its structure, based mainly on the evaluation of the evolution of bridge characteristics over time. This main objective requires the accomplishment of these phases:

1. Identification of objectives:
 - a. Analysis of the structural behaviour, vulnerability factors and damage phenomena
 - b. Identification of Damage scenarios and physical quantities to be monitored
2. Definition of monitoring schemes
 - a. Selection of the elements to be monitored
 - b. Definition of Sensor Types and Positions
3. Design of the Monitoring System
 - a. Design of the global architecture of the monitoring system
 - b. Design of the acquisition, power supply and network communication systems (global and local)
 - c. redundancy, expandability and flexibility
4. Installation and testing of the monitoring system
 - a. Design of details and planning of the installation
 - b. System supply and installation
5. Start of the Structural Health Monitoring Service
 - a. Definition of the automatic algorithms for the data analysis and management
 - b. Manual data processing and interpretation processing

Depending on the type of quantity to be monitored, different sensors are used, such as those shown in the table:

Table 2 Types of sensors for different scenarios

Scenarios to be monitored		Damage Indicators/Magnitude to Monitor	Sensors
Evolutionary situation of damage/degradation	Loss of deck stiffness / Reduction of prestressing	Rotation of beams in the longitudinal and transverse plane at several points	Biaxial inclinometers along the beams
Evolutionary situation of damage/degradation	Loss of stiffness of piers	Rotation of the piers in the longitudinal and transverse plane at the bottom and at the top	Biaxial inclinometers at the bottom and the top of piers
Evolutionary situation of damage/degradation	Loss of verticality (sagging) of piers and abutment	Rotation of abutments and piers	Biaxial inclinometers on piers and abutment



Scenarios to be monitored		Damage Indicators/Magnitude to Monitor	Sensors
Evolutionary situation of damage/degradation	Loss of functionality or limit switch of support/restraint devices	Relative Displacements Between Structural Components	Longitudinal/transverse displacement transducers on the support devices
Evolutionary situation of damage/degradation	Evolution of cracks of concrete, extension of metal	Crack dimension, Strain of steel	Strain sensors
Evolutionary situation of damage/degradation	Bridge defects due to insulator defects and consequent water penetration	Humidity under the insulation layer	Printable Moisture sensors under the moisture insulation layer
Evolutionary situation of damage/degradation and/or Natural actions of high intensity and relevance such as earthquakes	Loss of stiffness due to widespread degradation (cracking, reduction of prestressing, localized damage)	Changes in the dynamic behavior	Accelerometers, velocity transducers or strain sensors for dynamic characterization on piers, abutments, and decks
Evolutionary situation of damage/degradation and/or Natural actions of high intensity and relevance such as earthquakes	Loss of functionality or limit switches of support/restraint devices	Changes in Deck Dynamic behavior	Accelerometers, velocity transducers or strain sensors for dynamic characterization
Natural actions of high intensity and significance such as earthquakes	Damage induced by seismic events	Peak Seismic Accelerations on Vertical Elements	Accelerometers at the top of piers and/or abutments
External actions	Interference between the structure and natural events	Wind direction and speed, rain, air temperature and humidity	Weather station complete with thermometer, hygrometer, anemometer and rain gauge
External actions	Influence of temperature gradient on the structure behavior	Temperature of the structure elements	Printable flexible temperature sensors that can measure the temperature gradient of large-scale objects
External actions	Interference between the structure and Heavy Traffic Load	Traffic load	Weigh in motion systems based on printable pressure sensors based on piezoelectric effect or capacitive measurement

The main sensors proposed depend on the type of monitoring and are better summarized in the following table:

Table 3 Types of sensors based on type of monitoring system

Dynamic monitoring	
Sensor Type	Position
Triaxle accelerometer on deck	Beam/Deck
Triaxial accelerometer on pier or abutment	Pier/Abutment
Strain sensors	Beam/Deck
Static monitoring	
Sensor type	Position
Biaxial inclinometer on deck	Beam/Deck
Biaxial inclinometer on pier or abutment	Pier/Abutment
Longitudinal displacement transducer	Support/Restraint device
Transverse displacement transducer	Support/Restraint device
Strain sensors	Beam/Deck/Pier/Abutment/Support Device



Environmental monitoring	
Sensor type	Position
Printable flexible temperature sensors	Beam/Deck/Pier
Weather Station	Deck top surface/Top of abutment
Printable Moisture sensors under the moisture insulation layer	Deck, under the moisture insulation layer
Printable Pressure sensors based on piezoelectric effect or capacitive measurement	Deck

4.1. Dynamic monitoring

4.1.1. Triaxial accelerometers for dynamic monitoring

Triaxial accelerometer sensor uses MEMS technology for structural and seismic monitoring applications.

The main feature of MEMS accelerometers lies in the DC frequency response, useful for kinematic measurements at very low frequencies, where for example piezoelectric accelerometers cannot reach. These sensors integrate a MEMS (micro-machined) sensing element.

In its most general form, a MEMS consists of mechanical microstructures and microelectronic circuitry, all integrated within the same silicon chip. Microsensors detect changes in the surrounding environment by measuring mechanical, thermal, magnetic, chemical, or electromagnetic information or phenomena. The microelectronic circuitry transforms this information into digital/analog signals and sends commands to the micro activators to direct them into some form of activation with respect to the events of interest.

The technologically advanced sensor, whose operation is based on the capacitive measurement principle, is ideal for dynamic structural monitoring applications, ideal for bridges and Viaducts.



Figure 1 Triaxial accelerometer

The accelerometer is encased in a rugged, IP67-rated aluminum housing. This sensor offers users all the advantages of state-of-the-art MEMS chip technology along with the ability to monitor the temperature thanks to a probe integrated directly into the sensor.

This accelerometer guarantees the monitoring of accelerations and vibrations on bridges, viaducts, buildings, monuments, constructions, structural elements and in all contexts where modal analysis on the monitored element is required.



4.1.2. Strain sensor

Another type of sensors to be used in the dynamic monitoring of the deck is extensometers. In particular extensometers must be able to give output at a sampling rate compliant with the experimental dynamic characterization of bridges, e.g. between 100 and 200 Hz. One example are SiWIM ST-504.



Figure 2 ST-504 sensors

ST-504 are custom-made sensors designed for use in the SiWIM bridge WIM system. They are designed to be either bolted with two bolts to the deck or the beams of a bridge or bolted to the steel plates, which are glued to the structure (in the case of steel bridges).

An excitation voltage is applied, and a voltage reading is taken from the output. Typical input voltages are 5 V or 12 V, and typical output readings are in millivolts. When used in the SiWIM bridge WIM system, the output of the system as a whole is the following:

- data on vehicles (GVW, axle loads, speed, axle distances, etc.)
- influence line of the bridge
- dynamic amplification factor
- girder distribution factor

The Siwim system's modular design allows for the easy substitution of the ST-504 sensor with various types of strain sensors, such as extensometers or strain gauges, as long as they are compatible with the Siwim architecture.



Figure 3 ST-504 sensors installed on the deck of a bridge

4.2. Static monitoring

4.2.1. Biaxial inclinometers for static monitoring

The biaxial inclinometer sensor in high-precision, high-resolution MEMS technology that detects the rotations of elements.

The technologically advanced sensor, which operates on the capacitive measuring principle, is ideal for structural monitoring applications such as bridges, viaducts, and buildings.



Figure 4 Biaxial inclinometer

The inclinometer is encased in a rugged, IP67-rated aluminum housing. This sensor offers users all the advantages of state-of-the-art MEMS chip technology along with the ability to monitor the temperature thanks to a probe integrated directly into the sensor.

This inclinometer guarantees the monitoring of the rotations of buildings, monuments, constructions, structural elements and in all contexts where it is necessary to control the stability of vertical structures over time.



4.2.2. Longitudinal and transverse displacement transducers for static monitoring

The primary element of the displacement transducers is a mounted 3D Hall effect chip on an electronic board and coupled with a helical magnetic field.

The primary element is free to move linearly inside the magnet.

From the variation of the angle of the vector of magnetic field along the housing cylindrical, the position of the Hall chip and therefore the measurement of the displacement can be deduced.

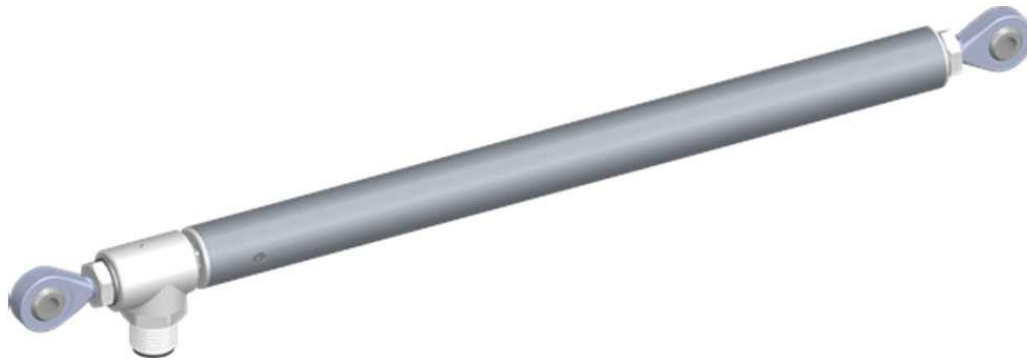


Figure 5 Displacement transducer



Figure 6 Detail of Hall Chip inside the transducer

This represents a new concept of sensor:

Besides "hall" effect chips can be inserted in electronics:

- Tri-axial accelerometer
- Gyroscope
- Temperature sensor

In this way the sensor becomes multivariable, also allowing the measurement of:

- Speed
- Acceleration
- Vibrations
- Gyro-compensated inclination
- Temperature

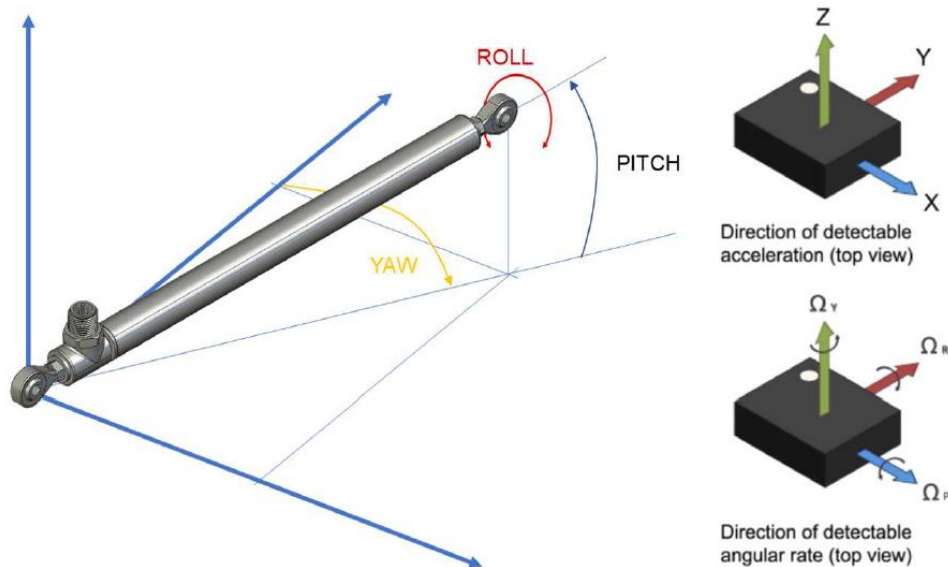


Figure 7 Multi-variability of the sensor

The sensor is equipped with a built-in microprocessor to write algorithms that correlate the information read by the various sensitive elements.

It is thus possible to obtain functions of:

- Self-diagnostics.
- Self-calibration.
- Virtual sensor.
- More generally, customizable functions for analyse the behaviour of the machine

Furthermore, the sensor is equipped with a Boot Loader with which you can update it directly in the field via the available BUS.

4.2.3. Strain sensor

Extensometers and strain gauges are both tools used to measure deformation (strain) in materials, but they operate on different principles and are suited for different applications. Extensometers measure strain by mechanically gauging the change in distance between two points on a material's surface, while strain gauges require physical contact and are bonded to the surface of the material. Crackmeters are similar to extensometers but are specifically designed to monitor movements across surface joints or cracks, mainly in concrete structures or rocks.

Crackmeter consists of a vibrating wire or potentiometer displacement transducer housed in a stainless-steel telescopic body with two anchoring points.

These anchors have self-lubricating ball joints allowing lateral movements up to $\pm 10^\circ$ in the orthogonal planes (Y - Z axis) not influencing the operation of the jointmeter.

APPLICATIONS

- Cracks on concrete structures or rock
- Structural joints like in concrete dams



- Displacements on pile bearing
- Monitoring of rock faults

FEATURES

- 3-D mounting kit available for triaxial displacement monitoring
- Ball joints allow small lateral movement
- Suitable for long term monitoring

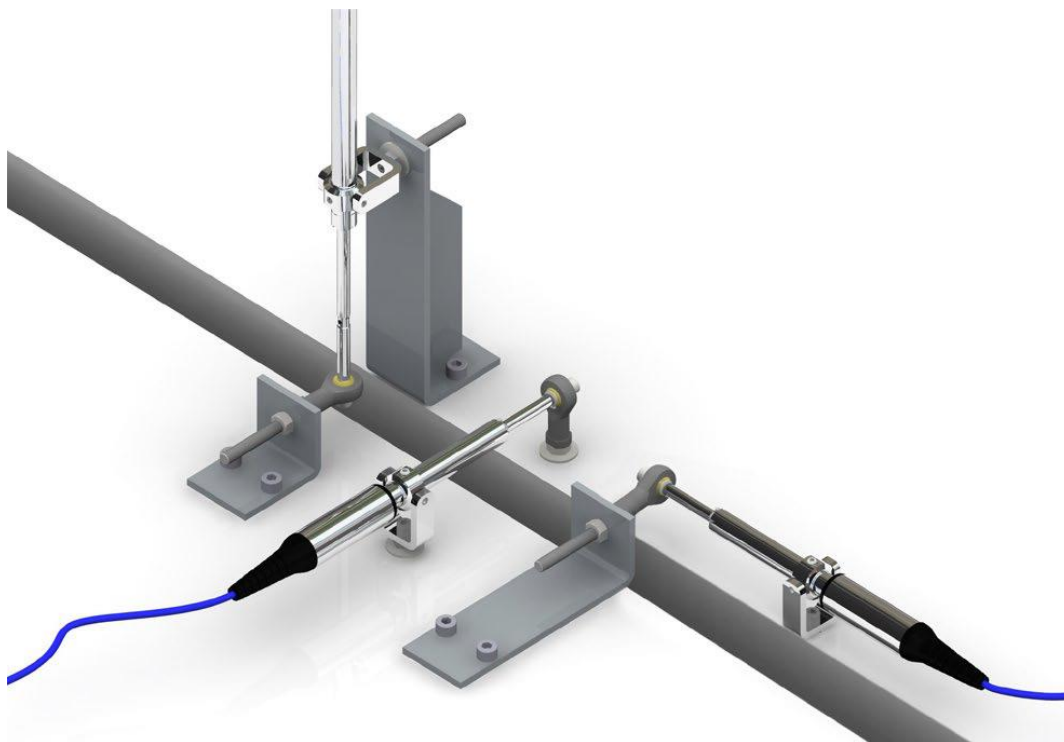


Figure 8 Electrical and vibrating wire crackmeters

Another example of extensometers is the sensor SiWIM ST-504 already explained for dynamic monitoring. This sensor can give useful data for both static and dynamic monitoring. In case of static one, a resample of the acquired data is carried out to obtain quasi-static information or to verify the possible evolution of kinematic mechanisms or slowly evolving damage phenomena.

4.2.4. Printable Pressure sensors based on piezoelectric effect or capacitive measurement can track the traffic on the bridge

Measuring the deterioration of a bridge during its operational life is very important and allows estimating possible maintenance works. Thus, one way to predict the deterioration of a bridge is to estimate the amount of daily traffic passing over it. In the laboratory of the TU Dresden a pressure sensor based on capacitive measurement of the effect of external forces is being developed. The features of this sensor are that it is fully flexible, scalable, and printed on a functional printer. This sensor can serve as an alternative to the already existing means of optical traffic surveillance and measure the amount of traffic passing through it by measuring the force applied to it. The main feature of this sensor is its low cost, resistance to aggressive conditions, lack of corrosion as the



sensor consists of polymeric materials, and accordingly the possibility of integration with other printed sensors developed in the laboratories of TU Dresden.

4.2.5. Printable Moisture sensors under the moisture insulation layer that can track the defects on the insulator and water penetration that can cause bridge defects.

Printed pressure sensors are a completely new product not yet available in any bridge monitoring system. The flexible printing technology actively used by TU Dresden makes it possible to create scalable water sensors at a relatively low cost. This type of sensor allows to detect possible damage to the insulation layer that protects the cement and metal structure of the bridge from water penetration, which, in turn, when freezing in the cracks of the cement can cause enormous damage to the bridge structure. Early detection of insulation damage with the use of flexible condensation sensors located under the insulation will help to avoid costly repairs to the bridge. Finally, this type of sensors can be used in conjunction with the other sensors developed in the Dresden TU, such as temperature, pressure, and strain gauge. This saves the wiring costs and simplifies the transfer of information from the sensors.

4.3. Environmental monitoring

4.3.1. Printable flexible temperature sensors that can measure the temperature gradient of large-scale objects with different shapes.

In addition to the development of pressure and moisture sensors, temperature sensors are being developed in the TU Dresden laboratory. The special feature of these sensors is that they can measure temperature gradients over long distances with only one connection contact due to the roll-to-roll technology. Moreover, these sensors can measure shapes of different types due to their flexibility and can be used in conjunction strain gauge sensors on the same substrate. While the strain gauge sensor measures the expansion of the material, the temperature sensor can measure the temperature of the surface and take into account the temperature factor.

4.3.2. Temperature sensors and a weather station for environmental monitoring

The weather stations are installed on special supports (poles) in positions that minimize the local effects due to vehicular traffic. The weather station used is autonomous from the point of view of acquisition and communication with the outside world and is equipped with the following sensors:

- rain gauge.
- anemometer for wind direction and intensity.
- thermo-hygrometer.



5. Monitoring technologies for bridges

As reported in the preceding chapter, monitoring systems can have different technologies in terms of sensors. Each modern sensor is developed to generate an electrical analogue signal proportional to the physical quantity you want to acquire. The most widespread technologies are Piezoelectric/IEPE, Capacitive/MEMS, Potentiometric, Inductive, Satellite, Fiber-optic, and Resistive sensors. The analog digital converters translate the electrical sensor outputs in digital arrays. This requires quantizing and discretizing the signal, i.e. passing from a continuous signal to a series of data characterized by a certain frequency and a certain resolution. After that, the digital arrays, with their attributes, can be pre-processed, transmitted over a communication network and managed.

The complete architecture of a monitoring system implies:

1. hardware architecture of monitoring systems
2. software architecture of monitoring systems

5.1. Hardware architecture of monitoring systems

Bridge monitoring systems have some special features compared to, for example, building monitoring systems. The first is linked to the geometry of bridges which can extend for several kilometers on the road sections. The second is given by the possible absence in the monitoring location of both an electricity supply network infrastructure and a wired communication network infrastructure and, in some cases, also the lack of coverage of a GSM network. Considering these aspects, the hardware architecture of monitoring systems can also significantly differ.

Local monitoring systems differ mainly according to:

- sensor and power supply typology,
- position of the A/D conversion nodes,
- type of communication network used for the synchronization and collection of the digitized data.

The sensors can be powered

- by means of electrical cables that supply low voltage direct current generated by special power supplies, which in turn are powered by direct or alternating current.
- by disposable batteries or by rechargeable batteries using small photovoltaic panels.

The A/D conversion can be performed:

- Inside or nearby each sensor
- Inside acquisition control units with multi-channel conversion modules where the electric signals from different sensors are collected through electrical cables

The synchronization and collection of digital arrays from the different A/D converters can be realized:

- with a wired communication local network based on different standards:
 - Optic fiber (local and global)
 - Ethernet (local)
 - EtherCAT (local)



- RS485 (local)
- PLC (Power Line Communication) (local)
- with a wireless communication network:
 - LoRaWAN (local)
 - Wifi (local)
 - 4G-LTE/5G (global)

Finally, the hardware architecture can include the presence on site of calculation machine capable of collect, pre-process, elaborate and analyse the results of the calculations, then archiving the data and generating alert signals, according to automated processes. Generally, the solution adopted involves the execution of part of the processes in the field, while others are carried out in a distributed Data Center or on Network Servers. This aspect is strictly correlated with the adopted software architecture.

5.2. Software architecture of monitoring systems

Performing the real-time monitoring service requires performing time-consuming analysis of big data from the SHM systems. Furthermore, in the current situation of continuous increase in the number of instrumented structures, manual analysis of all data can be considered impossible.

The software architecture generally consists of a distributed IT system with four logically overlapping levels:

- The first "field" level is made up of the various software able to perform for example:
 - acquisition, digitization, and collections of all the signals.
 - data local pre-treatment.
 - transmission of data on the network.
 - run auto-diagnostics tools to find monitoring system anomalies (power supply, acquisition, communication).
- The second level consists of the proprietary servers that may be necessary to carry out raw data pre-processing processes with proprietary algorithms.
- The third level presents the software for collecting and analyse all data coming from a single bridge, and perform the different required evaluation, such as the execution of the automated algorithms. This level should be located on the field, on distributed data centre, or on network server.
- The fourth and final level hosts the Web applications where end users can interact with systems and view data and results.

Generally, the execution of the monitoring service requires software tools capable to make possible the following minimum functions:

1. Visualization and georeferencing of bridges with SHM systems
2. Visualization of the geometry of the SHM systems, as well as the technical information of sensors and devices
3. Visualization of the operating status of the monitoring systems and setting up notification protocols for systems malfunction states



4. Remote access, control and setting of operation parameters and acquisition strategy (scheduled and triggered) of the acquisition systems
5. Definition of data involved in each damage scenario and definition of the analysis procedures.
6. Definition of alert scenarios for the early warning service:
 - a. define the parameters involved (directly on the acquired data or indirectly on the results of previous processing)
 - b. define the triggering thresholds of each parameter
 - c. define alert protocols, i.e. the type, content, and recipient of the alert messages
7. Definition and performing of automatable algorithm capable of:
 - a. perform plausibility analyses on the data to understand if they are reliable or if there are anomalies in the acquisition system
 - b. analyse the acquired reliable data with the defined procedures
 - c. start alert protocols in the encountered critical situations
 - d. filtering the data and selecting those of highest interest
 - e. draw statistical trends on structural behavior (directly on the acquired data or indirectly on the results of previous processing) and perform regression analyses with environmental data
8. Visualization of trends and results of the regression analyses, to find possible critical situations
9. Downloading data packages for subsequent manual processing with specific software of “critical” data, trends, and results of the regression analyses, to find possible critical situations
10. Report periodically the results of the SHM analysis and/or report the results of the analyses in the critical cases

6. Example of a bridge monitoring system

Below is an example of the design, supply, installation, and maintenance of the instrumental monitoring system of the Clarea viaduct, located along the A32 Turin-Bardonecchia motorway managed by SITAF S.p.A.

The existing viaduct is made of reinforced concrete piers (reinforced concrete) and prestressed reinforced concrete (prestressed concrete) deck and consists of 6 spans of 100 m in length for a total length of 600 and 650 m respectively for the carriageway in the direction of Bardonecchia (uphill) and in the direction of Turin (downhill). The road layout has a curve with a constant radius (variable for the two routes) with a longitudinal slope of about 2.5% and joins the Giaglione, to the east, and Ramat, to the west. The cross-section is made with a single-cell body with variable height. The longitudinal lateral actions are absorbed by a single fixed constraint at the shoulders on the Bardonecchia side, while the transverse actions are absorbed on each alignment.

The Clarea viaduct consists of two continuous beam decks, one for each carriageway, with a curvilinear development in plan, with a radius of curvature of about 535 m for the carriageway in the direction of Bardonecchia and 587 m for the carriageway in the direction of Turin. The ascent route



(towards Bardonecchia), on the inside of the curve, is shorter than the descent route (towards Turin), located on the outside.

The ascent route consists of two semi-spans of 50 m, the first at the entrance, from the SP2 abutment to the P5 pier on the Susa side, and the second at the exit, from the P1 pier to the SP2 abutment on the Bardonecchia side, and 5 intermediate spans of 100 m each.

The descent route, from Bardonecchia towards Turin, consists of a counterweight on the SP3 abutment at the entrance, then 6 spans of 100 m and a semi-span of 50 m at the exit between pier P2 and abutment SP4.

The piers vary in height between 15 and 48 m, due to the orography of the site, and have a rectangular box section with variable width depending on the height of the pier. All the piers are characterized by the same geometry in the 7 meters below the level of the beams; This area is in fact characterized, on each pier, by the presence of two 7 m high partitions, with a rectangular section of 5.4 m by 1.1 m, placed at a distance of about 5 m. At the head of these blades are placed the supports of the supports:

Each septum carries three supports aligned transversely for a total of six supports per pier. The two outermost supports of each antenna provide only the vertical constraint, while the intermediate support is dedicated to the horizontal constraint in the transverse direction.

Following the construction of the new Chiomonte junction, the first two 100 m spans of the ascent route and the first three 100 m spans of the descent route will be connected to a new viaduct made with a mixed steel-concrete section; In addition, the seismic adaptation of the final structure requires a variation of the static scheme with respect to lateral actions with the introduction of sliding pendulum isolators.

The structural solution envisaged in the project involves a variation in the behavior of the existing structure with potential criticalities resulting from the construction of new foundations adjacent to the existing ones and the coupling between two cross-sections (prestressed reinforced concrete caisson and mixed steel-concrete section) characterized by very different flexural and torsional stiffnesses. Hence the need for the design and installation of a monitoring system suitable for identifying changes in structural behavior resulting from changed boundary conditions.

6.1. How the monitoring system is carried out

This project outlines the characteristics of the following systems.

- Topographic monitoring system of the piers of the existing viaduct.
- Accelerometric monitoring system of piers and deck of the existing viaduct and new ramps.
- Thermometric monitoring system of piers and deck of the existing viaduct.
- Monitoring system of the relative displacements between piers and existing deck.
- Weather monitoring system.

6.1.1. Topographic monitoring of piles

For piers P4, P5 and P6 (ascent route) and P9, P10, P11 and P12 (descent route), i.e. the piers adjacent to the new ones, the project envisages the installation of an optical sight positioned at the base of the pile. It is also planned to carry out readings on a daily basis during the construction phases of the foundations of the piers of the new viaduct, while once the excavations have been completed, it is planned to continue with a frequency of n. 2 readings per week.



6.1.2. Inclinometric and accelerometric monitoring of piers and decks

The project includes two different monitoring configurations for the piles, differentiating between those adjacent to the new ones and the rest. Pier monitoring is intended to measure:

- the absolute rotations at the base of the piers.
- rotations at the top of the piers.
- accelerations at the top of the piers.

For piers P4, P5 and P6 (ascent route) and P9, P10, P11 and P12 (descent route) the following are provided:

- a biaxial inclinometer at the base of the pier.
- a biaxial inclinometer and a triaxial accelerometer at the base of the two blades at the head of the pier.

For piers P1, P2 and P3 (ascent route) and P7 and P8 (descent route) the following are provided:

- a biaxial inclinometer at the base of the pier.
- a biaxial inclinometer at the base of the two blades at the head of the pier.
- In addition, a triaxial accelerometer will be installed on the P5 pier to measure the underlying accelerations generated by exceptional construction site events or seismic phenomena

As far as decks are concerned, the following are to be measured:

- the vertical inflections of the decks.
- torsional rotations, which may vary with the connection of the new decks.
- The dynamic behavior of decks: frequencies and modal shapes.

Therefore, for each span, the following are envisaged:

- N. 4 biaxial inclinometers placed one on the pile axis, one in the centerline and two at the quarters of the span between the supports and the centerline.
- N. 1 vertical uniaxial accelerometer in the centerline of each span in correspondence with the central inclinometer.

A thermocouple will also be inserted at each span to measure the temperature of the decks.

6.1.1. Thermometric monitoring of piers and decks

For each pile, there are two thermocouples placed inside the pile drum on the north wall, respectively at the base and at the head of the box section, and four thermocouples placed externally to the piers, in the center of the four faces.

6.1.2. Monitoring of pier-deck relative displacements

The project involves the installation of two horizontal displacement transducers per pier, one in the longitudinal direction and one in the transverse direction, to monitor the relative movements between the pier and the deck.



6.1.3. Weather monitoring

The project involves the installation of two weather stations for the evaluation of temperature-induced effects. Weather stations are able to detect:

- wind speed and direction.
- atmospheric pressure.
- air humidity.
- temperature.
- Amount of solar radiation along the development of the deck.

6.1.4. System Durability, Durability and Maintenance

The monitoring system will have to remain active for at least 3 years. The system is installed in a mountainous area at about 800 m above sea level, outdoors, in environments that are not thermally insulated and exposed to the weather. The minimum temperatures expected are around -12°C in winter and around $+7^{\circ}\text{C}$ in summer. Maximum temperatures in winter reach $+12^{\circ}\text{C}$ and in summer $+31^{\circ}\text{C}$. The use of chloride-based de-icing salts is also planned in winter. The exposure class (environmental aggression) provided for the monitoring system is therefore XD3.

The construction site for the construction of the junctions and the excavation of the tunnel will interact with the instrumentation (e.g. generating dust). An IP68 level of protection for the instruments is therefore expected.

The maintenance of the system must cover the 3 years of installation with the following characteristics:

- Help desk response time in Italian: 4h.
- Replacement of secondary elements (individual sensors, sights, cables, connections, network interface, router (4G /5G) in case of malfunction or accidental breakage: 48h.
- Replacement of primary elements (acquisition modules, control units, topographic stations): 72h.

6.1.5. Sensor Placement

Particular attention is required for the placement of the sensors on the existing reinforced concrete deck to limit possible interference between the monitoring system and the necessary work to the connection of the decks and which involve drilling the original deck and laying anchors inside it.

The thermocouples related to the original deck must be installed inside the reinforced concrete walls of the existing caisson by making small holes near the location inclinometers and accelerometers. The thermocouples related to the metal decks must be fixed to the load-bearing sheets, possibly on faces not exposed to direct sunlight and as protected as possible from the elements.



6.1.6. Synchronizing Sensors

The inclinometers and others “static” sensors must be synchronized with an accuracy of 0,10”. The accelerometers must be synchronized with an accuracy of 0,01”.

6.1.7. System Acquisition Parameters

The following methods of acquisition are envisaged:

- Inclinometers:
 - continuous reading.
 - acquisition cadence 15 minutes.
 - acquisition window to be defined in a variable interval between 1s and 10s.
 - measurement of the temperature and (if possible) of the humidity inside the instrument at the same time as the acquisition
- Accelerometers:
 - two 1-hour reading windows programmed at fixed times (e.g. from 09:00 to 10:00 and from 03:00 to 04:00).
 - sampling frequency equal to or greater than 200 Hz (value to be calibrated based on structural analysis results to be carried out).
 - automatic activation of the reading when a pre-set threshold value is exceeded (e.g. to detect exceptional events such as earthquakes or strong winds).
 - Measurement of the temperature and (if possible) of the humidity inside the instrument, at the same time as the acquisition, with reduced frequency (1 reading per minute).
- Thermometers:
 - continuous reading.
 - acquisition cadence 15 minutes.
 - acquisition window to be defined in a variable interval between 1s and 10s.

Acquisition modules are provided with:

- 24-bit digital encoding.
- long-term drift less than 50μV over 24 hours and less than 200μV over 8000 hours.
- temperature stability less than 200μV on zero and less than 0.01% on sensitivity with a variation of 10K.
- Signal-to-noise ratio: >100dB

Data buffering must be at least 2 days of capture in case network connectivity fails.

6.1.8. Storage and transmission of data

The project involves the storage of data from the monitoring system on a server located in one of the construction site buildings. The raw data of all acquisitions must be able to be accessed remotely



in form; The accessibility of the data and their management on the cloud must be possible through a dedicated summary platform capable of presenting the following data on a web interface in real time. Data:

- position and operation/log parameters of each sensor.
- weather data.
- graphs of the quantities measured by each sensor as a function of time.

The data must be stored on a cloud with high access speed for the last year prior to the request date and at medium speed for the following 1 to 2 years.

6.2. Instrumental monitoring system

The sensors used are made up of wired and non-wired sensors of different nature:

- Wired Sensors:
 - MEMS uniaxial accelerometers.
 - ultrasonic displacement transducers.
 - Thermometers (thermocouples and resistance thermometers), directly in the control unit or with analog node and wireless transmission.
 - Weather stations with:
 - > pyranometers.
 - > anemometer.
 - > hygrometer.
 - > barometer.
- Non-wired sensors:
 - MEMS biaxial inclinometers.

The wired sensors are partly directly connected by means of multi-core cables (both for power supply and signal transmission) to the acquisition panels, inside which special acquisition boards are placed, mounted on DAQ control units that collect them. These control units are connected via the data network, consisting of specific switches and the fiber optic backbone, to the main panel where the memory, the intelligent part (CPU) and the router for the data connection to the outside are located.

6.2.1. Position of sensors and acquisition panels

6.2.1.1. Sensors on deck

In accordance with the Project, the following instrumentation is provided on the standard span of the existing deck:

- Biaxial inclinometers corresponding:
 - of the axis of the piers.
 - of the quarters of the span.
 - of the centerline of the span.



- uniaxial accelerometer at the centerline of the span.
- thermometer at the axis of the piers.

Exceptions are the only two spans on the bank of the ascent route and the last span on the Turin side of the descent route, where there is only one inclinometer in the center of the span.

A thermometer is then placed at each accelerometer to evaluate the temperature near the sensor. In the case of biaxial inclinometers, due to the use of sensors with integrated temperature measurement, it was not necessary to use additional thermometers.

6.2.1.2. Pier sensors

In addition to the topographic instrumentation, the following instrumentation is provided on the piers of the existing structure (Figure 19):

- Biaxial inclinometers corresponding:
 - of the base of the piers.
 - the head section of the pile caisson (partition set section).
- triaxial accelerometers at the head section of the body (partition section) of piers P4, P5, P6 of the ascent route and P9, P10, P11 and P12 of the descent route.
- triaxial accelerometer at the base of the P5 pier.
- thermometers inside the box corresponding:
 - of the base of the piers.
 - the head section of the pile caisson (partition set section).
- thermometers on the four outer faces of the battery box in correspondence with the half-height section of the piers.
- transverse and longitudinal displacement transducers in correspondence with the impost section of the pile supports.

6.2.1.3. Weather stations

In agreement with the system designer, in charge of carrying out the monitoring service, it is planned to install two weather stations above the deck, in correspondence with the P2 pile of the ascent route and pile P11 of the descent route. The two weather stations include the following sensors:

- anemometer for measuring wind speed and direction.
- two pyranometers for measuring solar irradiance.
- barometer for measuring blood pressure.
- hygrometer for measuring relative humidity.
- Thermometer for measuring air temperature.



7. Costs and budget restrains

Costs of the entire monitoring service are reported in the followings table:

Table 4 Costs of the entire monitoring

Description	% on the total
engineering analyses aimed at designing the monitoring system	10 %
supply of components (acquisition system, and communication and power supply local network)	50 %
installation of the monitoring system (and subsequent decommissioning)	20 %
ordinary and extraordinary maintenance of hardware components	5 %
supply and maintenance of the software platform	5 %
engineering analyses aimed at performing the SHM service	10 %

In addition to the costs listed in the table, some additional costs should be considered, such as general administrative costs, and, eventually, costs required to connect the SHM system to the global power supply and communication network.

Looking specifically at the supplying of local monitoring systems, the cost is significantly influenced by the type of monitoring you intend to adopt, the type and geometry of the structure and the morphology of the place. For the adoption of a complete monitoring system (considering 24 sensors, such as 8 inclinometers, 6 accelerometers, 4 displacement transducer, 2 thermometers, and 4 strain gauge) the amount of costs is around € 20,000 per span, which can be divided into:

- € 10,000 (50 %) per span for the sensors
- € 6,000 (30 %) per span for the acquisition and analysis devices, including the CPU
- € 2,000 (10 %) per span for the sensor wiring
- € 2,000 (10 %) per span for the local communication and power supply network

Regarding budget limits, to completely monitor the structure, including both dynamic and static global monitoring and the monitoring of some local vulnerabilities, operators generally fix a budget limit of € 50,000 per span (with an average length of 35 m) to allow all the costs discussed above.



8. Conclusion

This document reports the results of the analysis of the State of the art of structural monitoring systems, with reference to those installed on bridges. The different types of monitoring systems were analyzed in detail about the objective of the systems and the types of sensors generally used to obtain the desired results. We then moved on to the technical analysis of the different types of monitoring systems installed on site, with attention to the hardware components of the acquisition, power supply and communication sub-systems. Finally, a description of the software components is reported, with particular attention to the different logical organization levels and the functions that must be guaranteed. To conclude the analyses, some information is provided on costs and the budget limits that you generally encounter when designing a monitoring system.

9. References

D.1.3.1.: Report on existing bridge types in CE including criteria for selection for target bridge type