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Automated Pipeline for the Analysis of a Scale-reduced Steel Cable Net

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Abstract

This paper proposes a digitally twinned experimental analysis of a scale-reduced laboratory-sized steel cable net subjected to vertical loading. The test is aimed at establishing automated pipelines of information and analysis between the measurements (displacements of nodes) and the numerical model of the cable net, which are seamlessly interconnected through a BIM model. These automated pipelines erect the frame of the development of a digital twin of the cable net with structural analysis purposes. For the sake of measurements, a terrestrial laser scanner is used. Displacements of the nodes are extracted using computational geometry tools. For the sake of analysis, a data-based numerical model is proposed to obtain the tensile state of the cables. Precisely understanding the force distribution along nets is a challenge at design, construction and operation stages. This research belongs to a vaster project related to the development of automated pipelines of information for European infrastructure in the form of digital twins. The outcome of this laboratory test results is of great use when developing similar automated pipelines of information in real sites including cable nets in roofs.

Keywords

Digital Twin, Cable net, Terrestrial Laser Scanner, BIM, Automated pipelines.

1 Introduction

Cable nets are tensile structures that are stabilised by tension rather than compression. To increase height and load capabilities, cables can be combined in manifold arrangements. By doing so, system designs can be developed for double curvature walls as well as flat walls. The Plexiglas-clad cable net of the 1972 Munich Olympic Stadium represents an icon in European architecture with 74800 square meters of doubly curved cable nets. The clean aesthetic and large-spanning potential can be integrated with adjacent structures to reduce the need for conventional supports. Understanding precisely the force distribution along the net is a challenge at design, construction and operation stages.

In the H2020 European project ASHVIN "Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using a Digital Twin" [1], the Munich Olympic Stadium represents one of the sites for demonstrating the capabilities of digital twins on maintenance of built assets [2].

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Digital twins can be deemed as to digital living replica of the physical one that provides real time information throughout adequate connectivity (sensors, images, remote sensing) and provides automated visualization of the asset for decision-making purposes (performance indicator that are assessed continuously). Presently, civil engineering related assets are at developmental stages. The vast majority of infrastructure systems with a digital replica focus on specific behaviours of the real site. The level of comprehensiveness is still rather low.

In this particular site, maintenance of the roof represents a key aspect for managers. A digital twin of the roof structure in which both physical measurements and numerical calculations are intertwined may allow managers to take adequate decisions on maintenance plans. Thus, even though it is focused on a specific aspect of the structural behaviour only, the digital replica provides valuable information for predictive maintenance purposes.

For the development of an adequate connectivity, certain site complexities arise. The main cables are either strand bundles or fully locked steel cables. Due to large cable forces and the diameter of the cables (82 mm to 182 mm), a direct measurement of forces may require unpinning the cables and applying hydraulic jacks or using cable tension meters. This is not feasible in regular analysis for site managers. It would represent an intrusive as well as expensive procedure. In order to determine the cable forces in redundant structures, indirect measurement methods such as local strains, vibration measurements or remote sensing methods need to be considered as alternative procedures. Throughout the development of Ashvin, many different information pipelines are under scrutiny. Remote sensing using laser scanners may represent a non-intrusive indirect measurement with potential interest from site managers.

In order to develop a thorough understanding of measurements using indirect procedures that gather information about the movement of the nodes of the net, a scale reduced model has been developed at Laboratory scale. In such model, design, connectivity, automated pipelines of information, simulation and prediction of the structural behaviour of a cable net are addressed. A terrestrial laser scanner is used for measuring. Information is seamlessly connected to numerical models for response analysis and prediction. The aim of the reduced model is to provide a testbed of methods for subsequent deployment of adequate methods in the Munich Olympic Stadium with the aim of developing a digital twin of the structure.

2 Olympic Stadium. Munich

The Olympic Roof in Munich was built for the 1972 Olympic Games and will its 50th anniversary in 2022 (Figure. 1). This cable net structure is, both from an aesthetic - architectural point of view and as a technical venture, an icon of the construction and engineering art of the second half of the 20th century. The Olympiapark ensemble is one of the most important event venues and sports centres in the south of Germany. The Olympic tent roof structure consists of four almost independent and highly prestressed cable net constructions as shown in Figure 2. In total, the cable net forms a roof area of 74,000 square meters. Prior to the upcoming anniversary, a comprehensive structural survey was carried out by SBP [3] (Stuttgart) and Prof. Feix ingenieure [4] (Munich). As part of this investigation, a complete static model of the cable net construction was done by sbp for the first time since the roof's existence. The core task was to determine the existing internal force or pre-stressing state in the cable net structure using novel calculation techniques in combination with cable force measurements [5]. In Ashvin, sbp and the technical University of Catalonia are studying a specific sector of the roof for digital twinning purposes (the intermediate sector depicted in Figure. 3).

Figure 1 Cable net structure of the Munich Olympic Stadium

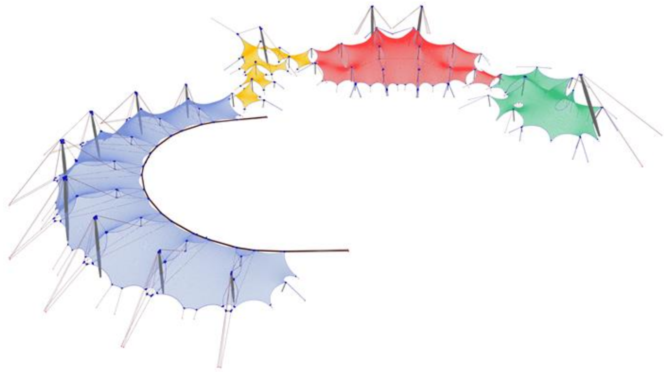

Figure 2 Overview of the four cable net structures forming the Olympic roof; Stadium (blue), Intermediate roof (yellow), Sports arena (red), and Swimming arena (green). Source: sbp

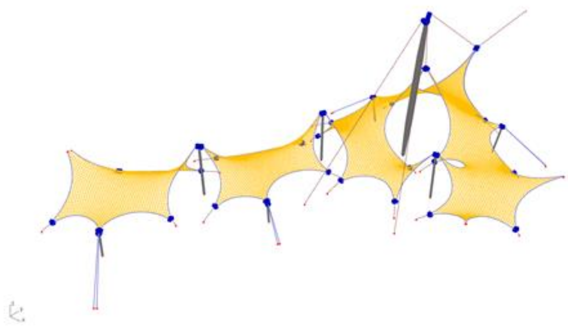

Figure 3 Cable net structures forming the intermediate roof. Source: sbp

A hybrid method to determine the internal forces in the structure could be a combination of node displacement measurements and the use of the existing calculation model. With the structural analysis model, a load and internal force state should be back calculated based on deformations. The necessary methods and the theoretical approach is under development.

In the research project, the action plan presented in this demo site is:

- With minimum intervention, to deploy measurements of cable forces, strain, displacements, weather data (wind data locally and weather stations around Munich; temperature (surrounding, cable surface), snow pattern on roof (satellite photographs), over a certain time period (2-3 months).

- Correlate data of measurements with structural model (automatic creation of load cases, etc.); or using the existing structural model to back-calculate internal forces from displacement measurements.

Previous surveys on the roof using terrestrial laser scanner have provided vast point clouds whose systematic use for operational purposes is being assessed. Figure 4 displays a detail of the mast-to-net connection. The main challenge is to automatically extract useful information related to all nodes position from these vast point clouds. Consequently, understanding the force distribution of the cables becomes a task within the numerical model.

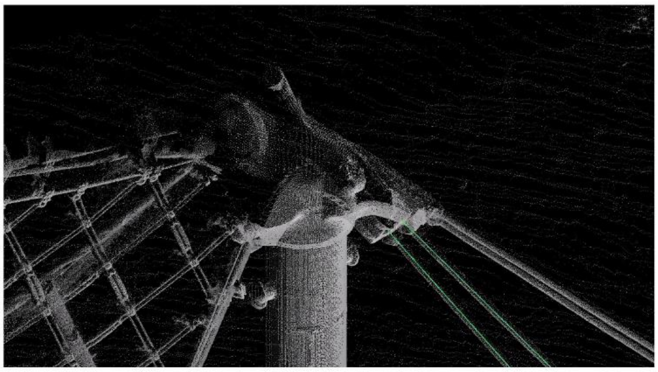

Figure 4 Point cloud from the roof cable net. Detail of mast and cables. Source: sbp

3 The Laboratory test.

Generating a structurally meaningful Digital Twin of such a complex asset represents a major challenge. For preliminary studies, a laboratory-sized instrumentation of a cable net was developed at the Department of Civil and Environmental Engineering at UPC. A terrestrial laser scanner (TLS) was used for the sake of acquiring information related to the tensional state of the asset, implementing systematic data-gathering assessments with a systematic variation of actions (in the elastic domain) for establishing the information pipeline.

3.1 Design of the cable net

The Force Density Method (FDM) was used for the design of the net. It was implemented using a python script within Rhinoceros-Grasshopper framework. Details about the algorithm can be found in [7].

The final design aims at obtaining a cable net geometry as shown in Figure 1, where two nodes are anchored to the ground while the opposites are anchored 1m above it.

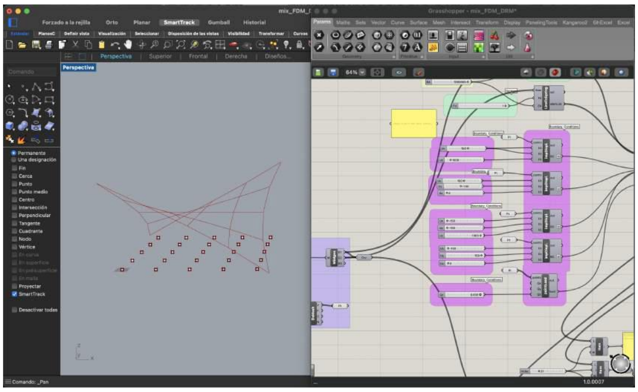

Figure 5 Design model Source: Authors

After the implementation of the FDM algorithm, the deformed configuration of the cables as well as the distribution of cable forces is obtained. From these results, the non-tensioned lengths of the cables can be calculated. These results allow to determine the position of the net nodes, the cable section and the tensile strength required for the anchors. A summary of the procedure is shown in Figure 6.

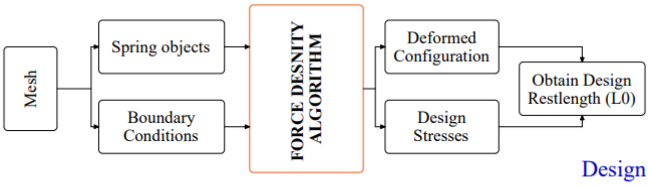

Figure 6 Force density design process. Source: Authors

The cable net force distribution showed that the maximum forces are found in the cables connected to the anchorages withstanding forces of approximately 270 kg (2700 N).

3.2 Construction of the cable net

Basing on the results obtained in the design phase, the relative position the nodes of the net can be calculated and, thus, the whole layout of the net can be sketched. In this section, the construction details and methods are presented.

3.2.1 Construction details

In order to ensure structural integrity, a pair collaborating stranded-wire tendons with a diameter of 3 mm and an ultimate force of 560 kg were utilized for the construction of each cable element.

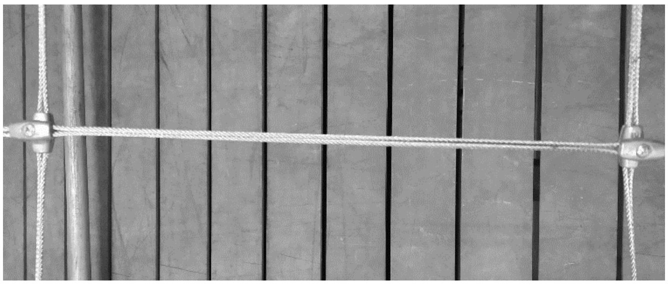

Figure 6 double-tendon cable element. Source: Authors

Nodes connecting the terminations of cable elements were arranged in two levels, to allow relative rotations of the cables attached to them. It is composed by two compressive clamps connected by a frictionless through bolt, as it is illustrated in Figure 7.

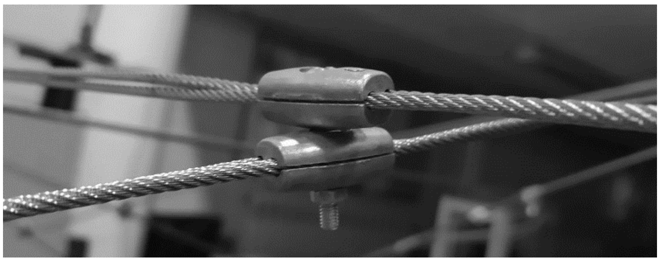

Figure 7 Two-level node of the scale reduced cable net. Source: Authors.

The anchors are formed by two “C-shaped” steel beams perforated at their terminations. At one of its terminations, a steel mast is bolted to provide the lift to some of the anchors. Perforations located in the mast and beam allow the anchorage of the cable net by means of a combination of hooks, which perform as a link between the corner nodes of the net and the anchorage points (Figure 8).

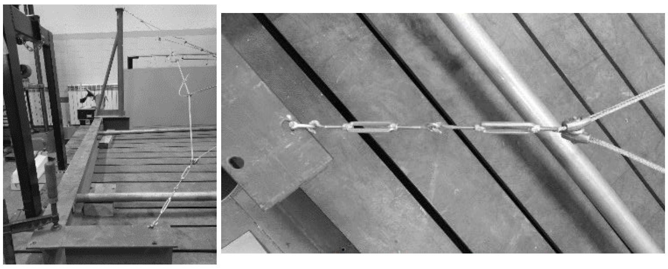

Figure 8 Anchorage of the cable net. To the left, general view of beam and mast anchors. To the right, hook system to link the corner node with the anchoring point of the beam. Source: Authors

3.2.2 Construction method

First, the assembly of the net is done initially on the ground, where nodes are fixed according to the design specifications

Figure 6 Organization of the cables before tensioning. Source: Authors

Once the net is correctly arranged, the anchor beams and masts are place parallelly at a short distance, facilitating to hook the net to the anchors by hand. Finally, struts have been used to move the anchor beams until the desired position is reached, tensioning the net and obtaining the as-designed geometry (see Figure 6).

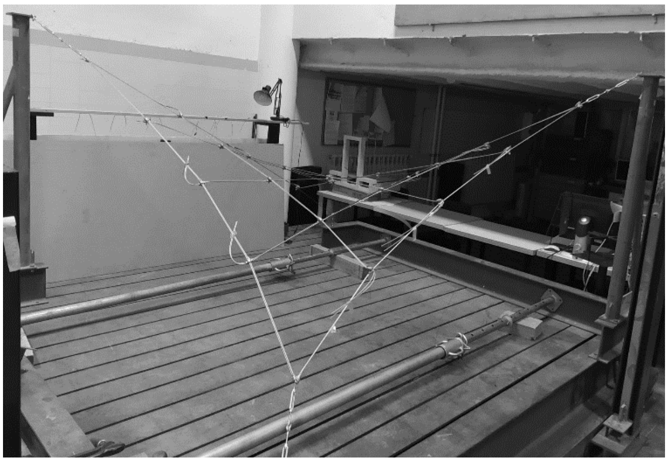

Figure 6 prestressed cable net. Source: Authors

The scale at which the mock-up of the cable net has been built entails errors in the position of the nodes and anchors, leading to misunderstandings between the model and the real structure in terms of the shape and the internal tensile stress of the cables. However, it is not the subject of this study to carry out a precise construction. The built mock-up and the unknowns of its tensional state, position the problem to solve in a scenario akin to the one it is found in the Olympic Stadium of Munich.

4 Measurements.

In order to obtain information about the current state of the cable net, a geometrical assessment using a Terrestrial Laser scanner (TLS) has been performed. TLS allow registering accurately and efficiently enormous 3D 'as-built' geometric information of built assets in the form of point clouds, which have impacted the manner surveying and management is conducted in structural assessment [8]. Point cloud data results in an unstructured list of points located in the 3D space from which information need to be abstracted to simplified geometries to be used subsequently.

The cable net mock-up geometry was digitized using a single measurement from a TLS placed below the net. The scan was performed with a visual of 360 degrees using a resolution of one point every 3mm at a distance of 10 meters. The resulting point cloud provided accurate positioning of the nodes, however, the thin geometry of the cables was delivered with considerable amounts of noise, as can be observed in Figure 9.

Figure 9 Initial TLS scan of the prestressed cable net mock-up.

Sequential realizations of this type of assessment unlock digital twins' ability to analyze structural performance based on geometrical variations along the cable net life. Time lags between scans could take from a couple of months to several years. Therefore, the positions and orientations of the TLS during the initial assessment need to be accurately referenced to ease its replication in future scans, thus avoiding the need of registration processes, which always lead to precision losses due to errors in the superposition of new and old scans.

A set of 2 sequential scans have been performed in the laboratory-sized cable net at different load configurations, from where relative displacements of nodes and cable elements can be identified, as can be seen in Figure 10.

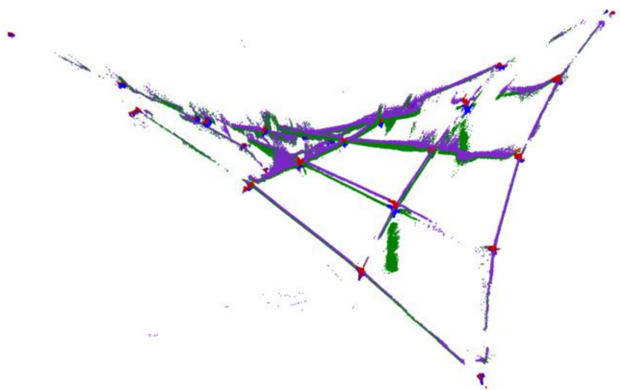

Figure 10 Superposition of the initial scan of the cable net (purple) and the scan when the net is loaded with hanging weights (green). Source: Authors

Point clouds representing the cable net need to be processed to obtain abstracted geometries that are to be utilized in subsequent calculations. The automation of such processes still remains a challenge in the industry, then, human intervention is always needed. In this study, point clouds are imported into Rhinoceros 3D software [9], in which the nodes identified in the point cloud are abstracted as rhino 3D points. The cable net design model is used to determine node connectivity to form the cable elements as straight lines joining node points (see Figure 11).

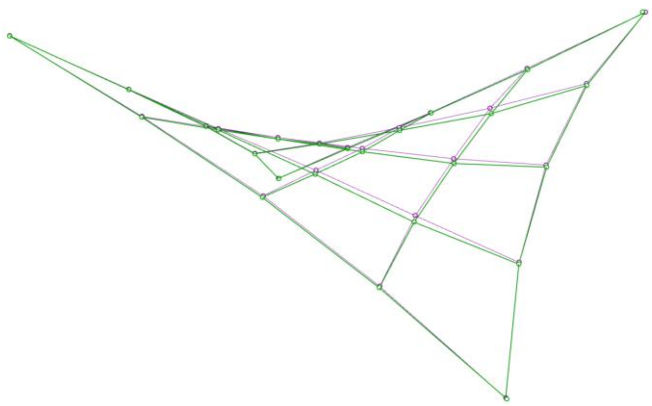

Figure 11 superposition of processed Initial (purple) and loaded (green) scans of the cable net in Rhinoceros and Grasshopper. Source: Authors

At this point, node displacement and cable deformation can be quantified, and geometries can be introduced into more complex built asset representations such as BIM models.

5 BIM model

Digital representations of the cable net elements can be included within BIM environments, in which constitutive elements of the net are assigned physical properties and semantic information, constituting a reliable digital representation of the physical asset.

Industry efforts to achieve standardization of digital representations of built assets led to the deployment in 2018 of the open international standard ISO 16739: Industry Foundation Classes (IFC) [10]. IFC is a comprehensive and structured data schema that accurately describes the built environment in which geometry, physical properties and semantic information are interconnected and hierarchized.

A BIM model of the unloaded cable net has been generated from the TLS scan, according to the IFC specification. The *IfcTendon* class is used as it is intended to represent steel elements such as wires, bars, rods or strands that are given a tensile stress. Thus, this class allow to define cable properties such as the sectional area and its current tension force, among others. Complementary classes as *IfcTendonAnchor* allow to also define the connected ends of the *IfcTendon* to the anchor structure. This IFC model is stored in a single file, providing a single source of truth from which external computational processes dedicated to analysing its behaviour access to essential information needed for them to operate

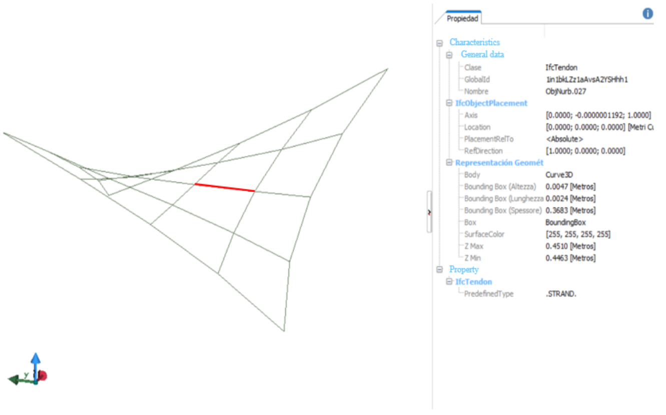

Figure 12 BIM model of the cable net. Basic properties of the cable highlighted in red are displayed.

6 Numerical model

In this chapter, the numerical model used to analyze the structural performance based on cable net node deformation between scans is presented. It is considered that cable deformations are elastic and that all cables are tensioned, in order to model them as straight linear elements:

Given a cable net formed by N nodes, each node is defined in equation (1)

$$P_n \; for \; n: 1, \dots, N \tag{1}$$

The net contains M cable segments that are defined by the connection of two nodes.

$$\{P_i, P_j\}_m \; for \; m: 1, \dots, M \tag{2}$$

Then, the connectivity matrix that define the cable elements is defined in equation (3):

$$C_{MxN} \; where \; C_{mn} = \begin{cases} 1 \; where \; n = i \\ -1 \; where \; n = j \\ 0 \; elsewhere \end{cases} \tag{3}$$

Node coordinates at any tensional state are defined from the TLS scanned geometry as shown in equation (4):

$$\begin{aligned} P_{Nx3} &= \\ &= [[P_{medX} - \varepsilon_X]_{Nx1} \quad [P_{medY} - \varepsilon_Y]_{Nx1} \quad [P_{medZ} - \varepsilon_Z]_{Nx1}]_{Nx3} \\ &= [P_{med}]_{Nx3} - [\varepsilon_P]_{Nx3} \end{aligned} \tag{4}$$

Where P_{med} is the measured point and $\varepsilon_P$is the measurement error. From the node coordinates, equation (5) provides the length vector of each cable element.

$$[L]_{Mx3} = [C]_{MxN} P_{Nx3} \tag{5}$$

The tensile force of each cable is calculated from the difference between the length at the current state $\overline{L^m}$ and the initial length of the cable before the prestressing process. Note that the construction process may add uncertainty (ε_{Const}) to this quantity, which can differ from design specifications. Additionally, other factors that affect the elongation of the cables such as temperature effects are also accounted.

$$[\bar{L}]_{MxM} = \begin{bmatrix} \bar{L}^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \bar{L}^m \end{bmatrix}_{MxM} \quad where\ \bar{L}^m = \|L^m_{1x3}\|, \tag{6}$$

$$[L_0]_{MxM} = \begin{bmatrix} L_0^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & L_0^m \end{bmatrix}_{MxM} = [L_{design}]_{MxM} - [\varepsilon_{Const}]_{MxM}, \tag{7}$$

$$[\Delta Temp]_{MxM} = [\Delta Temp_{med}]_{MxM} - [\varepsilon_{Temp}]_{MxM} \tag{8}$$

$$[\Delta]_{MxM} =$$

$$= \begin{bmatrix} \frac{L^1 - L^0(1+\alpha^1 \Delta Temp^1)}{L^1} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \frac{L^m - L^0(1+\alpha^m \Delta Temp^m)}{L^m} \end{bmatrix}_{MxM} \tag{9}$$

$$= [I]_{MxM} - [\bar{L}^{-1}]_{MxM}[L_0]_{MxM} - [\bar{L}^{-1}]_{MxM}[\alpha]_{MxM}[\Delta Temp]_{MxM}[L_0]_{MxM}$$

$$[\Delta L]_{Mx3} = [\Delta]_{MxM}[L]_{Mx3} \tag{10}$$

The tensile force at each cable is calculated using Hooke's law.

$$[K]_{MxM} = \begin{bmatrix} k^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & k^m \end{bmatrix}_{MxM} \tag{11}$$

$$[T]_{Mx3} = [K]_{MxM}[\Delta L]_{Mx3} \tag{12}$$

For structural stability, the equilibrium condition between external and internal forces at the nodes must be satisfied. The internal force is defined as the sum of contributions of all cables connected to the same node.

$$[F^{int}]_{Nx3} = [C^T]_{NxM}[T]_{Mx3} \tag{13}$$

$$[F^{int}]_{Nx3} = [F^{ext}]_{Nx3} \tag{14}$$

Then, equation (15) must be satisfied at any tensional state of the cable net:

$$[C^T]_{NxM}[K]_{MxM}([I]_{MxM} - [\bar{L}^{-1}]_{MxM}[L_0]_{MxM} - [\bar{L}^{-1}]_{MxM}[\alpha]_{MxM}[\Delta Temp]_{MxM}[L_0]_{MxM})[L]_{Mx3} = [F^{ext}]_{Nx3} \tag{15}$$

Note that from equation (15) $[K]_{MxM}$ and $[\alpha]_{MxM}$ are material parameters that are defined within the BIM model, $[L_0]_{MxM}$ is deduced from the initial tensile force defined in the *IfcTendon* class, $[C^T]_{NxM}$ is also deduced from spatial coincidences in the model, $[L]_{Mx3}$ and $[\bar{L}^{-1}]$ are measured from the TLS data, $[\Delta Temp]_{MxM}$ is measured from weather stations and $[F^{ext}]_{Nx3}$ is known in this study. Therefore, the updated internal forces of the cables can be obtained within a certain degree of certainty, determined by the accuracy of measuring devices, and on provided by the owner of the structural asset.

7 Digital twin pipeline

Digital twins are cyber-physical systems able to accurately simulate built assets behaviour, as well as accurately represent all relevant processes during their design, construction, and operation stages. Representations of processes are introduced within the digital twin as specific information pipelines, where data, information models and numerical procedures collaborate seamlessly to provide relevant information of the current state of the asset.

In this paper, a BIM model and a numerical representation have been proposed to establish a pipeline to incorporate cable net point cloud information to the digital twin of the cable net: a new TLS assessment is carried out on the net, which is pre-process to acquire new nodal information. When a new 3D scan assessment I produced, nodal information is introduced within the digital twin framework, triggering a specific automated built-in action. The digital twin of the net operates the numerical model using information contained in the in its BIM model. The process can be used to update the BIM elements properties with calibrated material parameters or to obtain updated tensional force distribution in the cables. All results are timestamped and stored within a database containing the timeline of similar assessments, which enables the acquisition of a continuous flow of performance metrics for monitoring the evolution structural state of the net throughout its operation life. Figure 13 depicts the information flow within the pipeline.

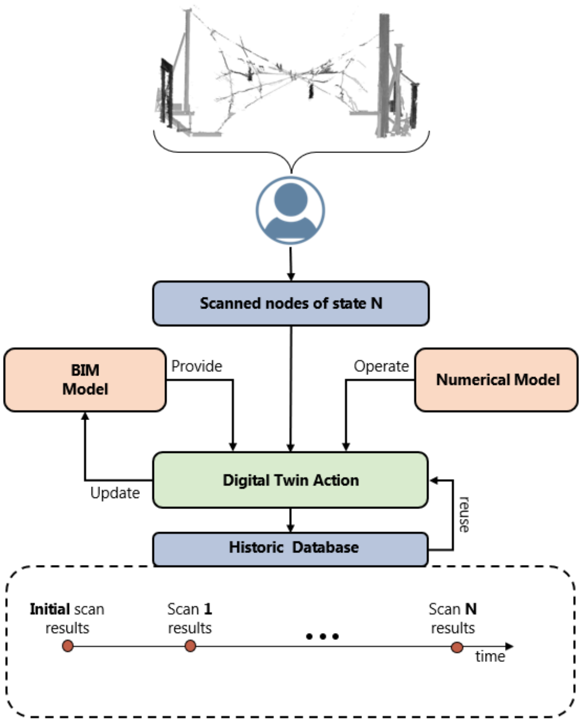

Figure 13 Scheme of the information pipeline. Source: Authors.

8 Conclusions

The paper proposes an automated pipeline to process 3D point cloud data containing nodal information of prestressed steel cable nets. The pipeline is intended to be used within H2020 research project where the Olympic Stadium of Munich is digitally twinned. For that purpose, a laboratory-sized model of the stadium cable net is designed and constructed to be used as a testbed for the pipeline. The cable net has been sequentially scanned with different load configurations. Results show relative displacements of nodes between loaded and unloaded configurations. The net point cloud is pre-processed to abstract simplified geometries that can be subsequently analysed. For that purpose, Rhino and grasshopper are used to transform the point cloud into 3D points for the nodes and straight lines for the cables. A BIM model following IFC specifications have been developed, as well as a numerical model for linear structural analysis. Finally, the pipeline is posed as the automated collaboration between the information model of the net and its numerical structural representation to process updated nodal position information.

9 Acknowledgments

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