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Abstract

Outdoor hybrid solar road demonstrator monitoring using infrared thermography with embedded local probes for energy harvesting performances evaluation †

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Abstract

This study investigates in natural environment the thermal behavior of an innovative pavement system with thermal and solar energy collection functionalities. The whole structure is continuously monitored using temperature and heat flux sensors probes integrated inside the structure. The local weather conditions are also monitored. Infrared Thermography is used as a complementary non-invasive technique to monitor temperature surface distributions with time and assess the efficiency of heat transfer within the pavement structure. All sensors are connected to a newly developed platform that centralizes data access, visualization, and storage, enabling seamless management and users interactions. Results obtained are presented and discussed.

1. Introduction

The road network is daily exposed to the sunlight radiation and it can coexist with some energy harvesting technology. According to [1], the total length of the pavements in the world is around 22 million km; assuming an average width of 6 m for the roads, the total surface would be around 0.25% of the land on Earth, which is comparable with Lewis's results [2].

The solar radiation intercepted by the road network could be converted into electricity through the solar cells, or it could be harvested through a heat-exchange fluid, based on the principle of the solar thermal collectors.

Obviously, the adding of these new features requires to re-think the design, the manufacturing, the installation and the maintenance of the road infrastructure.

To this end, academia and industry are conducting R&D works on two solutions: the photovoltaic pavement and the asphalt solar collectors.

Using solar cells require to add a semi-transparent layer on the wearing course while keeping skid resistance for vehicles and load bearing capacity of the pavement structure. On the other hand, many works focused on embedded pipe for solar collector to harvest the thermal energy or deliver energy for de-icing in winter conditions. An average efficiency of 26% was observed on different system studied presented in litterature.

As an alternative, research works were conducted on replacing the asphalt base

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course with integrated pipes by a porous one [3-5]. An average efficiency of 38% was observed on different system studied.

More recent R&D works [6] have proposed to replace the asphalt porous layer by a cement concrete porous layer in combination with new approach for hydraulic layer in-situ impermeability to enhance thermal fluid flow rate and conductive heat transfer inside the structure.

The present study investigates the thermal behavior of such innovative pavement system integrating thermal and solar energy collection functionalities but in real outdoor conditions with a dedicated integrated instrumentation.

Previous numerical modeling [5] and laboratory-scale experiments [7] validated the feasibility of the concept, demonstrating promising thermal performance under controlled conditions. The transition to outdoor testing aims to evaluate the system's response to real environmental factors, including solar radiation, ambient temperature variations, and convective exchanges.

In the present study, the prototype pavement mock-up is continuously monitored using temperature and heat flux sensors probes inserted in the structure. Local environmental conditions are monitored thanks to the deployment of a local weather station and a pyranometer. Finally, Infrared Thermography is used as a complementary non-invasive technique to monitor temperature surface distributions with time. All sensors are connected to a newly developed platform that centralizes data access, visualization, and storage, enabling seamless management and users interactions.

We first present the instrumented mock-up, the outdoor test site and the new monitoring system. Preliminary results are shown and discussed, followed by conclusion and perspectives.

2. Instrumented outdoor test site

We first introduce the instrumented outdoor test site and present the hybrid solar road mock-up built with its instrumentation at heart. Then, the new H24 monitoring system architecture is introduced and completed with a focus on the generic infrared camera management and acquisition platform.

Designed and built instrumented mock-up

A mock-up of the SUNROAD system [6] of 2m x 1 m dimension was built in our laboratory facilities, allowing instrumentation integration in various layer and different location inside the structure. The system has been implemented in an outdoor test site equipped with additional local weather and sun illumination sensors. Figure 1 presents a schematic view of the test site and a view of the built system.

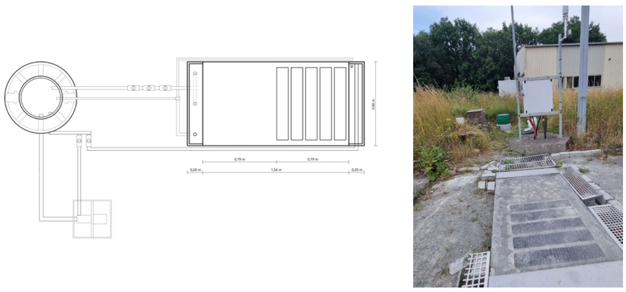

Figure 1. Scheme of the test site (left) and view of built system (right).

Five rows of solar cells are integrated below a semi transparent layer in the first part of the hybrid road system surface. The second part, is only recovered by the semi-transparent layer. The thermal fluid flow first below the solar cell (inside the porous layer and by natural gravity). At the outlet, it flows to a hydraulic underground storage. A pump is used to raise the thermal fluid at the inlet of the system. The control- command and monitoring system connected to all sensors are integrated in a protective housing located on the shoulder of the system (see Figure 1)

H24 monitoring system : Supervisor

A chain of various software called "Supervisor" have been designed [8] as a "system of systems" to support the development and operation of Structural Health Monitoring (SHM) Digital Twins. Those software are managed by a central supervisor that handles the data gathering from various sensors and sources, such as meteorological data from various providers, while a recorder handles data and metadata storage using the HDF5 format. One of the key component of the Supervisor is to embed data assimilation capabilities combined with specific physical or statistical models, including inverse thermal and/or mechanical ones up to predictive models. It therefore interconnects hardware and software layers to enable the extraction and provision of key parameters essential for Digital Twin-based decision-making tools or predictive control monitoring application.

As illustrated in Figure 2 the Supervisor natively integrates data collection from both local sources and external systems, supporting real-time synchronization and updates. Its Model-View-Controller (MVC) design pattern ensures extensibility, customization, and interoperability with existing applications.

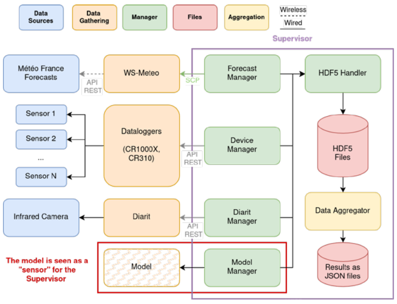

Figure 2. Schematic view of the supervisor architecture.

The Single-Writer-Multiple-Readers feature of HDF5 allows real-time visualization and live computation of Digital Twin models. Supervisor's flexible data handling supports various sensor types, and its deployment capabilities are reinforced by Ansible automation and GitLab automatic updates. As a cornerstone in the SHM Digital Twins research framework, Supervisor also contributes to maintenance planning by providing insights on both monitored structures and deployed sensors, with future improvements aimed at broader data integration and more generic configuration mechanisms.

Infrared images acquisition platform: Diarit

As part of the Supervisor toolchain, the 'Diarit' module [8] manages and schedules the acquisition of infrared images, supporting a variety of camera vendors. Diarit is built around a generic abstract class for infrared cameras, which serves as a high-level API. This design facilitates the integration of new camera vendors and provides standardized functionalities such as a unified user interface for camera control, live stream visualization, and the ability to plan and manage image recordings. Its integration with the Supervisor toolchain enables advanced in-situ monitoring capabilities across diverse camera vendors SDK and data structures, while addressing challenges related to data synchronization, storage, and visualization.

3. Results and discussion

Figure 3 presents the evolution of the thermal fluid temperature evolution overs 4 days, at the inlet, the outlet and in the underground storage. The solar irradiance received at the mock-up surface is also shown.

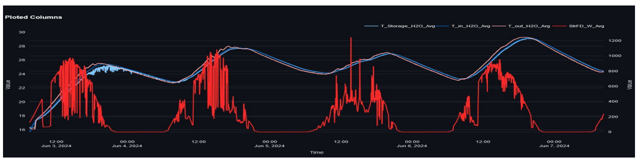

Figure 3. Thermal fluid temperature and solar irradiance evolution with time over 4 days.

Figure 4 shows an example of thermal energy harvested on the fluid loop over 9 days.

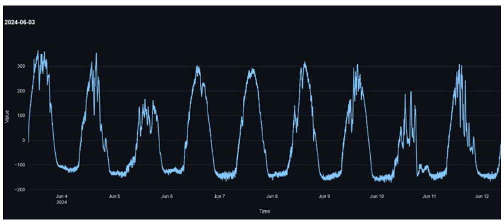

Figure 4. Thermal energy harvested in the fluid loop over 9 days.

On June 5-6, it can be observed a decay of the amount of solar energy harvested with low solar irradiance available this particular day.

The Figure 5 presents infrared images acquired at different time step showing the raise of apparent surface temperature over the photovoltaic part of the mock-up with no fluid flow in the porous layer.

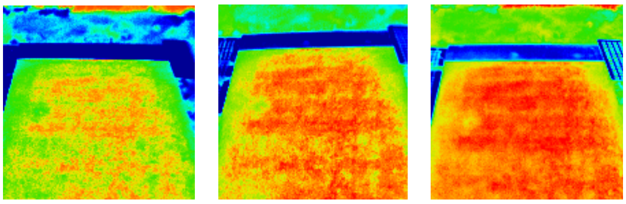

Figure 5. Infrared images acquired over the photovoltaic part of the mock-up at 3 time step.

Supervisor connection with Diarit the infrared image acquisition platform allows measurement correction [9] induced by variable environmental conditions measured on site.

4. Conclusion perspectives

This study contributes to the development of sustainable pavement technologies by optimizing energy efficiency, durability, and performance under real-world conditions. It also addresses the monitoring architecture and data standards research works carried out to allow large scale deployment on real structures or transport infrastructures. Preliminary results obtained are promising.

As a perspective, data collected from IRT measurements and embedded temperature and heat flux sensors will be used to refine the existing numerical models, ensuring greater accuracy in predicting long-term thermal behavior.

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References

1. Meijer J. R., Huijbregts M. A. J., Schotten K. C. G. J., Schipper A.M., ‘Global Patterns of Current and Future Road Infrastructure’. Environmental Research Letters 13(6): 064006, june 2018, DOI: 10.1088/1748-9326/aabd42
2. Lewis N. S. et al., “Basic Research Needs For Solar Energy Utilization”. Report on the Basic Energy Sciences Workshop on Solar Energy Utilization, Renée M. Nault publication, Argonne National Laboratory, 2005.
3. Pascual-Munoz P., Castro-Fresno D., Serrano-Bravo P., Alonso-Estébanez A., ‘Thermal and Hydraulic Analysis of Multilayered Asphalt Pavements as Active Solar Collectors’. Applied Energy 111: 324–32, https://doi.org/10.1016/j.apenergy.2013.05.013
4. Asfour S., Bernardin F., Toussaint E., Piau J-M., ‘Hydrothermal Modeling of Porous Pavement for Its Surface De-Freezing’, Applied Thermal Engineering, Volume 107, 25 August 2016, Pages 493-500, https://doi.org/10.1016/j.applthermaleng.2016.06.138.
5. Le Touz N., Dumoulin J., Piau J-M., ‘Multi-Physics Fem Model of Solar Hybrid Roads for Energy Harvesting Performance Evaluation in Presence of Semi-Transparent or Opaque Pavement Surface Layer’, IHTC 2018, 16th International Heat Transfer Conference, Aug 2018, Beijing, China, pp 1809-1816, DOI: 10.1615/IHTC16.cms.023896
6. European Patent ‘HYBRID SYSTEM FOR SOLAR ROADWAY’, EP4089912 (A1) — 2022-11-16.
7. Vizzari D., Dumoulin J., Chailleux E., Gennesseaux E., Lavaud S., Bouron S., Manceau J-L., " Thermal behaviour of a novel solar hybrid road for the energy harvesting," Journal of Testing and Evaluation, Ed. ASTM International, Vol.51, N° 4, July 2023, https://doi.org/10.1520/JTE20220283.
8. Dumoulin J., Toullier T., Simon M., Andrade-Barroso G. ‘DIARITSup: a framework to supervise live measurements, Digital Twins models computations and predictions for structures monitoring’. EGU General Assembly 2022, May 2022, Vienna, Austria. pp.1-2, ⟨10.5194/egusphere-egu22-11201⟩. ⟨hal-03895766⟩
9. Toullier T., Dumoulin J., "Bias and bottlenecks study in outdoor long term thermal monitoring by infrared thermography: Leveraging opportunistic data for temperature estimation", Infrared Physics & Technology Journal, Volume 141, August 2024, 105471. https://doi.org/10.1016/j.infrared.2024.105471