Software platform for imaging diagnostic exploitation applied to edge plasma physics and real-time PFC monitoring

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Abstract. In current tokamaks, imaging diagnostics (visible/infrared) have become increasingly used for real-time control of the temperature of the Plasma Facing Components (PFC) and for off-line physical analysis. Developing a full acquisition and control system based on a network of multiple cameras is a complex task requiring advanced software tools. Furthermore, such systems produce a large quantity of data encouraging end users to share tools and codes for data access and analysis.

In this paper, we introduce a software platform, named Thermavip, dedicated to these tasks. The main contribution of this software is to gather under the same framework different functionalities for (1) firm real-time video acquisition and PFC monitoring, (2) offline data access and display, (3) signal and video processing applied to plasma physics, (4) video annotation and thermal events database management. This software platform is widely used on the WEST (**W** **E**nvironment in **S**teady-state **T**okamak) tokamak (France) for offline study of infrared (IR) and almost all WEST diagnostics data, and online display of IR videos and temperature time traces for critical components. Thermavip platform is also used on the HADES (**H**igh he**A**t Loa**D** t**ES**t) facility (France) and the EAST (**E**xperimental **A**dvanced **S**uperconducting **T**okamak) tokamak (China) for offline signal analysis, and on the Wendelstein 7-X (W7-X) stellarator (Germany) for the IR diagnostic acquisition, PFC real-time (RT) monitoring, online display and offline video analysis. In addition, Thermavip provides a full featured video annotation tool used on both WEST and W7-X to build and manage thermal events datasets. These annotations are used as input dataset to train deep-learning models, like Region Based Convolutional Neural Networks, for automatic detection and classification of thermal events based on IR movies.

The Thermavip framework is composed of a unique C++ Software Development Kit (SDK) providing high-level classes for offline multi-sensor data analysis, firm real-time processing and online visualization of these sensor data. Its strength comes from its unique component block architecture, allowing to build multicore and distributed processing pipelines for both offline and firm real-time applications. Thermavip architecture relies on a versatile plugin mechanism to extend its functionalities using C++ code or Python scripts, facilitating the integration on new machines.

1 Introduction

In recent years, the use of imaging diagnostics has become increasingly important for plasma physics and tokamak operation. For instance, the infrared (IR) diagnostic of WEST is composed of 13 viewing lines covering about half of the WEST internal wall [1]. This diagnostic is used for offline physical studies as well as real-time monitoring [2] of Plasma Facing Components (PFC). Managing such network of cameras for both offline and real-time extraction of quantitative information from IR images is not a trivial task:

- Developing an acquisition and monitoring system for several cameras requires high level programming skills,
- Observed IR scenes are complex to interpret and usually require additional information like injected power, plasma current or plasma density for physical understanding.

This paper presents the Thermavip software platform which gathers under the same framework software components for:

- Real-time videos/signals acquisition,
- Real-time processing of acquired data and online display in control rooms,
- Offline visualization and synchronisation of multi-sensor data,

- Offline processing of signals and IR/visible videos applied to plasma physics,
- Offline IR video annotation and management of thermal events database.

This C++ platform has been developed since 2012 on the WEST tokamak and is also used on the HADES facility for IR data analysis, EAST tokamak for offline analysis of IR and other sensor data, and on W7-X stellarator for firm real-time acquisition and processing of infrared videos as well as offline signal analysis.

After an overview of Thermavip software architecture in Section 2, the platform features dedicated to offline sensor data analysis are presented in Section 3. The Section 4 describes the real-time module of Thermavip dedicated to video acquisition and PFC monitoring. A new module dedicated to thermal events annotation in IR videos and events database management is presented in Section 5. Finally, future prospects are discussed in conclusion.

2 Thermavip software architecture

Thermavip was developed since 2012 at the Institute for Magnetic Fusion Research (IRFM) from the French Alternative Energies and Atomic Energy Commission (CEA), originally for the visualization and post-processing of IR data of the WEST tokamak. It since evolved to become a multi-sensor data analysis tool for both offline and real-time applications.

The software is composed of a *Software Development Kit* (SDK) written in C++11 with Qt[1] library as its unique dependency. While Qt is usually seen as a Graphical library, it is in fact a full featured general library which also provides Graphical Components. Thermavip supports the same platforms as Qt (Linux, MacOS, Windows, Android…) and compilers. Currently, Thermavip has been successfully compiled with msvc (Visual C++ 14.0 and 14.3) on Windows, GCC 10.1.0 on Windows and GCC 6.4.0 on Linux. Currently, Thermavip was tested on non real-time Operating Systems: Windows 7 and 10, Linux CentOS 7, Red Hat Enterprise Linux Server 7.7. The Thermavip SDK is composed of 5 libraries:

- *Logging*: thread/process safe logging purpose functionalities
- *DataType*: defines the data structures commonly manipulated within Thermavip: images, N-Dimensional arrays, curves, histograms, scene models. This library also contains the binary serialization functions for these types (usually for network communication).
- *Core*: base library of Thermavip's SDK. It defines the main concepts and classes that should be used to extend Thermavip through plugins: processing pipelines, plugins management, network communication, signal loading/saving, updates management.
- *Plotting*: library providing highly optimized 2D graphical plotting: images, spectrograms, curves, histograms, pie charts, bar charts, gauges… All plotting features (especially images/spectrograms) are highly optimized to display *online* huge data throughput using multi-threading techniques and optional OpenGL rendering.

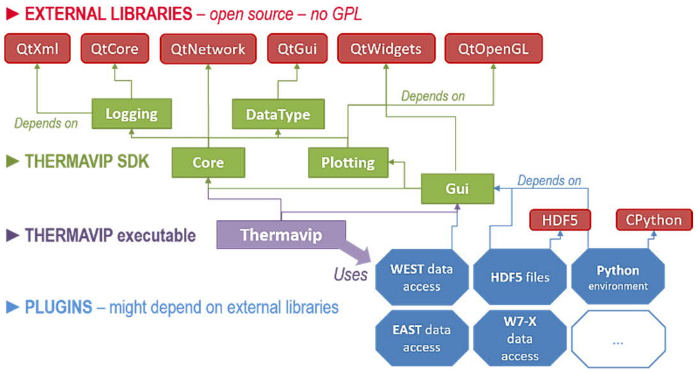

Figure 1: Thermavip software architecture

- *GUI (Graphical User Interface)*: defines all common widgets and the main Graphical User Interface of Thermavip.

The Figure 1 describes the software architecture of Thermavip and dependencies between libraries. Based on the SDK, all aspects of the software can be extended by user defined plugins written in C++: new camera management, additional signal/video processing, additional GUI components, and management of new video file formats. Plugins can depend on any additional external libraries. By default, Thermavip comes with a set of plugins for signal processing, HDF5 format handling and Python code integration to provide scripting functionalities.

The main Thermavip executable is a very simple program, and can be seen as a plugin container which goal is to load user plugins and display the main graphical interface. Based on the loaded plugin configuration, Thermavip might exist in several versions. For instance, the versions used on WEST, HADES, W7-X and EAST provide different functionalities.

Thermavip source code is currently not open source, but is available through collaboration agreements with CEA/IRFM.

3 Offline sensor data analysis

The first main set of Thermavip features are dedicated to offline analysis of multi-sensor data for plasma physics studies or any other study related to tokamak exploitation.

Thermavip provides a unique Graphical Interface for:

[1] https://www.qt.io/

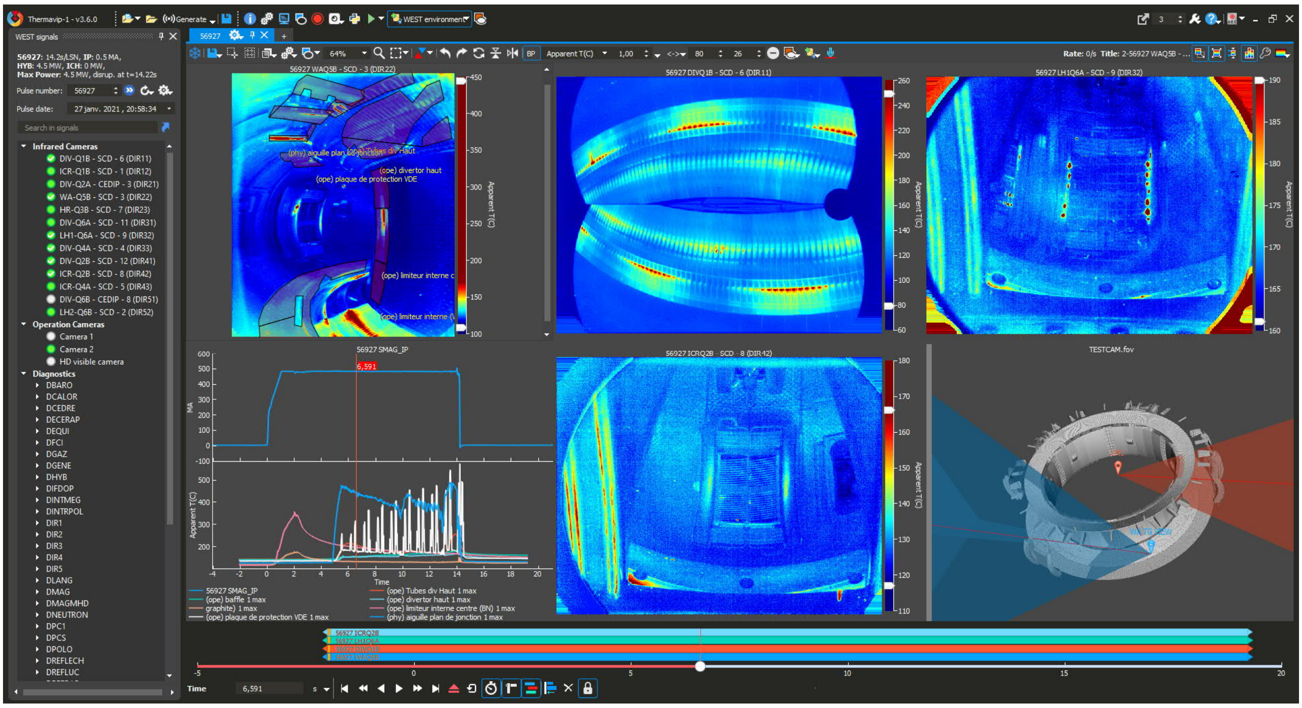

Figure 2: Main Thermavip interface for the WEST version. It displays (from top left corner to bottom right corner): IR video of the Wide Angle (WA) view, IR video of a divertor view, IR video of a LH launcher view, signal of plasma current and temperature time traces inside security ROIs for the WA view, simplified CAD models of WEST with the field of view of 2 cameras overlaid.

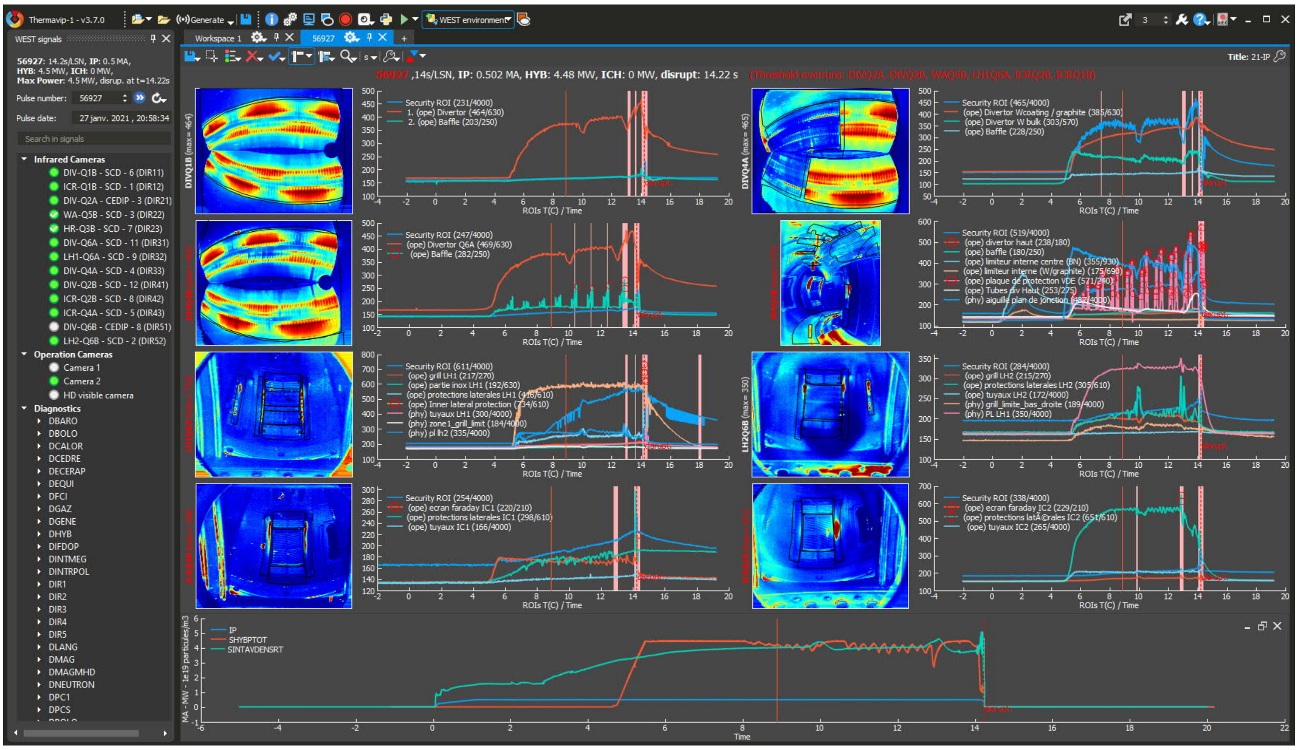

Figure 3: Example of Discharge Summary on WEST for pulse #56927. Each image is obtained by computed the cumulated maximum of the IR video, excluding potential disruption. Security ROIs temperature time traces are displayed at the right of each IR video. Threshold overruns inside ROIs are highlighted in red. Total injected power, plasma current and plasma density are displayed on the bottom part.

- Signal database browsing/searching. This feature is usually provided by a dedicated plugin as all machines use different offline data access schemes.
- Visualization and synchronization of videos (IR and/or visible) and 1D + time signals. Thermavip can also display other types of information like histograms and 3D CAD models.
- Post-processing data: Thermavip provides tools for extracting time traces inside user defined Regions Of Interests (ROIs) on IR videos, several image/signal processing algorithms (filters, fits, FFT, etc.), histogram extraction in ROIs, and various numerical operations on and between signals. Thanks to a dedicated plugin, Thermavip offers an embedded Python

environment to apply custom processing on videos and signals.

- Exporting signals and videos. Thermavip provides tools to export sensor data in several formats like HDF5, and to generate paper quality figures or MPEG videos for scientific presentations.

The Figure 2 presents an example of Thermavip interface for WEST tokamak and displaying several IR videos as well as 1D signals, 3D simplified CAD models of the machine and overlaid camera fields of views.

Depending on the loaded plugins, Thermavip provides additional features related to the considered machine. For instance, the WEST version adds tools to modify the temperature calibration for IR videos (setting custom emissivity, changing optical transmission coefficients) or displaying security ROIs superimposed to IR videos. An additional tool has been developed to provide a one page Discharge Summary (see Figure 3) at the end of each pulse combining IR videos, security ROIs time traces with highlighted temperature overruns, signals of injected power, plasma current and plasma density for a quick understanding of the discharge.

Such machine-dependent plugins have been developed for W7-X stellarator, EAST tokamak and the HADES facility [3] located on Cadarache (France).

Thermavip version dedicated to offline sensor data analysis has been used for several physical studies like heat load studies on the first wall of W7-X [4], assessment of the emissivity of tungsten PFC of WEST [5], or validation and assessment of WEST Wall Monitoring System [2]. It is currently the standard tool for the post-processing of video data on WEST, X7-X and EAST.

4 Firm real-time processing pipelines

Thermavip provides the concept of *Processing* within the *Core* library of the SDK. Within Thermavip, almost everything is considered as a *Processing*: video acquisition, any kind of video/signal treatment, signal recording, video/curve display, etc. A *Processing* is an object defining any number of input(s), output(s), optional property(ies), and performing an action transforming these inputs. Each output of a *Processing* can be connected to any input(s)/property(ies) of any other *Processing*. All *Processing* are asynchronous, meaning that they all live in different threads and can be applied in parallel. A processing is simply triggered when a new input is available.

This lets the user build complex asynchronous workflows, as shown on Figure 4.

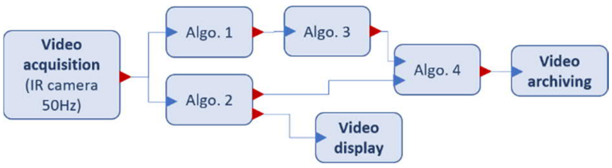

Figure 4: Processing pipeline going from the video acquisition up to video display and video archiving

In this example, the source *Processing* is the video acquisition that sends through its output an image every 20 ms. This image goes through processings *Algo.1* and *Algo.2*, and triggers them. They send their results to the following processings, until reaching the leaf processings *Video archiving* and *Video display*. Each processing input contains a circular buffer (either FIFO or LIFO) of incoming data which is filled by the source processing and unstacked at each processing iteration. The maximum capacity and type of circular buffer for each processing input can be configured using Thermavip SDK.

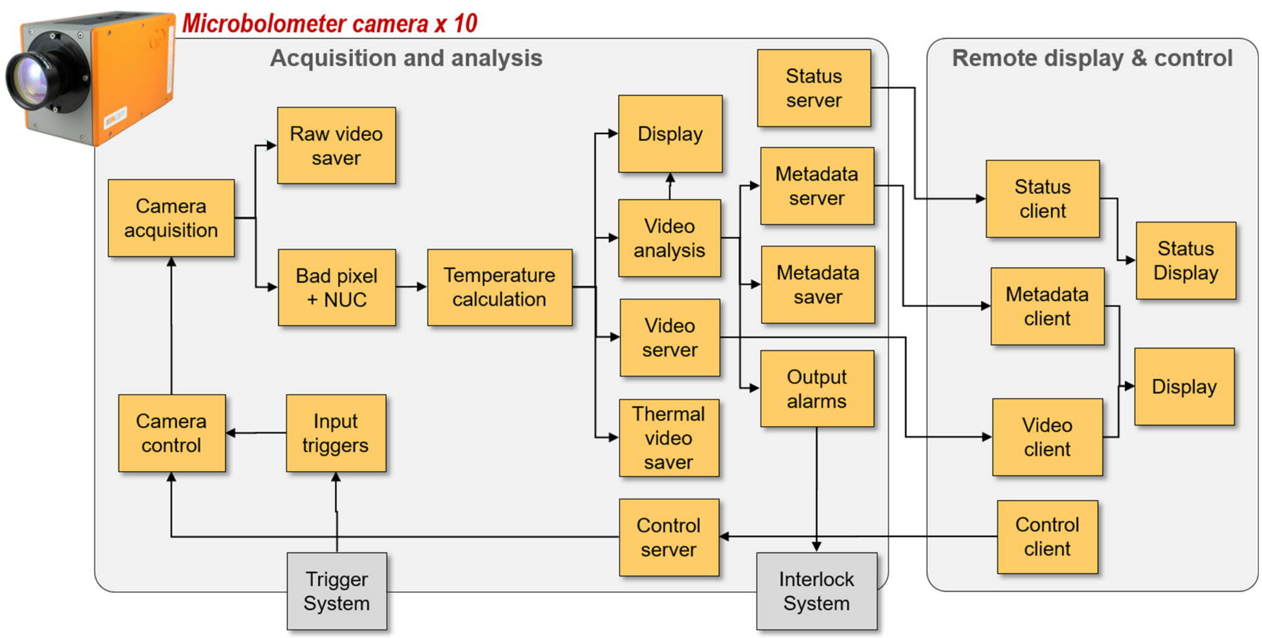

Figure 5: Distributed real-time processing pipelines used by W7-X IR acquisition system for OP1.2 based on Thermavip

In the configuration of Figure 4, the video acquisition defines the global processing pipeline clock. If a sink processing execution time is higher than 20 ms, its input buffer(s) keeps filling up, until reaching its maximum capacity and dropping incoming data. In such case, Thermavip displays a warning message and lets the user provide a custom fall-back strategy.

Thermavip was first developed to run on non real-time Operating Systems. As such, a processing pipeline defined with Thermavip SDK is suitable for firm real-time applications but will never provide hard real-time guarantees. It is possible to define a time limit for each processing within a pipeline in order to trigger custom behaviour in case of missed deadline.

Thermavip SDK let the user developed custom processing that can be inserted within any pipeline. This includes signal/image processing or computer vision processings, Video grabber or archiving processings, and processings sending triggers through the network or using a dedicated hardware.

The offline version of Thermavip discussed on the previous section also uses widely the concept of *Processing*. For instance, opening a video file for display also creates a processing pipelines going from the video file reading up to the video display. The difference with real-time pipeline is that offline pipelines are synchronous: the leaf processing requests an input from its sources, which in return request inputs from their sources, up to the first processing of the pipeline. All these synchronous operations are performed in the same thread. Therefore, any Processing developed initially for offline analysis (like an image processing one) can be used within a real-time pipeline as well.

Processing pipelines were used for the OP1.2 experimental campaign of W7-X to build the acquisition system of the IR diagnostic, as shown on Figure 5. The left processing pipeline was in charge of the firm real-time video acquisition, image processing and sending triggers to the interlock system. It was duplicated on 10 acquisition computers, one per microbolometer camera.

The right online processing pipeline (with relaxed time constraints) was in charge of collecting the 10 video streams through point to point network connections and display them in the control room with additional status information. Indeed, Thermavip can display online a wide amount of data (videos, curves, histograms, gauges…) with an auto-adapted frame rate in order to keep the Graphical Interface responsive. Video display is especially highly optimized in order to display multiple video streams in parallel using either software or OpenGL rendering.

The full W7-X acquisition system and its architecture (IR camera type, frame grabbing, computer architecture, and machine control) is described in [6] and [7]. This acquisition system was fully based on Thermavip SDK, and developed by W7-X system experts with the support of CEA developer's team.

5 Video annotation and events database

On WEST tokamak, deep-learning models like Region Based Convolutional Neural Network (RCNN) are more and more used to automatically detect and classify thermal events based on IR videos. These techniques require a dataset (or ground truth) of events to train the models, but also to assess their performances. The detection process is currently performed offline on WEST as explained in [8].

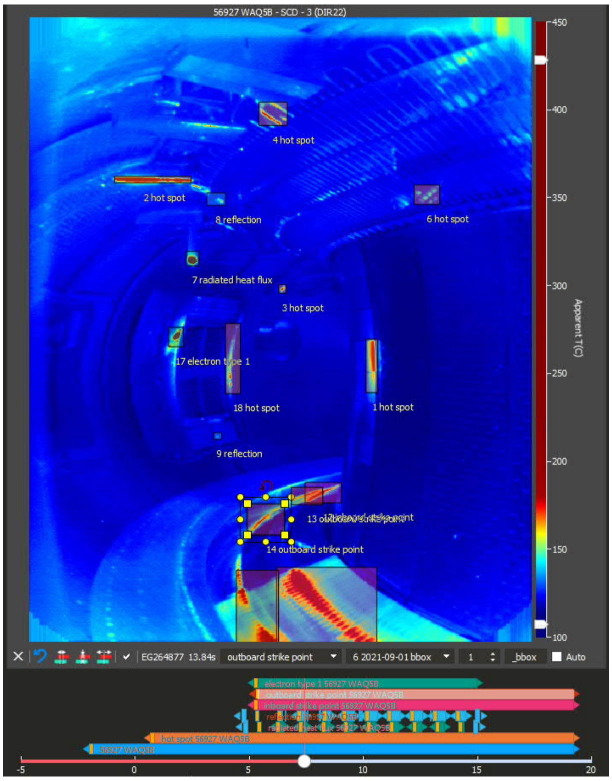

Figure 6: Example of video annotations on WEST Wide Angle IR view

To help setting up such models, Thermavip provides a plugin dedicated to video annotation and handling of a SQL thermal events database. This plugin provides:

- Graphical tools to manually define events on top of an IR video. An event is a polygon which shape can vary during the discharge.
- Graphical tools for supervised annotation based on image processing techniques as described in [9].
- Export of video annotations either to a centralized SQL database or to JSON file(s).
- Visualization/modification of events defined either manually or through an automatic process from a SQL database or JSON file(s).

The Figure 6 displays an example of video annotation on the Wide Angle view of WEST. User defined events are overlaid on top of the IR video, and each event duration is displayed on a timeline under the video.

This tool is now widely used on WEST and is also available on W7-X.

6 Conclusion

Thermavip is a software platform developed at IRFM since 2012 and dedicated to offline/real-time visualization and processing of multi-sensor data, with a strong emphasis on video data (IR/visible).

Initially developed for the post-processing of WEST data, the platform provides a SDK and a plugin mechanism in order to easily port it to other machines. It is currently available on WEST and EAST tokamaks for offline analysis of multi-sensor data, HADES facility for IR data analysis, and as a real-time acquisition system for IR diagnostic on W7-X stellarator. A plugin was successfully developed in 2020 in order to visualize and post-process sensor-data from servers based on the *Unified Data Access* (UDA) system used by ITER and KSTAR.

The future functionalities that will be embedded within the software (as plugins or extension of the SDK) will be strongly oriented to help PFC monitoring and deep learning models development for automatic recognition of thermal events.

While the source code of Thermavip is currently not open source, it is available through collaborations with CEA/IRFM, and the CEA might provide support to develop custom plugins based on user's needs.

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