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APPLICATION OF A DESIGN STRUCTURE MATRIX METHODOLOGY TO STEP PLASMA CONTROL SYSTEM DESIGN AND SENSOR OPTIMISATION

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ABSTRACT

- This work presents a novel application of a Design Structure Matrix (DSM) methodology to mapping the functional dependencies of the STEP Plasma Control System (PCS).
- A provisional DSM for the STEP prototype reactor (SPR) is presented, demonstrating how clustering decomposes the key elements of the PCS design into relatively independent subproblems.
- The work demonstrates the benefits of DSM methodology in the design of complex systems and outline future directions of work in this area.

BACKGROUND

Background and Motivation

Controlling a burning plasma is a critical challenge for achieving a viable fusion power plant. This requires a real-time, closed-loop Plasma Control System (PCS) capable of sensing plasma states, computing control actions, and actuating responses. The complexity of interdependencies between sensors, actuators, and control algorithms make PCS design highly challenging. A structured, systems-engineering-led approach is essential to manage these complexities from concept through to operation.

Design Structure Matrix (DSM)

A DSM is a square matrix that captures interdependencies between system elements, such as actuators, sensors, and physical processes [1]. Off-diagonal entries indicate dependencies or interfaces, which can be binary, weighted, or categorized. DSM variants exist for different domains, including technical, organizational, and temporal systems. DSM allows interfaces to be clustered based on grouped functional relations (as shown in Figure 2), providing a systematic way of minimising interface complexity.

CHALLENGES / METHODS / IMPLEMENTATION

Metamodel and Data Definition

A metamodel defining six element types (plant components, physical processes, actuators, sensors, state parameters, and requirements) was used as a basis for the model. A diagram of the full metamodel is shown in Figure 1. The initial data set for the model presented was sourced from UKAEA design documentation, expert input, and DIFFER datasets. These elements were used to develop a plant DSM model for the STEP PCS.

Technical Implementation

The model was implemented using the Elephant Specification Language (ESL) and parsed with the RaESL Python package to generate graph-based representations [2]. Automated workflows in Jupyter notebooks enabled DSM construction, clustering, and export in multiple formats. Configuration files allowed customization of DSM organization and viewpoints.

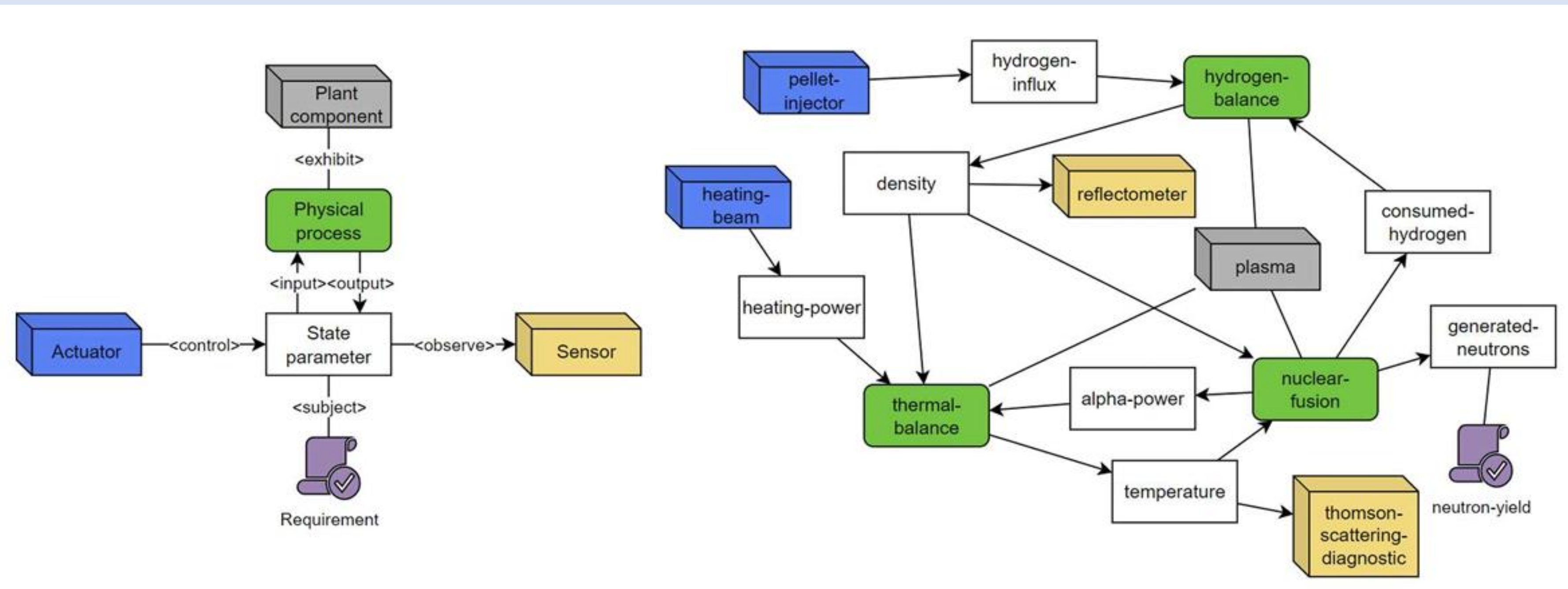

*Figure 1 - **Left:** Overview of the metamodel defining the element and dependency categories used to model the PCS. **Right:** An example instance of the metamodel covering a subset of the actual elements and dependencies of the STEP PCS.*

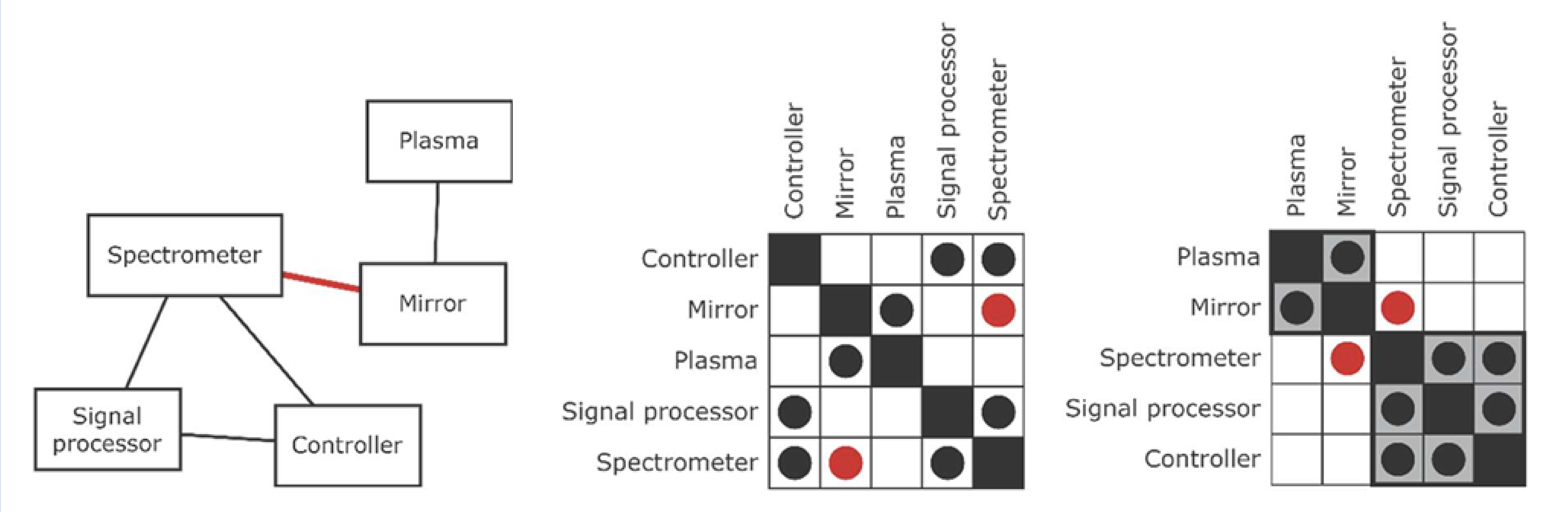

*Figure 2 - **Left:** A diagnostic system as a network of interdependent components. **Centre:** A DSM representation of the system maps dependencies as off-diagonal marks. **Right:** A clustered matrix. [3]*

OUTCOME

The full DSM mode, mapping dependencies among actuators, sensors, and plasma processes, is shown in Figure 3. Four primary clusters were identified - magnetics, core, edge (including plasma-wall interactions), and divertor (including divertor targets). The remaining inter-cluster dependencies are minimal, typically covering well-characterized phenomena such as plasma current, bootstrap current and pellet injection.

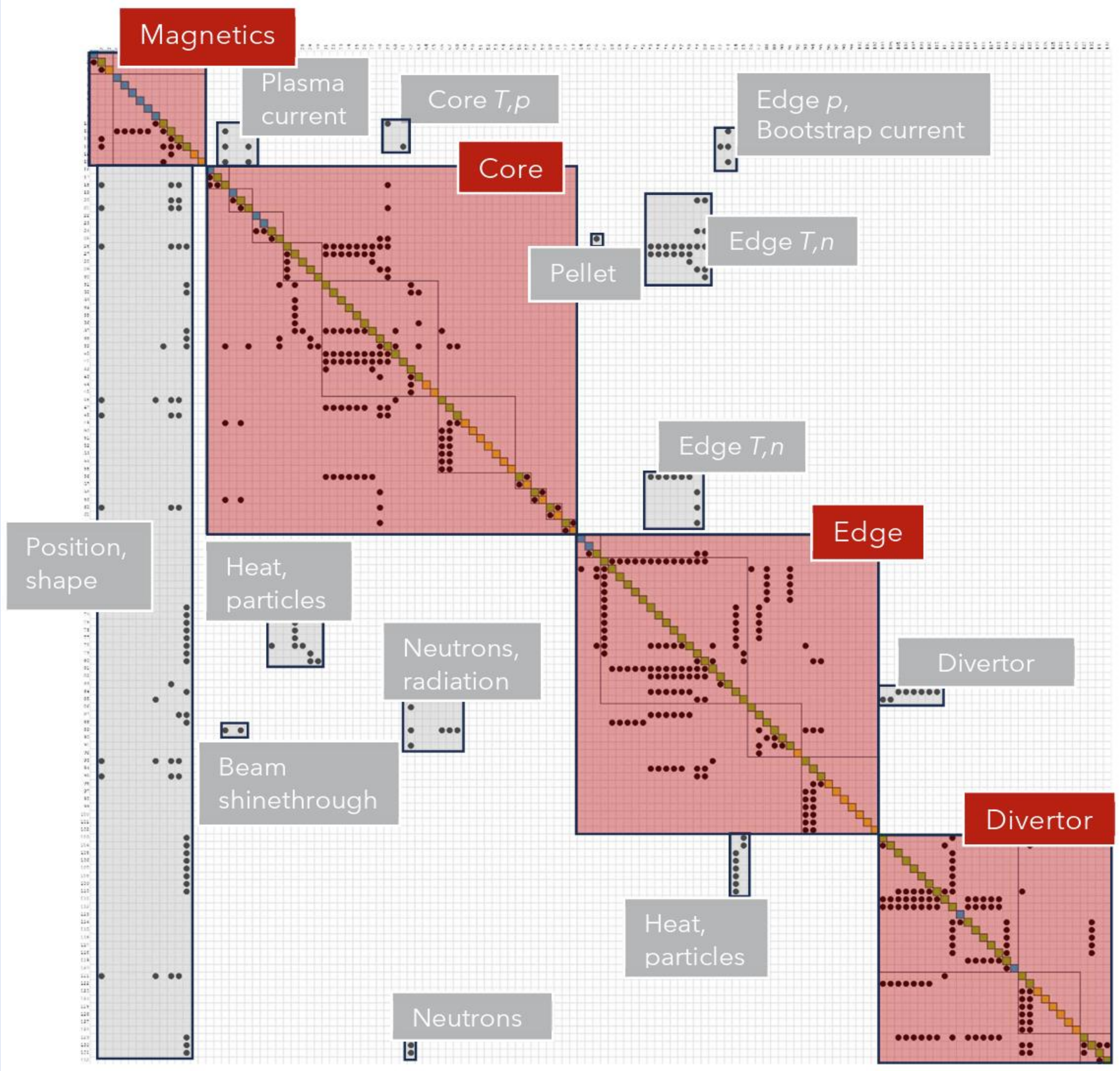

Figure 3 -Plant DSM for the STEP PCS with functional groups labelled.

CONCLUSION

- A provisional DSM model (covering, actuators, sensors, physical processes, parameters, and requirements) of the STEP PCS is presented, showing grouped areas of functional dependency.
- The work demonstrates the applicability of DSM methodology to the iterative design of the STEP PCS as the programme matures and broader applicability to design challenges in fusion control systems.
- Areas of future work include measurement systems, operational scenarios, simulation model development and discrete events and states.

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