DEVELOPMENT OF A VIRTUAL CYBER-PHYSICAL TESTBED FOR RESILIENT EXTRA-TERRESTRIAL HABITATS

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ABSTRACT

Establishing permanent and sustainable human settlements outside Earth presents numerous challenges. The Resilient Extra-Terrestrial Habitat Institute (RETHi) has been established to advance the fundamental knowledge needed to enable and design resilient habitats in deep space, that will adapt, absorb, and rapidly recover from expected and unexpected disruptions without fundamental changes in function or sacrifices in safety.

Future extra-terrestrial habitats will rely on several subsystems working synergistically to ensure adequate power supply, life support to crew members, manage extreme environmental conditions, and monitor the health status of the equipment. To study extra-terrestrial habitats, a combination of modeling approaches and experimental validations is necessary, but deep-space conditions cannot be entirely reproduced in a laboratory setting (e.g., micro-gravity effects). To this end, real-time multi-physics cyber-physical testing is a novel approach of simulating and evaluating complex system-of-systems (SoS) that has been applied to investigate the behavior of extra-terrestrial habitats under different scenarios. The developed cyber-physical testbed consists of a real-time computational environment that includes dynamic models of the structural protective layer of the habitat, power generation system, ECLSS and exterior environment, and a physical environment that features a structural dome and a thermal transfer system. Such comprehensive framework that couples virtual and physical aspects will allow the simulation of fault scenarios, emergent behaviors, emergency situations (e.g., meteorite strikes) and actions to be taken to restore a safe state of operation of the habitat. One of most critical features of the cyber-physical testbed is the interface between the two environments. A dedicated thermal transfer system has been designed and constructed to provide realistic thermal boundary conditions to the physical habitat. The extreme temperatures to be found at the interface between the external protective layer of the habitat and the interior structural elements are emulated by means of a low-temperature chiller and an array of cooled panels that cover a dome-style structure. The surface temperatures of the thermal panels are conditioned according to the results of virtual simulation, which take the output heat flux from the physical system as a feedback.

This work will describe the overall architecture of the cyber-physical testbed, the partitioning of the virtual and physical environments, and communication schemes. A meteorite impact and consequent thermal management scenario will be employed as a case scenario to demonstrate

the capabilities of the cyber-physical testbed. In addition, preliminary commissioning of the physical thermal transfer system and next steps will be covered.

INTRODUCTION

The Resilient Extra-Terrestrial Habitat Institute (RETHi) has been established to advance the fundamental knowledge needed to enable and design resilient habitats in deep space, that will adapt, absorb, and rapidly recover from expected and unexpected disruptions without significant changes in function or sacrifices in safety. These disruptions include a wide range of scenarios from periodic variation of solar irradiation by a planet's rotation to more complex situations such as meteorite impacts on physical structure of the habitat itself or unexpected faults/failures. Under these circumstances, resilient habitats rely on their subsystems working synergistically to ensure adequate power supply, life support to crew members, manage extreme environmental conditions, and monitor the health status of the equipment. RETHi has been developing numerical system-of-systems (SoS) covering multiple subsystem environments such as structural mechanical and thermal system, power generation system, ECLSS and exterior environment system to conduct quantitative research into designing and operating resilient and autonomous extra-terrestrial settlements. However, experimental validations to these numerical models are a great challenge as many deep-space conditions cannot be entirely reproduced in a laboratory setting (e.g., micro-gravity effects).

To this end, real-time multi-physics cyber-physical testing is a novel approach of simulating and evaluating complex system-of-systems (SoS) where full-scale testing and validation are very expensive and traditionally done with tremendous constraints in lab settings. Some of the example cases of how the real-time hybrid simulation method are applied can be found in [1], where geographically distributed real-time hybrid simulations were conducted to examine effect of earthquake on two-story shear beam structure, and [2] where system-level analysis on four-story building was conducted with one beam subject to direct fire. As real-time hybrid simulations are designed to capture rate dependent behavior in physical substructure, it is critical to ensure steady and undisturbed signal communication between virtual and physical subsystems. While researchers choose to partition the most interesting or the least well-known part of the system for physical investigation, the overall fidelity of the numerical model representing the rest of the system has substantial impact on the success of the simulation. Recent technological advances in computational hardware have enabled researchers to run more accurate, higher-order models in real-time. However, when real-time hybrid simulations are conducted for multi-physics systems at high sampling rates, low-order or mid-order numerical models are still widely used with or without a multi-rate simulation approach discussed in [3].

Due to their complex nature, real-time hybrid simulation tests can vary in stability and performance depending on how they are configured, especially by partitioning choices. Therefore, it is advisable to prepare a procedure to quantify how safe and reliable the tests are. In [4], predictive stability and performance indicators (PSI) were suggested as design tools to optimize simulation configurations. [5] presented a framework for developing a method for quantifying, estimating, and predicting uncertainty both during and at the end of real-time hybrid simulations. Conventionally, real-time hybrid simulations have been applied to evaluate dynamics of structural mechanical systems. In this case, a hydraulic actuator or a shake table serves as the transfer system enforcing boundary conditions at the interface between physical and virtual systems. Forces and displacements are enforced interface conditions for a structurally partitioned system. Accurate measurements of these conditions are the key requirements for realistic simulations results [6]. Research studies such as Li *et al*. [7] and Meghareh *et al.* [8] call attention to the proper design and control scheme for developing transfer systems. For the hybrid simulations involving thermal systems and interfaces, we suggest temperature and heat flux as the interfaces conditions to be enforced. Rest of this paper will discuss the framework of the entire setup by dividing it into cyber, physical, and transfer system and the process of developing reduced-order prototype experiment setup.

For the scope of this paper, hybrid systems will focus on thermal dynamics of habitat structural system even though plans for adjoining other subsystems are under development as well.

VIRTUAL AND PHYSICAL SYSTEMS

The Cyber-Physical Testbed (CPT) real-time simulation environment is based on the architecture of the Modular Coupled Virtual Testbed (MCVT), also developed by RETHi. MCVT aims to include realistic models of the testbed transfer systems and replicate the dynamics and controls needed to enforce boundary conditions between the partitioned cyber and physical components. The different MCVT subsystems are partitioned into cyber and virtual components for the CPT. The current stage of the CPT includes the following subsystems: Structural System, Power System, ECLSS, Interior Environment, and Exterior Environment. The Structural System is expanded into three components: Structural Protective Layer (SPL), Structural Mechanical System (SMM), and Structural Thermal System (STM). The partitioning and clustering of the MCVT subsystems previously mentioned are shown in Figure 1. For structural system, the structural protective layer is treated as a part of computational environment, and the rest two are considered as parts of physical environment. Inputs to the physical systems are administered by transfer systems, denoted as TA in the figure, and outputs from the physical systems are collected and sent back to the virtual systems as feedback via sensors, denoted as TS in the figure.

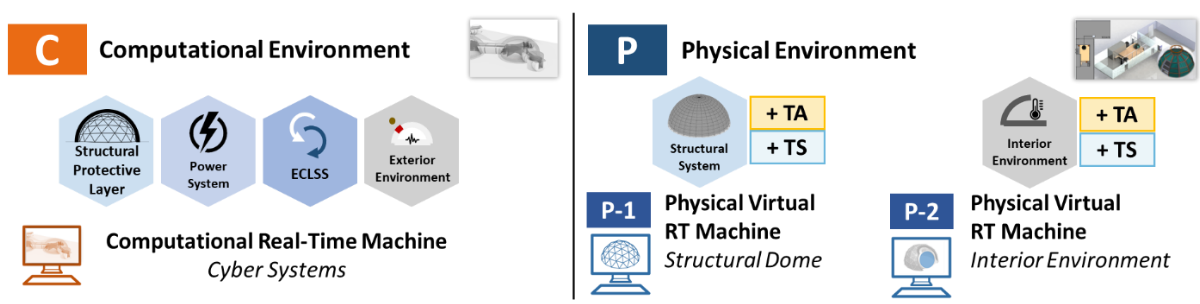

Figure 1. Partitioning of computational and physical environment for the Cyber-Physical Testbed (CPT).

One of the major goals for the CPT is to replicate meteorite impact scenarios based on their severity as thermal problems. In the four MCVT Scenarios currently under development, the meteorite directly impacts the SPL, causing cascading effects for the structural dome and interior environment. In Figure 1, it is shown that the SPL will be part of the cyber environment. In contrast, the structural dome (mechanical and thermal) and interior environment will be physical components in the laboratory. Though still under discussion, RETHi does not plan on reproducing mechanical impact force through these layers at the early stages of the experiments but does plan to replicate the thermal impact through thermal boundary conditions at different magnitudes. For example, in MCVT Scenarios, the SPL experiences major damage due to meteorite impact as illustrated in **Figure 2**. The removal of the protective material, including lunar regolith and any other material, will result in temperature changes for the surface of the structural dome in the damaged area. The thermal transfer system will be responsible for enforcing the temperature changes physically in the laboratory environment. How this transition is carried out is further illustrated in

Figure 3.

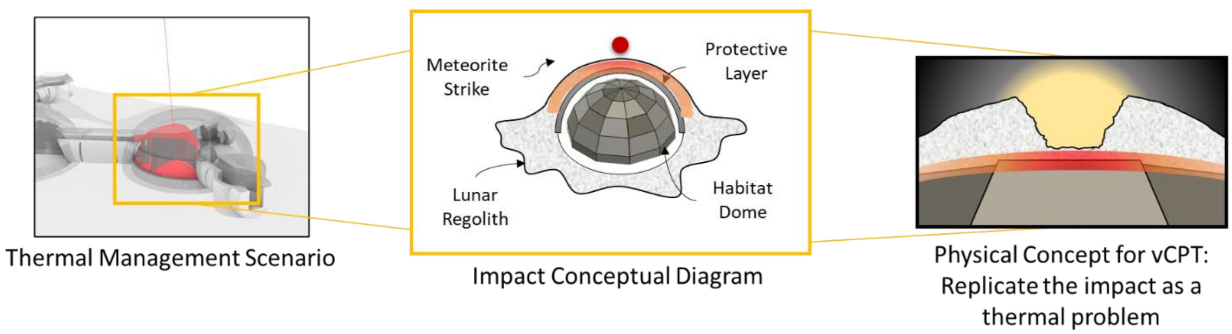

Figure 2. Impact scenario replicated in the physical environment as a thermal problem.

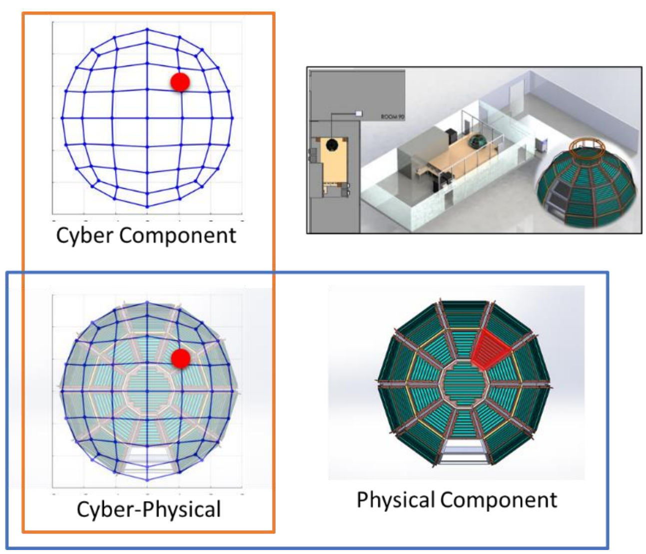

Figure 3. Impact scenario interface diagram.

In the virtual environment, the SPL receives a meteorite impact at a specified location. The consequence of the numerical calculation is transferred as the interface boundary condition to the physical structural thermal system. The thermal transfer panels at the node junction connecting these virtual and physical systems will enforce the appropriate interface condition, surface temperature. Then, physical response from all three physical systems, SMM, STM, and Interior Environment, will be captured by the respective sensors and used as feedback for the virtual environment, numerical models.

TRANSFER SYSTEM AND PHYSICAL LAYOUT

Thermal transfer system functions as a bridge between physical (e.g., dome structure) and virtual components (e.g., impact scenarios, case studies) of the cyber-physical testbed. Within the context of modelling of a future extraterrestrial habitat, the thermal transfer system emulates the interface between SPL and STM. It provides accurate and responsive thermal boundary conditions to the physical habitat structure. Practically, it is built as an attachment, in the form of heat transfer panels consisting of pipes and heat-spreader plates, to the structural dome which is the portrayal of the lunar habitat.

Based on the proposed design of the structural system, general shapes and dimensions of heat transfer panels were determined to ensure the compatibility of the assembly. Figure 4 (A) shows the five shapes of heat transfer panels corresponding to the faces of the structural dome at different height levels. Figure 4 (B) illustrates the assembly of these panels on to the structural testbed. To cover all the significant surfaces of the structural dome, a total of 38 panels are to be prepared for manufacturing. With dimensions of the bottom plates of the panels as a guideline, design parameters for the rest of the components were determined. Figure 5 shows the break-down of the components in one heat transfer panel. Structural panel, which is the part of the structural system rather than the thermal transfer system, was added to the diagram for better depiction of installation orientation of the heat transfer panels. Each heat transfer panel is composed of a thin metal plate, a heat spreader, and copper pipes. The metal plate is in direct contact with the matching structural panel and provides cooling by conduction. The heat spreader functions as a junction between the plate and pipes. The copper pipes allow heat transfer fluid flow inside. For design decisions of the components, especially the ones involving pipe layouts and sizes, MATLAB Simulink was used to conduct parametric studies regarding the control responses of the panels, and Ansys Fluent was used for analyzing detailed conjugate heat transfer behaviors of the panel. The design parameters were chosen to achieve the minimum variation in surface temperature profile of the plate and the shortest transient response time while taking ease of manufacturing in consideration. According to the flow simulations and pressure estimation calculations, a layout of pipe connections was settled as shown in Figure 6 for the distribution of the heat transfer fluid to each of the panels. Heat transfer fluid is to travel through the large supply pipeline from the chiller situated in the room adjacent to the main experimentation room. It is divided into ten channels to flow through the pipes of the heat transfer panels which are serially connected along the arc of the dome. Heat transfer fluids from the ten branches are then combined into one flow to be returned to the chiller.

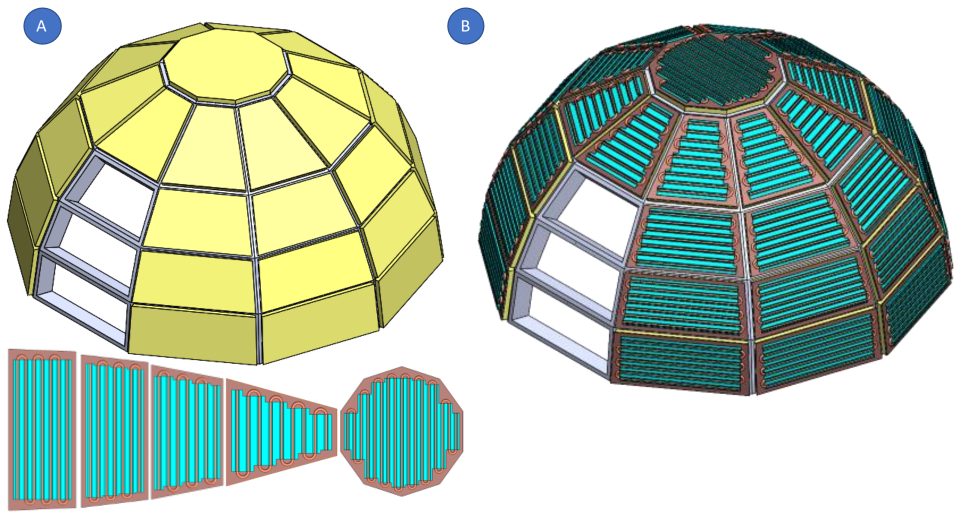

Figure 4. (A) Structural dome testbed with pairing heat transfer panels. (B) Assembly of heat transfer panels on structural dome.

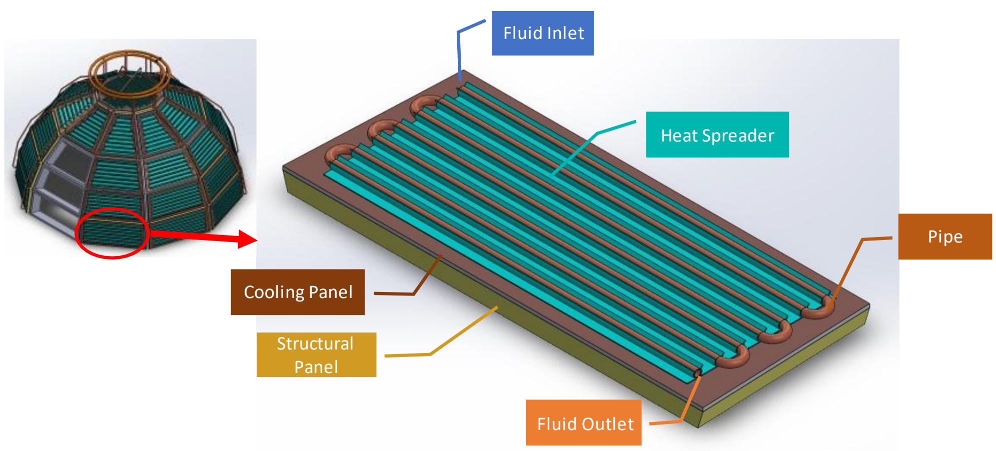

Figure 5. Components of heat transfer panel. Only the bottom-most panel presented as an example.

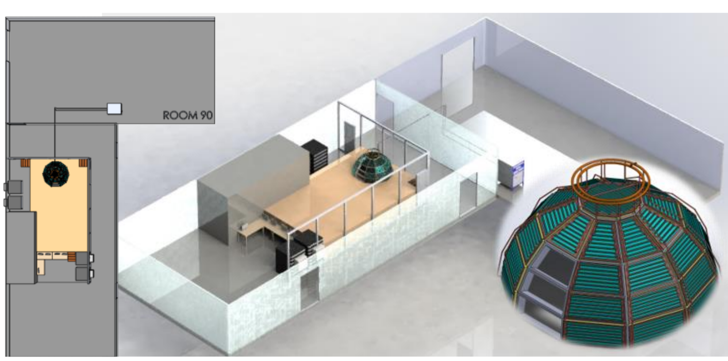

Figure 6. Layout of the full-dome experimental setup with distribution pipelines.

PROTOTYPE EXPERIMENT SETUP

To finalize the heat transfer panel design for production, a reduced-size experimental setup was contrived to validate the calculations and simulation results for a single heat transfer panel. Figure 7 shows the setup in both CAD drawing and real implementation. The experimental setup includes one heat transfer panel with single inlet and outlet pipe layout. It is connected to a chiller which circulates Syltherm XLT, silicone-based heat transfer fluid. A control valve with an actuator regulates the fluid flow, followed by a turbine flow meter which measures the volumetric flow rate of the fluid. To make fine adjustment to the fluid inlet temperature, a heating strip is attached to the pipe after the flowmeter. There is a total of 16 thermocouples installed for the test setup. Four of these thermocouples are used for fluid temperature measurements at the inlet and outlet of main supply channel and panel pipe channel. Rest of the thermocouples are used for capturing the surface temperature profile of the panel. The result of this prototype panel testing is to be analyzed to make a final decision on the material of the heat transfer plate, either copper or aluminum, to obtain valve characteristics at different chiller operating points along with pressure losses, and to map out the plate surface temperature distribution at various flow rates of the heat transfer fluid. In addition, a base design of the data acquisition and simulation platform which combines physical and virtual systems will be completed with this experimental setup.

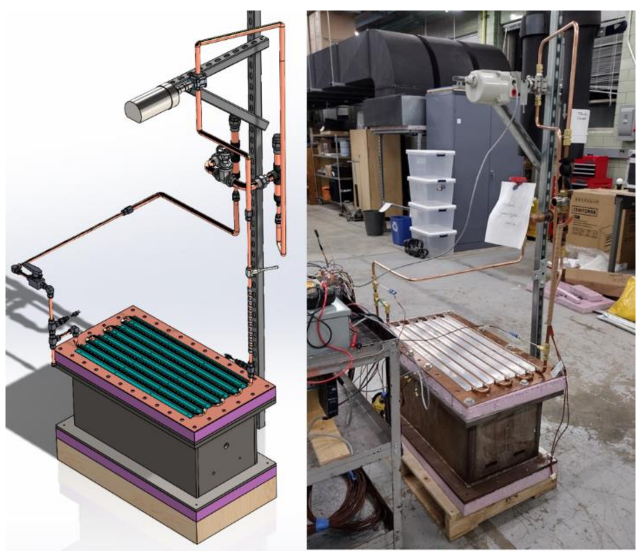

Figure 7. Single-panel testbed in CAD and real implementation.

Figure 8 illustrates the temperature profile of the panel at three different chiller output temperature, 10 °C, 0 °C, -10 °C, and -20 °C, respectively. Heat transfer fluid enters from the top right corner and exits to the bottom left corner. Temperature values at the center region is always lower than those of outer region and show variances which can be considered to be within measurement uncertainty of $\pm$5 °C. Outer region of the panel tends to have warmer temperature values, and the trend becomes more apparent as the chiller output temperature decreases. This is due to lack of sufficient insulation over the top surface of the panel and the exposed flange of the panel which is not in contact with the heat spreader. Summary of the thermal transfer panel characteristic is presented in Table 1, describing average surface temperature and range of temperature variation at given chiller outlet temperature values.

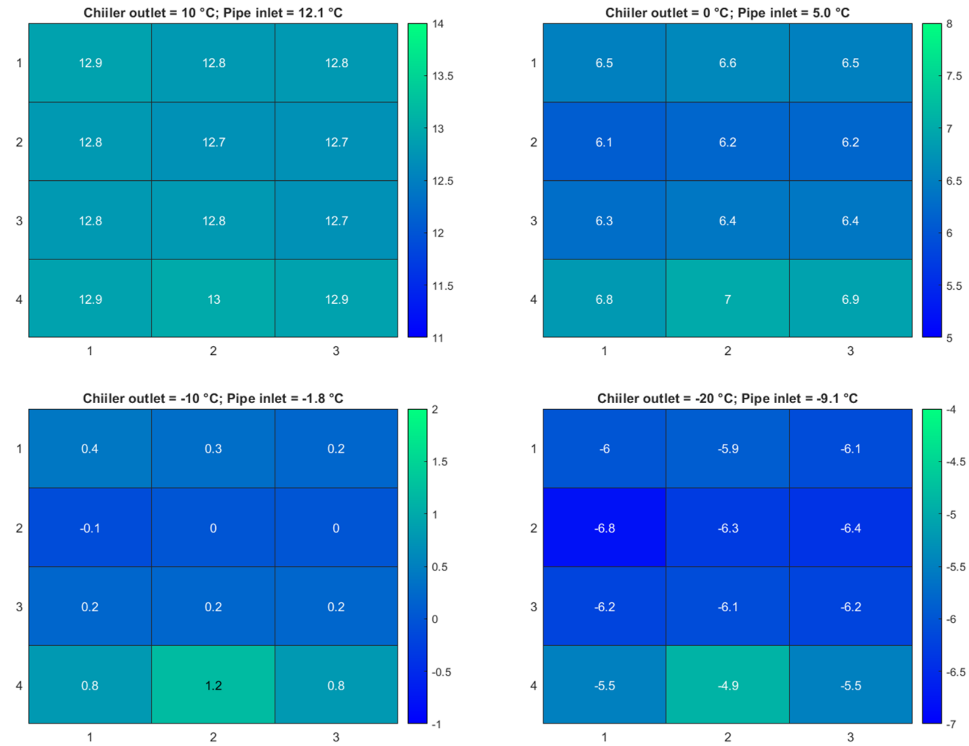

Figure 8. Surface temperature profile of heat transfer panel at 10 °C, 0 °C, -10 °C, and -20 °C chiller output temperature.

Table 1. Temperature Characteristics of Thermal Transfer Panel

Chiller Outlet Temperature	Average Panel Temperature	Temperature Variation
10 °C	12.82 °C	0.3 °C
0 °C	6.49 °C	0.9 °C
-10 °C	0.35 °C	1.3 °C
-20 °C	-6.00 °C	1.9 °C

Figure 9 summarizes the result of preliminary testing with temperature measurements at different inlet temperature for heat transfer fluid with respect to time. The chiller pump operation begins at around 20 °C for the heat transfer fluid at the start of the measurement. Temperature values start to drop as the chiller setpoint temperature is lowered. At around 600 s, fluid inlet temperature converges to -0.5 °C. It takes some more time for the average solid temperature to show convergence at 1.8 °C. The chiller setpoint is adjusted for two more times to decrease the inlet temperature further. Fluid temperature at the inlet converges to -16.4 °C and -32.4 °C respectively, and average surface temperature for the panel converges to -11.7 °C and -27.0 °C.

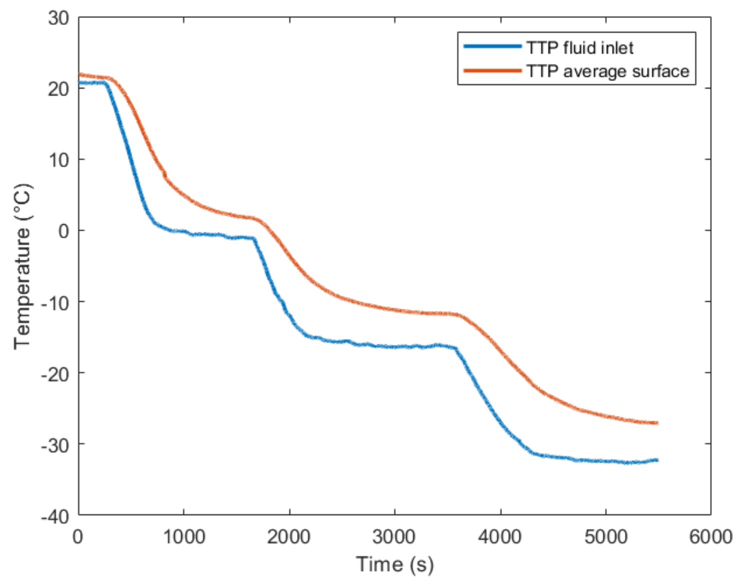

Figure 9. Average surface temperature and heat transfer fluid inlet temperature with respect to time.

VIRTUAL CYBER-PHYSICAL TESTBED (vCPT)

Parallel to the ongoing endeavor for developing a reliable thermal transfer system and physical substructures to be used in real-time hybrid simulation testing, the virtual cyber-physical testbed (vCPT) has been arranged as a realization of the cyber-physical testbed solely in a virtual form. The objective of vCPT is to virtually perform partitioning of cyber and physical subsystems based on the models developed in MCVT and to understand better the communication requirements necessary for future CPT and identifying potential limitations or complications involved in the hybrid testing. With further improvements made on current MCVT models, vCPT is also expected to serve as a reference system to the actual CPT.

The general structure of vCPT follows that of actual CPT. With the same constituents for each subsystem as the CPT, vCPT is executed by two physical machines. Models representing cyber subsystems are loaded to one machine, and the other models describing physical subsystems are allocated to the other machine as illustrated in Figure 10. Here, the cyber subsystem models are the same models planned to be used for the actual CPT. In the actual CPT, the physical subsystem models are to be replaced by the real physical systems. In the P-machine, which contains the physical subsystem models, transfer system models and sensor models are added to virtually simulate the dynamic behaviors of these physical components which will be implemented in the actual CPT.

At the current stage, vCPT does not yet have accurate models for transfer systems and sensors. However, in the light of the development of vCPT to this date, a detailed identification of inputs and outputs between cyber and physical subsystem has been conducted. A proper communication protocol between physical separated computational platform has been established. MCVT models are tailored specially to support the partitioning and inclusion of sensors and transfer systems. Preliminary vCPT simulation results confirmed that the physics-based models could be computed at the sampling frequency appropriate for the planned real-time hybrid testing on hardware prepared by RETHi without significant accuracy loss.

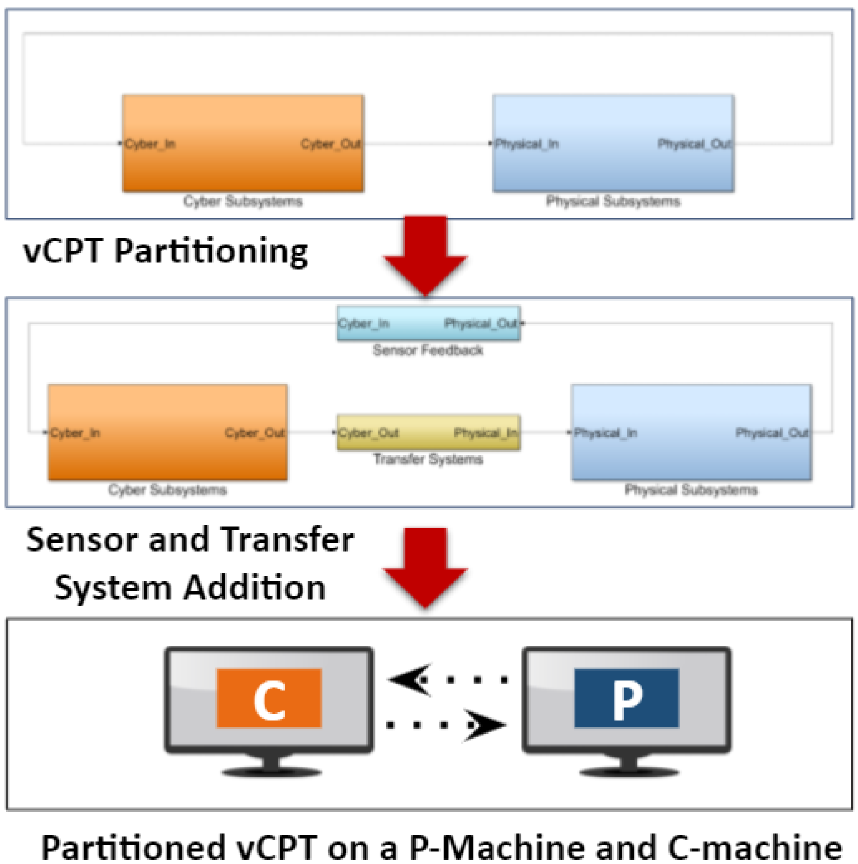

Figure 10. Virtual partitioning of cyber and physical systems based on MCVT models.

CONCLUSIONS AND FUTURE WORK

The development progress on cyber-physical testbed for resilient extra-terrestrial habitats at RETHi was presented in this paper. Subsystem structure and partitioning of MCVT, as a cyber computational system, was discussed. Construction of physical thermal transfer system which serves as a bridge between cyber and physical subsystems was described in detail. Virtual realization of the cyber-physical testbed, vCPT was also introduced. The methods demonstrated here aims to adapt the techniques conventionally used for structural mechanical systems to be compatible with thermal systems. Before moving on to commissioning the full-sized dome, a reduced-order test is scheduled to be performed with single thermal transfer panel attached to an outer surface of pressurized metal box, representing the habitat system in a lumped form. Dynamic analysis of thermal transfer panel will be conducted to design appropriate controllers and compensation schemes.

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