Status of the EDEN ISS Rack-like food production unit after five months in Antarctica

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Plant cultivation in large-scale closed environments is challenging and several key technologies necessary for space-based plant production are not yet space-qualified or remain in early stages of development. The Horizon2020 EDEN ISS project aims at development and demonstration of higher plant cultivation technologies, suitable for near term deployment on the International Space Station (ISS) and from a long-term perspective, within Moon and Mars habitats. The EDEN ISS consortium, as part of the performed activities, has designed and built a plant cultivation system to have form, fit and function of an European Drawer Rack 2 (EDR II) payload, with a modularity that would allow its incremental installation in the ISS homonymous rack, occupying from one-quarter rack to the full system. The developed system has been completed and tested in a laboratory environment in early 2017. The system was then integrated and tested at DLR Bremen into the main transport container (MTF). In the last 5 months the system was operated also in the highly-isolated German Antarctic Neumayer Station III, in the container-sized test facility to provide realistic mass flow relationships and interaction with a crewed environment. This paper describes the key results of the Bremen test phase as well as initial ISPR plant growth facility tests in Antarctica as space-analogue environment.

Nomenclature

DLR	=	*German Aerospace Center*
EDR	=	*European Drawer Rack*
EI	=	*Experimental Insert*
FEG	=	*Future Exploration Greenhouse*
GCS	=	*Growth Chamber Short (plants)*
GCT	=	*Growth Chamber Tall (plants)*
ISPR	=	*International Standard Payload Rack*
ISS	=	*International Space Station*
MTF	=	*Mobile Transport Facility*
RUCOLA	=	*Rack-like Unit for Consistent on-orbit Leafy crops Availability*
TAS	=	*Thales Alenia Space*
TEC	=	*Thermoelectric Cooler*

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I. Introduction

Crops production in space is a key capability for a sustainable human presence beyond Low Earth Orbit. In addition to the obvious food production function, the use of higher plants-based systems provides multiple additional benefits, such as contribute to air revitalization and water processing, as well as carrying the potential of providing psychological benefit to the crew. The goal of the EDEN ISS Horizon2020 project is to advance controlled environment agriculture technologies beyond the state-of-the-art through demonstration in laboratory and space-analog environment. The main task of Thales Alenia Space (TAS) Italia within the consortium led by the DLR Institute of Space Systems in Bremen was to develop a rack-like facility targeting at short-term safe food production and operation in microgravity, starting from a demonstration phase on-board the International Space Station (ISS), to be followed by more extensive testing in future orbiting habitats (e.g. the Deep Space Gateway, the Chinese space station, a commercial LEO space station). The system was conceived as the next step to past and currently on-orbit operated systems (e.g. NASA Veggie[3]) as extensively analyzed in a previous ICES paper[2]. It was developed as a potential payload for the European Drawer Rack MKII (EDR MKII). EDR MKII will be flown to the ISS in 2018 and will provide interfaces for multiple experimental inserts (EIs). The facility, formerly called EDEN ISS ISPR[4], is now referred as RUCOLA (Rack-like Unit for Consistent on-orbit Leafy crops Availability). RUCOLA has been developed and tested in the TAS Recyclab technological area in Turin. It was then shipped to Bremen for integration in a container-sized greenhouse Mobile Test Facility (MTF) for integrated testing and subsequent shipment in later 2017 to the German Neumayer III station in Antarctica. The station is operated by the Alfred Wegener Institute and has unique capabilities and infrastructure that allowed testing plant cultivation under extreme environmental and logistical conditions. The container-sized system hosts also a much bigger greenhouse facility[1], the FEG (Future Exploration Greenhouse), built under the responsibility of the other EDEN ISS project partners with DLR coordination, which will provide year-round fresh food supplementation for the Neumayer Station III crew.

The EDEN ISS project work plan and status, as well as the MTF preliminary design are described section by section in great detail in Bamsey et all. 2016[1]. The cited paper includes a description of the logistics and operations of the facility, as well as an illustration of the preliminary system budgets. The EDEN ISS RUCOLA “as designed” status is described in detail in Boscheri et all. 2016[4]. Related laboratory test campaign is described in Boscheri et all. 2017[5].

This paper quickly recalls the MTF configuration, focusing then on the developed RUCOLA system, describing the key results of the Bremen test phase as well as initial plant growth facility tests in Antarctica as space-analogue environment. Since the agronomical test will be completed at the end of 2018 and results with a sufficient statistical base will not be available before then, this paper will focus on the initial set of lessons learnt after 5 months of Antarctica operations.

II. Mobile Test Facility General Overview

The EDEN ISS MTF was designed to provide fresh produce for overwintering crews at the Neumayer III Antarctic station, as well as to advance the readiness of a number of plant growth technologies (including the RUCOLA plant cultivation system microgravity demonstrator) and operational procedures. The MTF, consisting of two 20 foot high cube containers, was assembled on top of an external platform at the end of 2017 approximately 200 m south from the Neumayer Station III Antarctic research station, see Figure 1.

Figure 1. The Neumayer III station (left), and the EDEN ISS MTF (right)

The MTF is subdivided into three distinct sections, as shown in Figure 2:

- Cold porch: a small room providing storage and acting as a buffer to prevent the entry of cold air into the plant cultivation and main working areas when the main entrance door of the facility is utilized.
- Service Section: houses the primary control, air management, thermal control, and nutrient delivery systems of the MTF as well as the RUCOLA plant growth demonstrator.
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, consisting of multilevel plant growth racks operating in a precisely controlled environment.

Figure 2. Overview of the EDEN ISS MTF main elements.

Most of the subsystems are housed in a rack system along the South-facing side of the Service Section. It was decided to place the RUCOLA system as close to the cold porch as possible, since there are no interfaces between the rack and the FEG, as opposed to the other subsystems which do interface with the FEG.

III. RUCOLA Cultivation System Overview

The main objective of the laboratory and Antarctica RUCOLA system demonstration is to advance the TRL of the plant growth facility technologies, as well as to identify necessary design and operational procedures updates in view of a near term experiment on the ISS. The laboratory test campaign was aimed at reaching TRL 4, starting from TRL 2-3 of the multiple technologies involved in the project. The analog test site test campaign is aimed at achieving TRL 5 for technologies not sensitive to microgravity, for which Antarctica represents a "relevant environment" (mainly microbial contamination control technologies). The facility was designed to represent an increment with respect to current flight capabilities represented by the NASA Veggie system, mainly in terms of:

- Higher available growth surface (0.5-1,0 m^2 range)
- Longer production cycle possible by complete nutrient solution circulation (and not only watering of substrate with slow release fertilization)
- Robust and reliable safe and high quality food production (while Veggie control capability may be considered limited)
- Taller crop can be accommodated (up to 60 cm available for tall growth chamber shoot zone)

Figure 3 is an image of the EDEN ISS RUCOLA system as integrated in the MTF together with a description of its main building blocks. It is designed as precursor of ISS European Drawer Rack EDR II plant growth payload. The lower section of the rack is dedicated to the interfaces (power, data and cooling water) with the Mobile Test Facility, mimicking the EDR II functions. Above this section are placed the interfaces between the rack and the plant growth facility, exactly as for EDR II EIs interface panels. In the central portion of the system, the following payload drawers are accommodated:

- Power, Command and Data Handling Module
- Nutrient Storage and Distribution Module
- Growth chamber Modules (1 for short plants, 1 for taller plants), including each chamber dedicated air management systems, root modules and crop shoot-zone volumes
- Illumination Modules (one for each growth chamber)

In the top portion of the rack, a panel for manual monitoring and control via a LabVIEW based interactive graphical user interface of the rack's functional parameters is present, together with a storage volume.

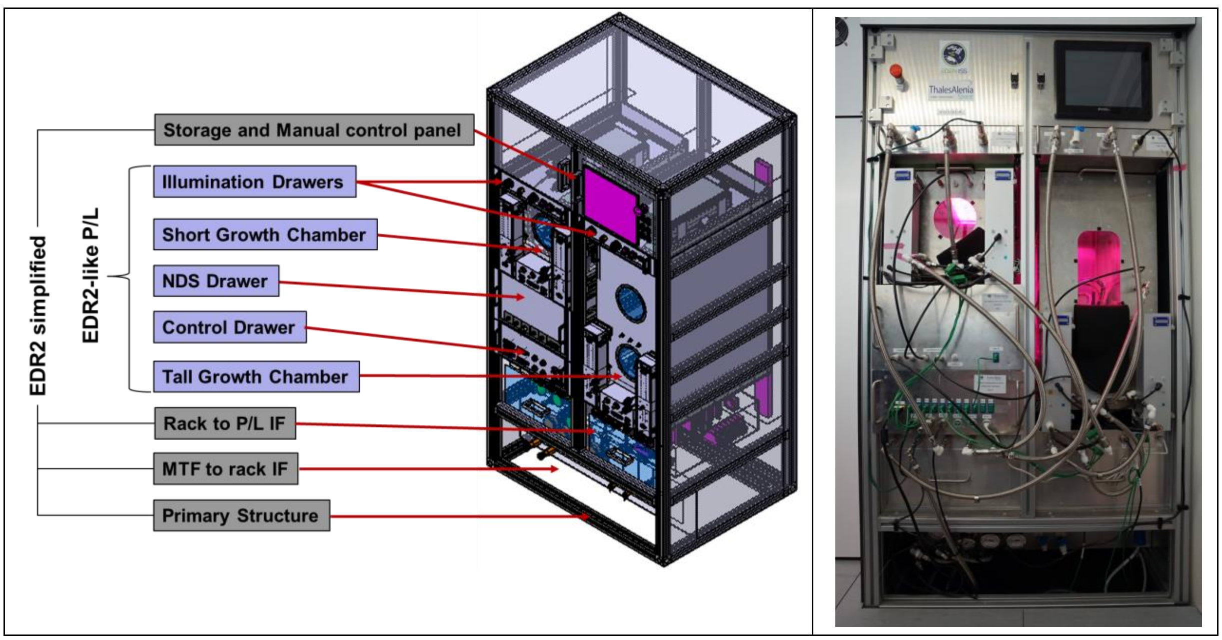

Figure 3. The EDEN ISS RUCOLA cultivation system 3D image (left) and Antarctica installed HW (right).

A. Air Management Subsystem

Each of the 2 plant growth volumes has an independent temperature and humidity control subsystem. Identical components have been used for both the tall growth chamber (GCT, 192L volume) and short growth chamber (GCS, 84L volume), despite the different volumes. The air extracted from the shoot-zone volume is cooled by a thermo-electric cooler (TEC, using Peltier effect) to remove sensible heat loads as well as latent heat loads through condensation of water vapor. The water vapor is then collected by gravity in a custom designed recipient, and then pumped through a 0.2µm filter to the DI water reservoir within the Nutrient Storage Module. The TEC is an air to water heat exchanger, and the heat collected at the water side is removed by a cooling water loop connected to a chiller external to the rack, designed to provide similar performance to the EDR II rack cooling provision (up to 180 L/h of water at 16-20°C). Each Growth chamber has two fully redundant temperature and humidity control easily replaceable units, nominally operating in parallel at about 50% of their maximum capabilities. Each of those is capable of sustaining the basic atmosphere control functions alone, in order to cope with the special logistics conditions of the Antarctica operating framework. There is indeed the possibility to not be able to access the MTF for multiple days in case of heavy storm, so a failure of the one element of the cooling HW (e.g. fan, TEC, etc.) would not be catastrophical for the crop growth.

The same logic is applied to the airborne contaminants control system, placed in series to each of the above mentioned air management lines, and consisting into a particulate filter, a 0.2µm HEPA filter including active charcoal in the mesh, followed by an additional filter for low molecular weight organics (like ethylene).

The overall air management subsystem block diagram is reported in Figure in a conceptual form.

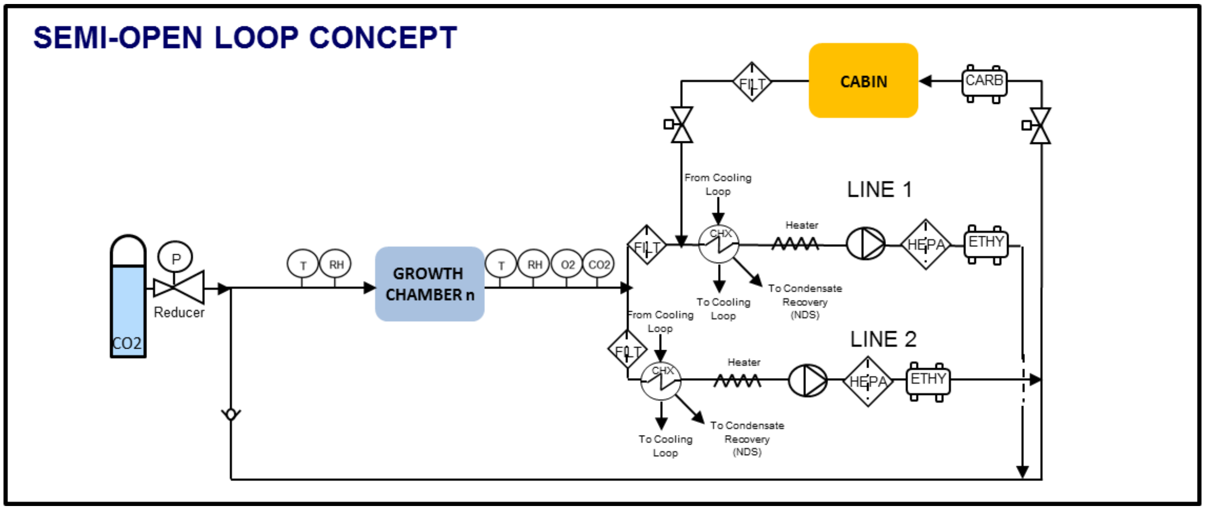

Figure 4. Overall air management system conceptual block diagram

The major performance of the built system as verified prior to deployment in Antarctica are reported in Table 1 for both the tall (GCT) and short (GCS) growth chambers. The testing phase in detailed in a previous ICES paper[5].

Table 1. Air management subsystem main performance (prior to deployment in Antarctica)

Performance Type	GCS	GCT
Temp. control range (sensible heat load <40W latent heat load <25W)	15-30°C ± 1.9°C	15-30°C ± 2.4°C
Humidity control range (sensible heat load <40W latent heat load <25W)	60-80% ± 6% (only de-humidification)	60-80% ± 7% (only de-humidification)
Growth chamber air volume average exchange rate	1.12 exchange/minute	0.41 exchange/minute
Microbial load at air inlet within growth chamber	0 CFU/m^3	0 CFU/m^3
Ethylene gas concentration at canopy closure (within growth chamber)	<50 ppb (LOD)	<50 ppb (LOD)

B. Nutrient Delivery Subsystem

The Nutrient Delivery System (NDS)[5] contains the reservoirs (stock solutions, acid/base, DI water, and nutrient solution), the delivery pumps, the nutrient solution quality monitoring sensors, and the condensate recovery system. DI water is used also in case of salt accumulation within the root module (EC increment within the substrate or porous elements cleaning to prevent clogging). The DI water pH is monitored and controlled by acid/base injection. The nutrient solution EC and pH are monitored and controlled by water or stock solution (from dedicated reservoirs) injection. Injection is allowed by LabVIEW® controlled piston pumps. Concentrated solution tanks are flexible, replaceable (self-locking QD), stored dry and filled with water only before use. Both the Main Nutrient Tank and the DI Water Tank are relying on a polymeric bellows technology, capable of allowing long term chemical and microbiological stability of the contained solutions and of operating also in microgravity conditions. Either DI water or nutrient solution can be delivered to the root modules. The NDS block diagram is reported in Figure 5.

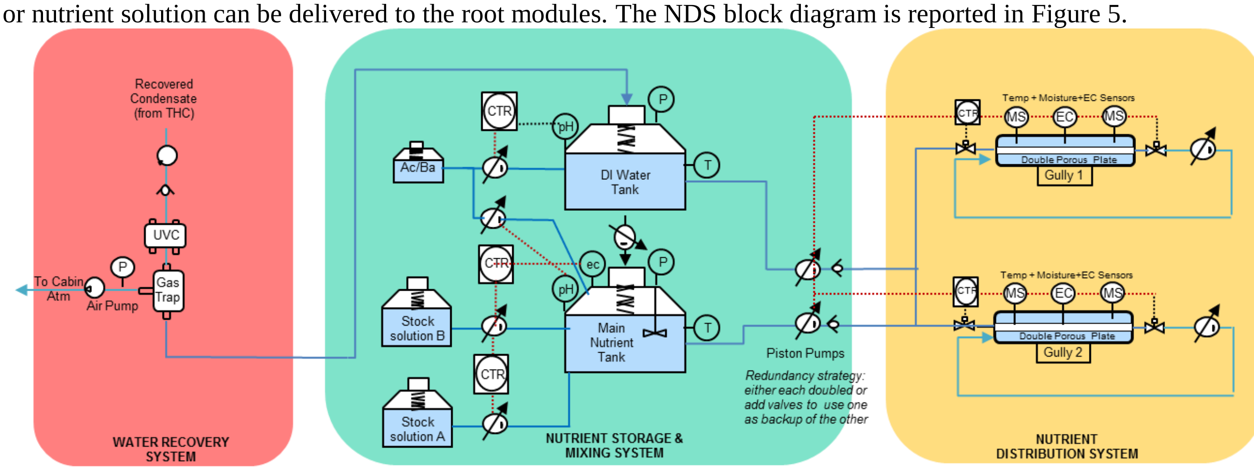

Figure 5. Nutrient Delivery System Conceptual Block Diagram

The main performances of the nutrient delivery subsystem components are summarized in Table 2. The testing phase in detailed in a previous ICES paper[5].

Table 2. Nutrient Delivery Subsystem Performance Testing Results

Component/ Performance Type	Value
Deliverable water volume	7.05 L
Maximum allowed water ullage	0.13 L
Maximum Design Pressure (MDP)	1 barg
Operative Pressure Range	-0.1 to 0.1 barg
Reservoir water volume measurement range	0.2 to 7 L
Reservoir water volume measurement accuracy	12.5 ml
Flow rate at 0.7 barg	10 ml/min
Continuous operative time	Up to 1 min
Deliverable water volume	>1.2L
Maximum allowed water ullage	4ml
MDP	Ok at 0.5barg
Deliverable water volume	>0.6L
Maximum allowed water ullage	4ml
First Containment MDP	0.35 barg
Second Containment MDP	0.35 barg

IV. Lessons learnt from the first 5 months of operations in Antarctica

The RUCOLA system was deployed in Antarctica within the Mobile Test Facility at the beginning of January 2018. The first month of activities was dedicated to integration and check out of the system, including a first plant growth trial with the key objective of testing procedures in situ and identifying site-dependent patterns of concern for the subsequent plant growth test phase. Multiple team members were on site in support to these activities. The main objectives of this phase are summarized as follows.

- Verification of HW functionality after shipment and re-assembly (the complete shipment mechanical environment, e.g. including transportation was not available and thus not easily assessed at design level)
- Verification of HW functionality in the Antarctica MTF installation configuration thermal environment (the external environment impacts also the boundary conditions between RUCOLA and the MTF)
- Operational procedures validation (the in-situ logistics was expected to have an impact on the procedure written after an experience in laboratory environment)
- Completion of training of the crew in situ (only one operator from DLR was trained to use the system, but other base crew members can provide support on a voluntary basis and need to be trained)
- Testing of remote connection and teleoperations from the Thales Alenia Space control center in Torino (Italy)

The second phase of the test campaign included the beginning of the first agronomical tests set in the two growth chambers, after seeding of Rucola (cultivated) in the GCS and of Dwarf Tomato in the GCT. In this second phase only the greenhouse operator from DLR was on site, while the rest of the team provided remote support. Since at this stage of the project no statistically representative results of the agronomical tests are yet available, the following list of lessons learnt will focus on logistics and operational matters.

Based on the previous considerations, the main lessons learnt from the initial phases of the Antarctica test campaign are discussed as follows.

A. Water Balance and related logistics

The nutrient storage system contains at test start about 15L of water divided among the DI water reservoir (≈7L), the Diluted Nutrient Solution reservoir (≈7L) and the concentrated nutrient solution reservoirs (≈1L). The following average behavior was expected after system laboratory testing:

- Initial priming of the system with about 2L
- water delivery to each growth chamber of about 0.75 L/day (≈3L/m^2-day)
- evaporation rate above 92% (about 1.38 L/day)
- leak rate of 1.6 chamber volumes/day for GCS and 2.9 chamber volumes/day for GCT, corresponding to a minimal water loss from the system as water vapor calculated (based on temperature and relative humidity both of growth chambers and outer environment, as well as chambers volume) as about 2 g/day for GCS and 7g/day for GCT
- condensate recovery efficiency above 81%

Based on these values, the reservoirs were expect to be fully depleted within about 33 days, allowing a full growth cycle at least for the GCS, where leafy crops like Rucola and Outrageous Lettuce are planned for seeding. Warning threshold for replenishment was set at less than 4 L in the system, expected later than 23 days from test start.

The Antarctica preliminary test phase highlighted a much different behavior, leading to more premature depletion of the reservoirs, reaching warning threshold in less than 2 weeks. The reasons for this lower performance with respect to maintaining the foreseen behavior were identified in the following root causes:

- Loss of priming of the condensate recovery line during transport caused gas accumulation in the downstream CFU filter, thus leading to much lower performance of the condensate recovery pump. This caused an overfilling of the condensate recovery reservoir which resulted into condensate finding a way to bypass it and exit the system (exploiting also damages to the sealing material during the transportation phase), with considerable loss of condensate recovery efficiency. With a manual intervention on the CFU filter degassing port priming was restored, and sealing material was replaced in order to restore the nominal condensate recovery functions;

- Leak rate was higher than during the laboratory test phase, probably for some small displacement of seals generated during the transport phase. The new leak rate was evaluated as about of 5.8 chamber volumes/day for GCS and 11.1 chamber volumes/day for GCT. A re-evaluation of the design of the air loop seal grooves need to be performed, as well as the possibility to identify transportation support means.
- External environment relative humidity (always below 50%) was lower than what experienced during the laboratory test campaign (always above 60%), due both to the Antarctica outer environmental conditions as well as well as improvement of sealing between the MTF service section and the FEG. This enhanced the water loss via air leakage.

The water balance lower performance allowed also identification on another operational/logistics issue of a certain interest. Since water depletion happened much earlier than expected, the preparation of the water for refilling purposes was not planned with enough margin to cope with the in situ meteorological conditions. Because of high winds, for a few days it was not possible to deliver water from the Neumayer III base to the MTF and it was not possible to perform the reservoir refilling, thus damaging the crop. In order to avoid further instances of this issue, the reservoirs warning water level was changed, monitoring of meteo conditions added into the procedures, and an extra water tank for backup purposes is now always to be stored within the MTF.

B. Temperature control system performance

The temperature and humidity control system was fully verified ahead of the Antarctica deployment phase with the RUCOLA rack in TAS Torino laboratory environment, with main results reported in the previous chapter of this paper. From the data available on the operative environment, that resulted as a worst case hot scenario, with lower temperature expected in the following phases. However, since no requirement on acoustics was placed, no verification on audible noise level was performed with the system operating installed in the MTF in fully operational conditions. Since the greenhouse Antarctica operator working station is just in front of the rack, it was clear soon after deployment that the fans audible noise was too high. There is no equipment in situ to measure sound intensity and frequency, so this measurement will be postponed to the next summer season. The resources available in situ also did not allow providing additional acoustics insulation. For this reason it was necessary to reduce sensibly the maximum fan speed during working hours. A lower allowed air circulation velocity resulted into a challenge for the temperature and humidity control functions, leading to a lower capability of managing sensible heat, since an increase in the thermoelectric cooler power resulted in higher condensation rates rather than reducing growth chambers temperature. In the winter season this will not be an issue, but in the initial test phase, with the sun shining 24 hours a day on the MTF, coupled with the snow albedo, as well as up to 5 persons present in the MTF in the same time, this required to reduce the greenhouse illumination level below nominal set point. For future development proper acoustics insulation will be implemented so to restore the nominal performance. Heritage on noise reduction actions already performed on ISS modules will be exploited for this task.

C. In situ operability

One of the key objectives of the initial Antarctica deployment phase was the verification of in situ RUCOLA operability based on available procedures. The main observations that already led to revision of procedures, as well as to future design changes are summarized as follows.

While in nominal operations the growth chambers volume is expected to be accessed by the crew only for a limited set of events (e.g. seeding, harvesting, detected malfunctions, etc.), in the initial deployment phase a much more frequent set of inspections of the root module and internal fluid distribution system was required. Since the access door is located on the lateral side of the chamber drawers, this operation required de-mating of fluidic and electrical connectors for drawer extraction (see figure 6). As a result, the maximum certified mating/de-mating cycles of the electrical connectors were largely surpassed. Although this did not result in any loss of performance, it triggered a revision of the design for future operations into a space environment.

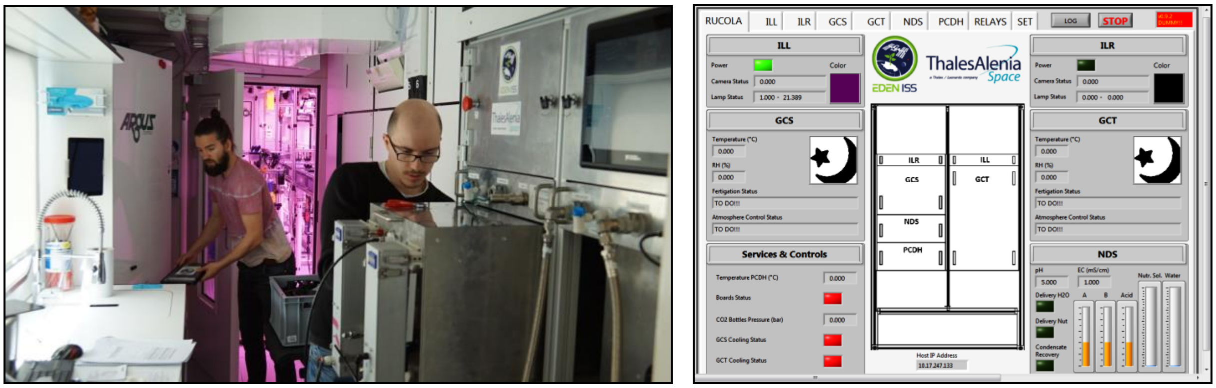

Figure 6. Working space in front of RUCOLA (left) and Graphical User Interface (right)

Another observation concerns ergonomics. While in laboratory environment luxury space was provided around the rack, in the MTF only 80cm of corridor depth are available in front of it. The reduced space resulted into the necessity to extract the experimental insert drawers from a lateral position rather than from the front (see Figure 6), leading to considerable difficulty for the crew of measuring the required pull force. In some extreme case this can lead to small injuries i.e. of the hands if hit by the male fluidic half quick disconnect tips. Procedures were updated highlighting the risk associated to this operation. Further design update shall study ergonomics in higher detail.

Another required change concerns the reservoirs filling procedure. The operation was initially planned to be performed manually by the crew, with a manual pump. However, the MTF working space does not allow the user to operate into a comfortable position, and the operation resulted as hostile to the crew wellbeing in such a confined environment. For this reason, an automatic filling procedure was implemented exploiting the capabilities provided by the LabVIEW-based Graphical User Interface and the condensate recovery line, already including line autonomous degassing capabilities. This change required this operation to be performed during night time only, when the production of water vapor is really low.

D. Information available to the in-situ crew

A touch screen is placed in the top right section of the rack, reporting all the system information into an interactive Graphical User Interface (GUI), see Figure 6. The GUI includes a main tab with the key parameters of each subsystem, a page dedicated to each subsystem, as well as another section for errors and warnings management. Errors and warnings are displayed in the main tab and are highlighted with blinking graphics. They are also communicated via e-mail in real time to the Remote Control Team. The list of reported errors and warnings included initially both malfunctions requiring user action as well as those not requiring any support (e.g. pump over-temperature signals that delayed water delivery to the root zone). This led to a not useful saturation of the displayed error list, with the risk of not providing prompt support to the more critical items. An error display logic change was then implemented, so to allow the in situ user to visualize only action generating alarms.

V. Summary and Next Steps

This paper summarizes the status of the RUCOLA crop growth facility currently installed and operating in Antarctica Neumayer III base. Performance results of the pre-deployment test campaign are presented for the air management system, as well as for the nutrient storage and delivery system. Lessons learnt from the first 5 months of operations within the Antarctica Mobile test Facility are discussed, addressing a set of required design and operational procedures updates. Lessons learnt include a higher understanding of the interaction of the water balance and related logistics with the selected analog test site, characterized by a really low relative humidity and extremely variable temperatures also in Antarctica summer time. Temperature control system functional profile was adjusted based on operational experience with a permanent greenhouse operator in order to mitigate any audible noise uncomfortable situation. Information available to the in-situ crew was also reviewed and adjusted, in order to optimize response time in case of warnings and malfunctions.

The Antarctica agronomical test campaign is scheduled for completion in December 2018 and it will make available a first set of crop growth performance data in a relevant environment.

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