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Lunar Habitat Wastewater Subsystem Power and Water Management

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***Abstract*—The water management in a lunar base includes interaction between the In-Situ Resource Utilization (ISRU), crew habitat, and wastewater subsystems. The ISRU produces water from the lunar regolith, while the wastewater subsystem provides fresh water after filtering wastewater generated from the crew habitat. A model for lunar base water filtration and management for autonomous control is yet to be developed. This paper describes a model to manage the water considering the interaction between different water and wastewater tanks in the lunar base. A methodology to generate crew members' water consumption and wastewater generation profiles is also discussed. The model considers the power demand of the wastewater subsystem. It is observed that the power demand of the wastewater subsystem depends on the power availability and the desired level of different water and wastewater tanks. It is concluded that to design an autonomous energy management system, the controller should be able to generate time-varying references for different water tanks and take into account the available power.**

***Index Terms*—Space microgrids, lunar base, energy management system, water management, Shackleton crater.**

LIST OF SYMBOLS

C_{FW}	Fresh H_2O collected amount (kg)
C_{UF}	Urine flush H_2O collected amount for filtration (kg)
C_{WRS}	Water recovery system freshwater collected amount (kg)
C_{WW}	Waste H_2O collected amount for filtration (kg)
CM	Total number of crew members
P_W^{avail}	Available power for the waste H_2O subsystem (W)
T_H	Optimization horizon (in h)
T_{FW}	Fresh H_2O tank (kg)
T_{FW}^{err}	Difference between T_{FW}^{ref} and T_{FW} (kg)
T_{FW}^{max}	Fresh H_2O tank maximum level (kg)
T_{FW}^{min}	Fresh H_2O tank minimum level (kg)
T_{FW}^{ref}	Fresh H_2O tank reference (kg)
$T_{hab_{H_2O}}$	Habitat H_2O tank (kg)
$T_{hab_{H_2O}}^{max}$	Habitat H_2O tank maximum (kg)
$T_{hab_{H_2O}}^{ref}$	Habitat H_2O tank reference (kg)
$T_{ISRU_{H_2O}}$	ISRU H_2O tank (kg)
$T_{ISRU_{H_2O}}^{min}$	ISRU H_2O tank minimum (kg)
$T_{ISRU_{H_2O}}^{ref}$	ISRU H_2O tank reference (kg)
T_{UF}	Urine flush H_2O tank (kg)
T_{UF}^{err}	Difference between T_{UF}^{ref} and T_{UF} (kg)
T_{UF}^{max}	Urine flush H_2O tank maximum (kg)
T_{UF}^{min}	Urine flush H_2O tank minimum (kg)
T_{UF}^{ref}	Urine flush H_2O tank reference (kg)
T_{WRS}^{ph}	Water recovery system wastewater processing capability (kg/h)
T_{WW}	Waste H_2O tank (kg)
T_{WW}^{err}	Difference between T_{WW}^{ref} and T_{WW} (kg)
T_{WW}^{max}	Waste H_2O tank maximum (kg)
T_{WW}^{min}	Waste H_2O tank minimum (kg)
T_{WW}^{ref}	Waste H_2O tank reference (kg)
$TOT_{H_2O_{out}}$	Total rate of H_2O transfer from ISRU H_2O tank to habitat H_2O tank (kg/h)
V_{ir}	Ilmenite intake per hour
$W_{FW_{out}}$	Rate of H_2O transfer from fresh H_2O tank to habitat H_2O tank (kg/h)
$W_{FW_{out}}^{max}$	Maximum rate of H_2O transfer from fresh H_2O tank to habitat H_2O tank (kg/h)
$W_{ISRU_{H_2O_{out}}}$	Rate of H_2O transfer from ISRU H_2O tank to habitat H_2O tank (kg/h)
$W_{ISRU_{H_2O_{out}}}^{max}$	Maximum rate of H_2O transfer from ISRU H_2O tank to habitat H_2O tank (kg/h)

I. INTRODUCTION

National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), China National Space Administration (CNSA), SpaceX [1], and several other space organisations [2] are looking forward to establishing a human base on the lunar surface starting from 2024 [3]–[5]. A lunar base consists of several electrical power-consuming units such as crew habitat, laboratories, environment control and life support systems (ECLSSs), and electric rovers, among others. Therefore, a complete electrical power system (EPS) consisting of power generation and energy storage systems (ESSs) is required that can be called a ***space microgrid (MG) on the Moon*** [6]. The in-situ resource utilisation (ISRU) produces water for the crew habitat using the lunar regolith. Maintaining an adequate amount of water for the crew members for the entire space mission is one of the vital goals of control and operation management. The ECLSS manages the water availability for the crew members, among other tasks. For the low Earth orbit

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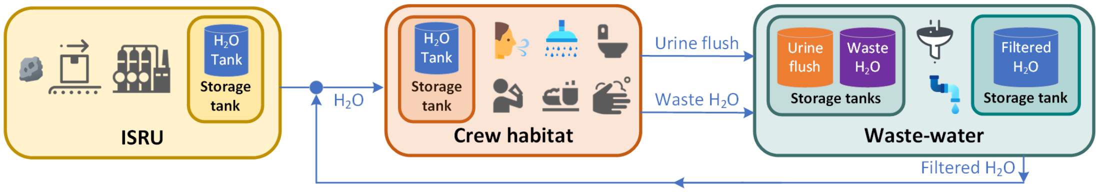

Fig. 1: Block diagram of the interacting subsystems for maintaining the water flow in the lunar base

TABLE I: Power demand of different power-consuming units for a lunar habitat with 6 crew members

Power-consuming unit (subsystems)	Power demand (kW)
Air	5.85
Biomass	6.10
Food	4.27
Water	1.29
Waste	0.01
Thermal	1.03
Extra-vehicular activity support	2.5
ISRU	10 to 100

space missions in the present days, the control and operation commands are communicated from ground stations [7], [8] as it allows almost instantaneous communication due to the short distance. However, The round trip communication delay can be approximately 10 sec in the case of lunar missions [9], and the delay can increase further if the commands are required to relay via orbiters. Therefore, an autonomous control system is vital for space MGs on the Moon.

The autonomous power control (APC) system is responsible for coordinating the operation, planning, and scheduling of several power-consuming units listed in Table I [7], [10]. Maintaining the power balance in a lunar base is a crucial task for ensuring the reliability of space MGs. Commonly, the power required by the power-consuming units is assumed to be constant, and only the average or peak power demand of the unit during its operation period is considered [10], [11]. However, the actual power demand is determined by the operation mode of the units. Due to the resource scarcity on the Moon, filtration and recycling are common practices to supply the crew habitat. The power consumption of the waste water subsystem depends on the rate of the waste water filtration process. Therefore, an effective APC system should schedule the operation of power-consuming units and coordinate their interactions, taking into account the power availability [12], space mission goals, and safe operating limits. To design such an APC, a model for waste water subsystem is needed for water filtration, recycling, and management considering the available power. To the best of our knowledge, such a model has not been reported in the literature.

In this paper, a closed-loop model for recycling water in a lunar base is discussed considering ISRU, crew habitat, and waste water subsystems. The methodology to generate the water consumption and waste water generation profiles of the crew members in the habitat and modeling waste water filtration are proposed. The desired reference levels of different fresh and waste water tanks are considered in the proposed methodology. An algorithm is proposed to transfer fresh water from the ISRU and filtered water from the waste water subsystem to the fresh water tank of the crew habitat considering the maximum safe water transfer rate. In the case of limited electrical power, the amount of available power for the waste water subsystem for water filtration is considered by the algorithm.

The rest of the paper is organized as follows. The complete diagram of the interacting parts for maintaining the water flow and different subsystems associated with the water recycling in the lunar base is described in Section II. Besides, the methodology to generate the water consumption profile in the crew habitat and different algorithms to maintain the tanks' references are explained. The waste water subsystem operation, power consumption, and reference tracking are presented in Section III. Finally, concluding remarks are discussed in Section IV.

II. LUNAR BASE CLOSED LOOP MODEL

The water management system in the lunar base involves three power-consuming units, which are the ISRU, crew habitat, and waste water subsystem, as shown in Fig. 1. It is assumed that the crew habitat receives fresh water from two sources, one is the water produced from the ISRU using the lunar regolith and another from the waste water subsystem. The fresh water is utilized by the crew for drinking, food rehydration, urine flush, and personal hygiene, among others. The waste water produced in the crew habitat is filtered and recycled for use in the crew habitat in the waste water subsystem. The power required by the waste water subsystem depends on the urine flush and waste water production rate and desired reference of storage tanks. Depending on the available power, the required power is supplied to the waste water subsystem. The following subsections present the water production, utilization, and filtration in the ISRU, crew habitat, and waste water subsystem models.

A. ISRU

To produce water in the ISRU, the lunar regolith is scooped and transported to the vibrating screen that does filtration to achieve the appropriate particle size. Then, particles are magnetically separated and transferred to the reactor. The process of scooping, transporting, filtering, and transferring consumes electrical power [10]. The reactor requires thermal power to perform catalyzed hydrogen reduction reactions and produce water [10]. Although solar radiations on the Moon can

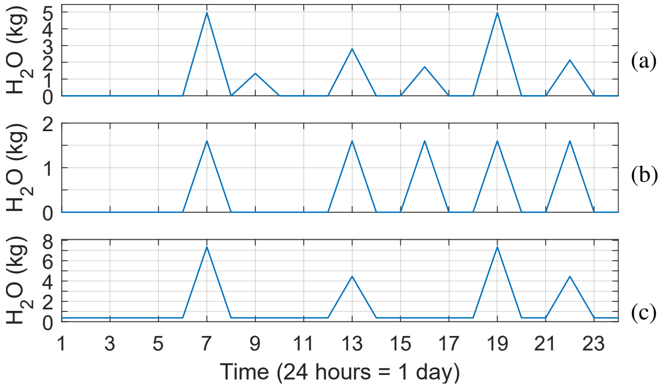

Fig. 2: Daily (a) water consumption, (b) urine waste water generation, and (c) waste water generation profiles for 4 crew members

TABLE II: Water consumption for different activities of one crew member

Activity	Water consumption (kg/day)
Drinking (DW)	2.00
Food rehydration (FR)	0.50
Urinal flush (UF)	0.50
Personal hygiene (PH)	0.40
Shower (SH)	1.08

TABLE III: Daily schedule of the crew members to generate the water consumption profile

Time of day (h)	Activity
00:01 - 06:00	None
06:01 - 07:00	DW + PH + UF + FR + SH or DW + PH + UF + FR
07:01 - 08:00	None
08:01 - 09:00	DW
09:01 - 12:00	None
12:01 - 13:00	DW + PH + UF + FR
13:01 - 15:00	None
15:01 - 16:00	DW + UF
16:01 - 18:00	None
18:01 - 19:00	DW + PH + UF + FR or DW + PH + UF + FR + SH
19:01 - 21:00	None
21:01 - 22:00	DW+PH+UF
22:01 - 00:00	None

TABLE IV: Waste water generated in the habitat by one crew member

Activity	Waste water generation (kg/day)
Urine	1.50
Urine flush	0.50
Total urine waste water	2.00
Oral hygiene	0.37
Hand wash	4.08
Shower	1.08
Crew latent humidity condensate	2.27
Total latent & hygiene waste water	7.80

be concentrated and directed using optical wave guides [13] to supply the required thermal power, electrical heaters can also be used [10]. The power consumption of the ISRU depends on the rate of ilmenite intake (V_{ir})that varies from 0 to 1 [10].

B. Crew habitat

Water is crucial for the survival of the crew and is utilized throughout the day for several activities. The amount of water required for different activities is listed in Table II [14]. These activities are scheduled for each day, as shown in Table III, to create the hourly water consumption profile of the crew members during the space mission. In this paper, 4 crew members are considered to be present in the lunar base for 708 h, which is equal to one lunar month. Fig. 2a shows the daily water consumption profile of all the 4 crew members in the habitat that is assumed to be the same over the mission duration.

C. Waste-water

The amount of waste water generated in the crew habitat due to different activities is listed in Table IV [14]. The daily urine waste water and waste water generation profile of 4 crew members in the habitat according to the schedule mentioned in Table III is shown in Fig. 2b and Fig. 2c, respectively, and is repeated to extend it for the complete mission duration. The waste water can be discarded by designing a suitable waste water disposal process on the Moon or transporting it back to the Earth, which considerably increases the cost of the space mission. Therefore, an alternative is to filter the waste water for further use in the crew habitat. At present, a novel alternative water processor (AWP) is under development to replace the state-of-the-art water recovery system in the International Space Station (ISS) [15]–[17]. The water recovery system in the ISS involves urine processor assembly (UPA) to purify urine flush and water processor assembly (WPA) to purify the distillate from the UPA, crew latent, and hygiene waste water as shown in Fig. 3 [18]. Currently, the UPA and WPA need 315 Wh/h and 320 Wh/h power in the operation mode, respectively, while 108 Wh/h power is required by other control modules (743 Wh/h in total). In the standby mode, the whole water recovery system needs 297 Wh/h [19]. It is assumed that the water recovery system can process 2.5 kg/h of waste water and approximately 81% of the waste water fed to the water recovery system can be recovered [19]. Algorithm 1 describes the process to filter fresh water from the urine flush and waste water. According to this algorithm, the reference, minimum, and maximum levels of several storage tanks are checked, and the amount of waste water for filtration and filling the fresh water tank are determined. When both the UPA and WPA are operating, the required water is collected proportionally from both, as 2.5 kg of waste water can be filtered by the whole water recovery system at each hour.

The methodology to transfer water from ISRU and wastewater subsystem to the fresh water tanks is described in Algorithm 2. The algorithm considers the maximum water transfer rate from the ISRU and fresh water tank of the wastewater subsystem. The recycled fresh water from the wastewater subsystem is prioritized higher than utilizing lunar resources to produce water using ISRU.

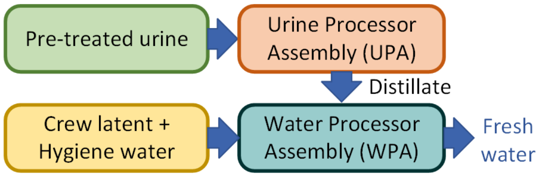

Fig. 3: Water recovery system in ISS

Algorithm 1 Urine and waste water filtration and storing in the fresh water tank

```
**Input data:** $P_W^{avail}, T_{UF}, T_{UF}^{ref}, T_{UF}^{min}, T_{UF}^{max}, T_{WW}, T_{WW}^{ref}, T_{WW}^{min}, T_{WW}^{max}, T_{WRS}^{ph}$
**Set:** $\Delta_h = 1h$
$T_{UF}^{err} = T_{UF}^{ref} - T_{UF}$
$T_{WW}^{err} = T_{WW}^{ref} - T_{WW}$
$T_{FW}^{err} = T_{FW}^{ref} - T_{FW}$
$C_{WRS} = 0.81 \times \left(T_{WRS}^{ph}\Delta_h\right)$
**if** $P_W^{avail} \geq 743$ and $T_{UF} \geq T_{UF}^{min}$ and $T_{UF} \geq \left(T_{WRS}^{ph}\Delta_h\right)$ and $T_{UF}^{err} < 0$ and $T_{WW} \geq T_{WW}^{min}$ and $T_{WW} \geq \left(T_{WRS}^{ph}\Delta_h\right)$ and $T_{WW}^{err} < 0$ and $(T_{FW} + C_{WRS}) \leq T_{FW}^{max}$ and $T_{FW}^{err} > 0$ **then**
    $C_{UF} = (T_{UF}^{err}/(T_{UF}^{err} + T_{WW}^{err})) \times \left(T_{WRS}^{ph}\Delta_h\right)$
    $C_{WW} = (T_{WW}^{err}/(T_{UF}^{err} + T_{WW}^{err})) \times \left(T_{WRS}^{ph}\Delta_h\right)$
    $T_{UF} = T_{UF} - C_{UF}$
    $T_{WW} = T_{WW} - C_{WW}$
    $WW_{total} = C_{UF} + C_{WW}$
    $C_{FW} = 0.81 \times WW_{total}$
    $T_{FW} = T_{FW} + C_{FW}$
    $P_W = 320 + 315 + 108$
**else if** $P_W^{avail} \geq 743$ and $T_{UF} \geq T_{UF}^{min}$ and $T_{UF} \geq \left(T_{WRS}^{ph}\Delta_h\right)$ and $T_{UF}^{err} < 0$ and $(T_{FW} + C_{WRS}) \leq T_{FW}^{max}$ and $T_{FW}^{err} > 0$ **then**
    $C_{UF} = T_{WRS}^{ph}\Delta_h$
    $T_{UF} = T_{UF} - C_{UF}$
    $WW_{total} = C_{UF}$
    $C_{FW} = 0.81 \times WW_{total}$
    $T_{FW} = T_{FW} + C_{FW}$
    $P_W = 320 + 315 + 108$
**else if** $P_W^{avail} \geq 428$ and $T_{WW} \geq T_{WW}^{min}$ and $T_{WW} \geq \left(T_{WRS}^{ph}\Delta_h\right)$ and $T_{WW}^{err} < 0$ and $(T_{FW} + C_{WRS}) \leq T_{FW}^{max}$ and $T_{FW}^{err} > 0$ **then**
    $C_{WW} = T_{WRS}^{ph}\Delta_h$
    $T_{WW} = T_{WW} - C_{WW}$
    $WW_{total} = C_{WW}$
    $C_{FW} = 0.81 \times WW_{total}$
    $T_{FW} = T_{FW} + C_{FW}$
    $P_W = 320 + 108$
```

Algorithm 2 Transfer water from ISRU and fresh water tank to the crew habitat water tank

```
**Input data:** $T_{hab_{H_2O}}, T_{hab_{H_2O}}^{ref}, T_{FW}, T_{FW}^{min}, T_{ISRU_{H_2O}}, T_{ISRU_{H_2O}}^{min}, W_{FW_{out}}^{max}, W_{ISRU_{H_2O_{out}}}^{max}$
**Set:** $\Delta_h = 1h$
$T_{hab_{H_2O}}^{err} = T_{hab_{H_2O}}^{ref} - T_{hab_{H_2O}}$
**if** $T_{hab_{H_2O}}^{err} > 0$ **then**
    **if** $T_{hab_{H_2O}}^{err} < \left(W_{FW_{out}}^{max}\Delta_h\right)$ and $(T_{FW} - T_{hab_{H_2O}}^{err}) > T_{FW}^{min}$ **then**
        $T_{FW} = T_{FW} - T_{hab_{H_2O}}^{err}$
        $TOT_{H_2O_{out}} = TOT_{H_2O_{out}} + T_{hab_{H_2O}}^{err}$
    **else if** $T_{hab_{H_2O}}^{err} \geq \left(W_{FW_{out}}^{max}\Delta_h\right)$ and $(T_{FW} - W_{FW_{out}}^{max}) > T_{FW}^{min}$ **then**
        $T_{FW} = T_{FW} - \left(W_{FW_{out}}^{max}\Delta_h\right)$
        $TOT_{H_2O_{out}} = TOT_{H_2O_{out}} + \left(W_{FW_{out}}^{max}\Delta_h\right)$
$T_{hab_{H_2O}}^{err} = T_{hab_{H_2O}}^{err} - TOT_{H_2O_{out}}$
**if** $T_{hab_{H_2O}}^{err} > 0$ **then**
    **if** $T_{hab_{H_2O}}^{err} < \left(W_{ISRU_{H_2O_{out}}}^{max}\Delta_h\right)$ and $(T_{ISRU_{H_2O}} - T_{hab_{H_2O}}^{err}) > T_{ISRU_{H_2O}}^{min}$ **then**
        $T_{ISRU_{H_2O}} = T_{ISRU_{H_2O}} - T_{hab_{H_2O}}^{err}$
        $TOT_{H_2O_{out}} = TOT_{H_2O_{out}} + T_{hab_{H_2O}}^{err}$
    **else if** $T_{hab_{H_2O}}^{err} \geq \left(W_{ISRU_{H_2O_{out}}}^{max}\Delta_h\right)$ and $(T_{ISRU_{H_2O}} - T_{hab_{H_2O}}^{err}) > T_{ISRU_{H_2O}}^{min}$ **then**
        $T_{ISRU_{H_2O}} = T_{ISRU_{H_2O}} - \left(W_{ISRU_{H_2O_{out}}}^{max}\Delta_h\right)$
        $TOT_{H_2O_{out}} = TOT_{H_2O_{out}} + \left(W_{ISRU_{H_2O_{out}}}^{max}\Delta_h\right)$
$T_{hab_{H_2O}} = T_{hab_{H_2O}} + TOT_{H_2O_{out}}$
```

III. RESULTS

The model is implemented and verified in *MATLAB* assuming that 4 crew members are present in the lunar habitat for a mission duration of 708 h, which is equal to one lunar month. The initial and maximum capacity of the ISRU water tank is assumed to be set to 0 and 6000 kg, respectively. The ISRU water tank reference is assumed to be set to 90% of the tank's maximum capacity. The power consumption of the ISRU to generate water using the lunar regolith is shown in Fig. 4a. Comparing Fig. 4a and Fig. 4b, it can be seen that the power consumption by the ISRU is dependent on the regolith intake rate (V_{ir}). It can be seen from Fig. 4c that the water level in the tank reaches its reference at approximately 450 h. While the ISRU water tank level is below the reference, the ISRU continues to consume power, and the power consumption reduces when the water level in the tank is close to its reference.

The power consumption of the wastewater subsystem is shown in Fig. 5a. It can be observed that when UPA and WPA are non-operational, it consumes a standby power of 297 W. The waste water tank reference level is set to 20 kg, and it can be seen in Fig. 5c that as soon as the waste water tank is filled up to the reference level, power consumption increases to 428 W as the WPA starts its operation. After approximately 55 h, the urine flush tank also reaches its reference level set to 20 kg and the wastewater subsystem power consumption increases

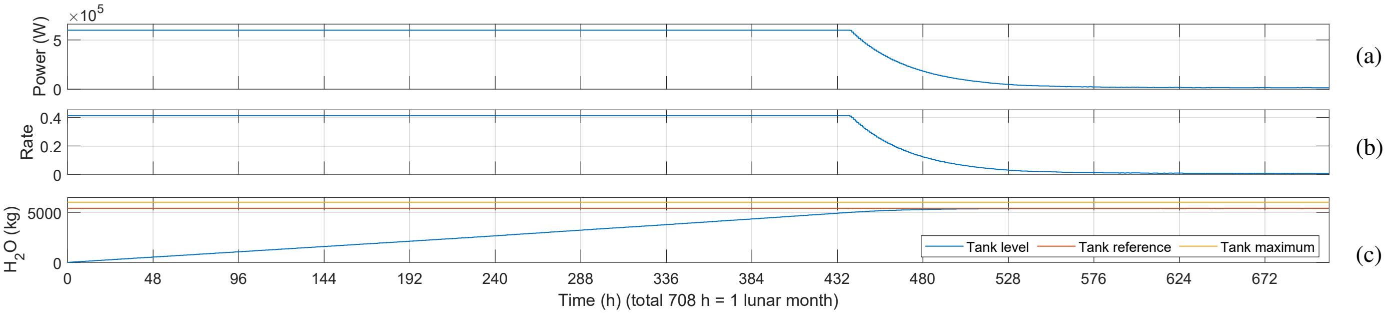

Fig. 4: (a) ISRU Power consumption (b) V_{ir} intake rate (c) Water stored in ISRU water tank and its reference

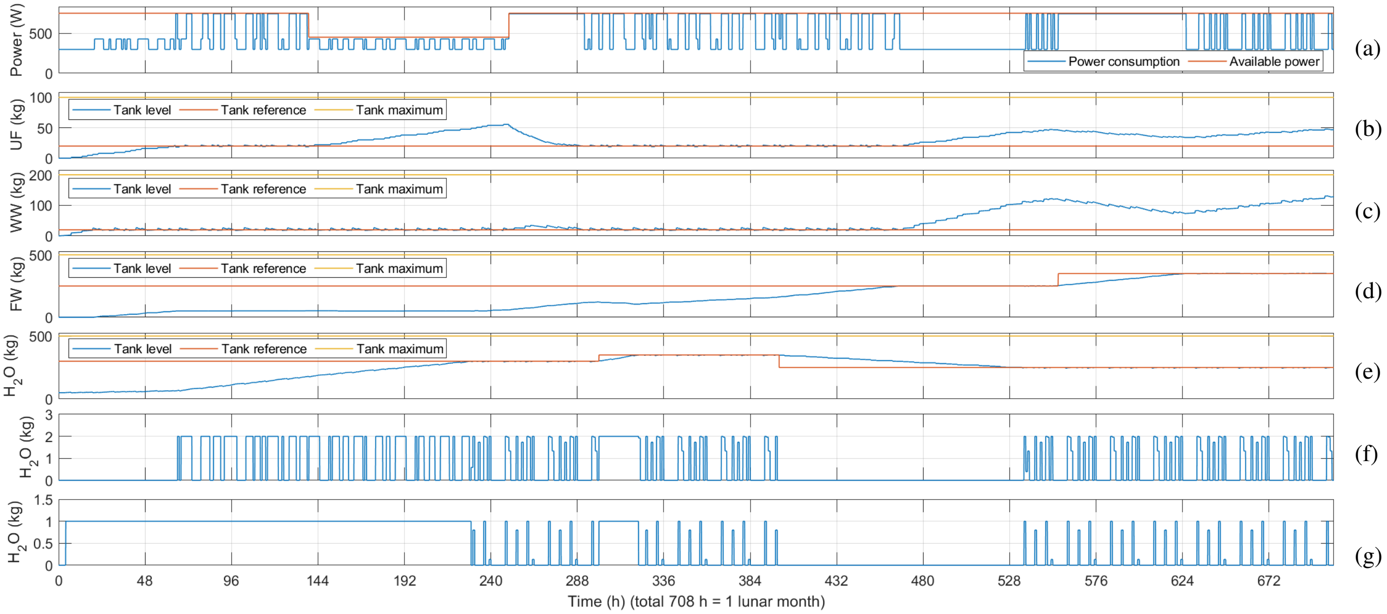

Fig. 5: (a) Wastewater subsystem power consumption and power availability (b) Urine flush (UF) tank level and reference tracking (c) Waste water (WW) tank level and reference tracking (d) Filtered fresh water (FW) tank level and reference tracking (e) Crew habitat water tank level and reference tracking (f) Water transfer from the fresh water tank in the wastewater subsystem to the crew habitat water tank (g) Water transfer from ISRU to the crew habitat water tank

to 743 W as both UPA, and WPA start their operation. The fluctuations in the power consumption are because during some intervals, both UPA and WPA are operational, while in other intervals, only WPA is operating, and it consumes lower power. It is assumed that at around 140 h, the available power to the wastewater subsystem is limited, and therefore, despite the urine flush tank reaching its reference level, UPA is not operational and the urine flush tank contents are not filtered. At approximately 250 h, the available power to the wastewater subsystem is increased, and the urine flush tank contents are filtered to bring its level down to the reference value. During this time, a small deviation in the waste water tank is observed as the filtration capacity of the water recovery system is limited to 2.5 kg/h and therefore, during this time, the contents of both the urine flush and waste water tanks are filtered proportionally through Algorithm 1. At around 288 h, both urine flush and waste water tank levels reach their reference levels. From the initial start till approximately 230 h, the water level in the crew habitat water tank increases from the assumed initial level of 50 kg to the assumed reference level of 300 kg. The crew habitat water tank receives water from the fresh water tank in the wastewater subsystem and ISRU water tank as can be seen in Fig. 5f and Fig. 5g. It is assumed that $W^{max}_{FW_{out}}$ and $W^{max}_{ISRU_{H_2O_{out}}}$ are set to 2 kg/h and 1 kg/h, respectively. At around 295 h, the desired reference level of the crew habitat water tank is increased to 350 kg, and it is observed that there is a continuous transfer of water from the fresh water and ISRU water tanks till the crew habitat water tank reaches its reference at approximately 325 h. This reference level is then brought down to 250 kg at around 395 h, and since the crew habitat water tank level is more than the set reference level, there is no transfer of water from the fresh water and ISRU water tanks. During this time, the urine flush and waste water filtration continue operating, and the fresh water tank is filled as it has not reached its reference level. At around 445 h, the fresh water tank reaches its set reference level of 250 kg, and also the water level at the crew habitat water tank is more than the set reference level and therefore, the operation of both UPA and WPA ceases. It can be observed in Fig. 5b and Fig. 5c that at around 445 h the urine flush and waste water tank levels rise above the reference level, and the water recovery system goes to the standby mode as can be seen in Fig. 5a. At around 530 h, the water level in the crew habitat water tank reaches its reference level as shown in Fig. 5e and therefore, both the UPA and WPA start their operation and consuming power as can be seen in Fig. 5a. At approximately 558 h, it is assumed that the fresh water tank reference level is increased to 350 kg (as shown in Fig. 5d) and it can be seen from Fig. 5f, Fig. 5g, and Fig. 5a that both UPA and WPA consume power. The water level in the fresh water tank reaches its reference at approximately 624 h. Since the water level at both fresh water and crew habitat water tanks has reached its reference, UPA and WPA only operate when there is a transfer of water from the fresh water tank to the crew habitat water tank for the rest of the mission duration. Therefore, from this simulation, it can be observed that the power consumption of the wastewater subsystem depends on the available power to the wastewater subsystem and reference levels of the urine flush, waste water, fresh water and crew habitat water tanks. For coordinated and efficient operation of the lunar base, the APC system is responsible for generating time-varying reference levels for different water storage tanks taking into account the available power and different system requirements such as safety and reliability.

IV. CONCLUSION

In this paper, a model to study the interaction between different subsystems of the water management system in a lunar base was developed. The water consumption profile of the crew habitat was created considering the different activities of the crew members throughout the day. The model considered the maximum, minimum, and desired reference levels of different tanks in the water management system. The maximum water transfer rate from different water tanks to the crew habitat was also taken into account. The power consumption of the wastewater subsystem was considered in the model and was verified using several simulations implemented in *MATLAB*. It was observed that the power consumption of the wastewater subsystem depends on the available power and the desired reference levels of several tanks in different subsystems. For effective power management of the lunar base, the APC should be able to set time-varying references for water storage tanks in different subsystems taking into account the available power and the operating requirements of the lunar base.

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