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Benefits of a rotating – Partial gravity – Spacecraft

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ABSTRACT

A long-duration microgravity environment has numerous detrimental effects on the human physiology. The most obvious solution for this problem related to long duration space exploration missions is to remedy the lack of gravity. This could be done using short arm human centrifuges but they do not seem to be sufficiently effective, perhaps because of the short duration exposure of this countermeasure and/or the huge body gravity gradient. New views have to be investigated, such as to see if a (very) long-arm rotating system generating a continuous 1 g or partial gravity field might resolve this issue.

Besides the expected benefits regarding astronauts' microgravity pathologies, additionally the spacecraft itself, its on-board (sub-)systems and procedures might benefit from a rotating configuration.

In this paper we address very briefly the medical issues, but the work is mainly focused on the advantages regarding engineering, operations, life support, safety and budget of having a constantly rotating spacecraft first in Low Earth Orbit and later for long duration missions to Mars. A large rotating spacecraft is feasible and affordable to build, operate and maintain. It has advantages for governmental and commercial use but also in light of the expected increase in space tourism. It will also save crew time and billions of dollars now being spent to counteract the effects of microgravity.

1. Introduction

Since the very start of the space program we have learned that the space environment is harsh not only because of its low atmospheric pressure, high solar and cosmic radiation, electrical charging, micrometeoroids and large temperature differences, but also because of its near weightlessness. This microgravity condition in free falling orbital spacecrafts is also a very useful environment to perform research where the impact of gravity needs to be managed [1,2]. The very first examples of human orbiting spacecrafts for long duration missions were the Russian Salyut and Mir space stations, the US Skylab, the numerous Space Shuttle missions, in recent decades the International Space Station (ISS) and since 2021 the Chinese Tiangong space station. The Lunar Orbital Outpost Gateway being designed and manufactured to orbit the Moon in the coming years, as part of the Artemis program [3,4].

Although orbital spaceflight provides a unique near weightless research environment, it also comes with quite some adverse effects on the health and safety of the crew. There are also various engineering challenges where the function of a space station needs to be compatible with the microgravity environment, and such effects are cumulative and increased by the time spent in weightlessness.

In this paper we explore the possibility of having a space station where we eliminate the effects of microgravity by providing Artificial Gravity (AG), and address the question: "What would be the advantages of an artificial gravity system with respect to the station itself, its internal systems/subsystems and the crew?" We want to explore these questions addressing various aspects: engineering, operations, science, safety and budget. Finally, we also address the drawbacks of a rotating spacecraft compared to current systems.

Method: The items addressed in this paper are a culmination of

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various discussions and remote brainstorming creativity sessions we had with a group of experts (all co-authors of this paper) in the field of spacecraft and life support systems engineering, a fluids physicist, a microgravity life scientist and an experienced crew member, begun during the Covid-19 pandemic period.

In this position paper we do not address in detail the size or the gravity level of such an Artificial Gravity platform. From previous studies we know that the rotation velocity for a constantly rotating spacecraft generating 1 g should be somewhere between 3 and 6 revolutions per minute (see *e.g.* Refs. [5–9]. This would require the radius to be between 100 and 25 m, respectively.

Although we are addressing an Artificial Gravity spacecraft, we should not abandon the microgravity part of spaceflight especially when a station is also used as a research platform in Low Earth Orbit (LEO). There is a great need to have the possibility of a near weightlessness environment for scientific and sometimes commercial or future tourist activities. A plausible configuration of a future space station should then be one with a rotating outer part to generate AG while the center remains non-rotating and provide a microgravity environment (see Figs. 1 and 2). The crew could then work in the microgravity module and after a day's activity go back to the AG compartment of the station.

For a mission to Mars the central, near weightlessness, module might not be needed and only the outer, artificial gravity section, would be required.

1.1. Engineering

What are possible engineering benefits of having a rotating spacecraft generating 1 g and a partial gravity?

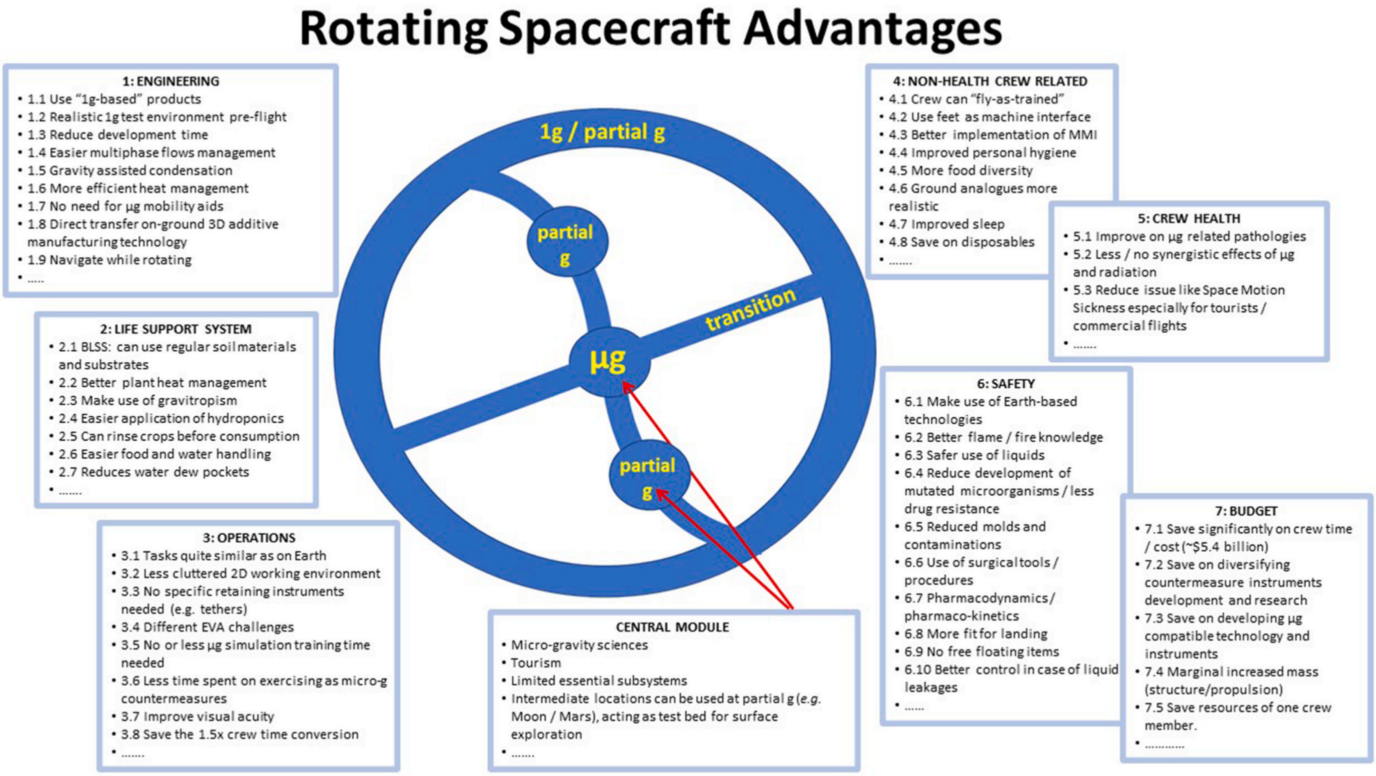
Preparing a system for a spaceflight application requires a thorough and lengthy preparation and validation. The use of a product or process for an in-flight AG application also requires pre-flight tests on ground, but such tests on Earth really represent the in-flight 1 g environment. The outcome of the tests are more reliable and do not need specific, and expensive, microgravity simulations [26].

In a microgravity environment, many issues arise in systems containing fluids. The management of multiphase flows in space is a current area of interest for the development of more efficient systems for propulsion, life support, etc. The different types of two-phase flows in microgravity and on Earth, make necessary the design of specific systems (*e.g.*, heat pipes for thermal management) for space. Moreover, phase separation (*e.g.*, for wastewater treatment) is a challenge in weightlessness, despite being a natural process on the ground. Many approaches (passive and active, static and rotary) for phase separation in space have been proposed in the past years [27]. However, their simplicity and efficiency are far from buoyancy-induced phase separation.

The lack of convective flows in space generates undesired accumulations of heat, which requires specific hardware for their control. In electronic devices, for example, an accumulation of heat for long periods of time can damage the device. This implies the need of generating liquid or air flows to remove heat. Also, an overheating in the walls of a propellant tank might induce boil-off, which implies the loss of liquid propellant and the need to keep these bubbles away from the tank outlet [28].

The determination of the volume of liquid in a tank in space is a challenging task given the multiple possible liquid-gas distributions. The use of wet-dry sensors is not an option as it is on the ground. Therefore, several mass gauging techniques are currently under study for their application in propellant tanks in space [29,30].

In a gravitational field one can make use of gravity-assisted phenomena and technologies for the above processes. Other examples of fluids processes that can benefit from gravity are the outflow of fluids from storage tanks (with no need for liquid acquisition devices), water



Rotating Spacecraft Advantages

1: ENGINEERING
- 1.1 Use "1g-based" products
- 1.2 Realistic 1g test environment pre-flight
- 1.3 Reduce development time
- 1.4 Easier multiphase flows management
- 1.5 Gravity assisted condensation
- 1.6 More efficient heat management
- 1.7 No need for µg mobility aids
- 1.8 Direct transfer on-ground 3D additive manufacturing technology
- 1.9 Navigate while rotating
- .....

2: LIFE SUPPORT SYSTEM
- 2.1 BLSS: can use regular soil materials and substrates
- 2.2 Better plant heat management
- 2.3 Make use of gravitropism
- 2.4 Easier application of hydroponics
- 2.5 Can rinse crops before consumption
- 2.6 Easier food and water handling
- 2.7 Reduces water dew pockets
- ....

3: OPERATIONS
- 3.1 Tasks quite similar as on Earth
- 3.2 Less cluttered 2D working environment
- 3.3 No specific retaining instruments needed (e.g. tethers)
- 3.4 Different EVA challenges
- 3.5 No or less µg simulation training time needed
- 3.6 Less time spent on exercising as micro-g countermeasures
- 3.7 Improve visual acuity
- 3.8 Save the 1.5x crew time conversion
- ....

CENTRAL MODULE
- Micro-gravity sciences
- Tourism
- Limited essential subsystems
- Intermediate locations can be used at partial g (*e.g.* Moon / Mars), acting as test bed for surface exploration
- ....

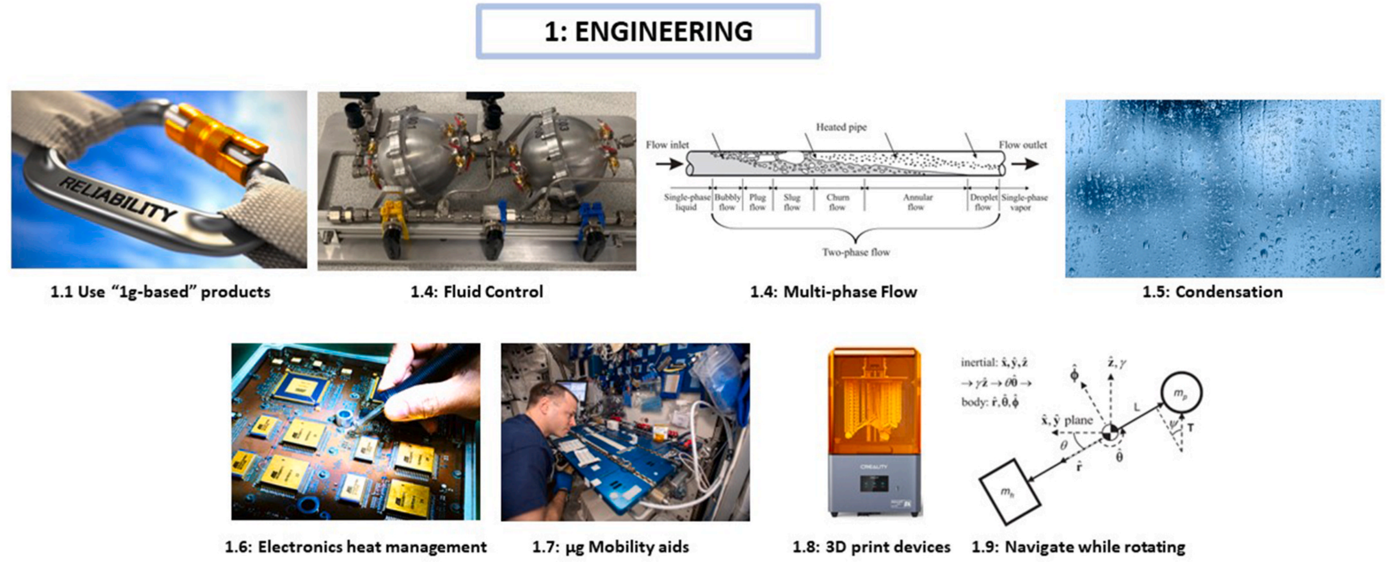
4: NON-HEALTH CREW RELATED
- 4.1 Crew can "fly-as-trained"
- 4.2 Use feet as machine interface
- 4.3 Better implementation of MMI
- 4.4 Improved personal hygiene
- 4.5 More food diversity
- 4.6 Ground analogues more realistic
- 4.7 Improved sleep
- 4.8 Save on disposables
- ....

5: CREW HEALTH
- 5.1 Improve on µg related pathologies
- 5.2 Less / no synergistic effects of µg and radiation
- 5.3 Reduce issue like Space Motion Sickness especially for tourists / commercial flights
- ....

6: SAFETY
- 6.1 Make use of Earth-based technologies
- 6.2 Better flame / fire knowledge
- 6.3 Safer use of liquids
- 6.4 Reduce development of mutated microorganisms / less drug resistance
- 6.5 Reduced molds and contaminations
- 6.6 Use of surgical tools / procedures
- 6.7 Pharmacodynamics/ pharmaco-kinetics
- 6.8 More fit for landing
- 6.9 No free floating items
- 6.10 Better control in case of liquid leakages
- ......

7: BUDGET
- 7.1 Save significantly on crew time / cost (~$5.4 billion)
- 7.2 Save on diversifying countermeasure instruments development and research
- 7.3 Save on developing µg compatible technology and instruments
- 7.4 Marginal increased mass (structure/propulsion)
- 7.5 Save resources of one crew member.
- ....

Fig. 1. A schematic layout for a large diameter rotating spacecraft, where the highest gravity is generated at the outer rims, locations for intermediate gravity levels could be implemented in the more internal structures while the center would be reserved for a non-rotating microgravity module. See for overall geometry also the works of Herman Potočnik/Hermann Noordung [10]. Advantages of a rotating system are enumerated for the various domains in the explanatory boxes and addressed in more detail in the main text.



1: ENGINEERING

1.1 Use "1g-based" products

1.4: Fluid Control

1.4: Multi-phase Flow

1.5: Condensation

1.6: Electronics heat management

1.7: µg Mobility aids

1.8: 3D print devices

1.9: Navigate while rotating

Fig. 2. A: 1.1 In an AG spacecraft one can make direct use of instruments that have been developed and used for a long time on Earth at 1 g. This provides an improved reliability of such systems (image: Adobe stock). **1.4** Better fluid control in "containers" (SMARTTS: University of Surrey). **1.4** Better control to separate two phase systems (image: [11]). **1.5** Condensation is better 'controlled' due to gravity compared to the sometimes niches or pockets of liquids in microgravity (image: Adobe stock). **1.6** Better heat management in *e.g.* electronic devices (image ESA). **1.7** Easier handling of instruments for *e.g.* in-flight assembly, test or repair (image: astronaut Nick Hague ISS/Expedition 59: image NASA). **1.8** On-Earth developed technologies for 3D printing, like this stereolithography (SLA) system, can nearly directly be applied in flight in an Artificial Gravity environment. **1.9** Some studies showed the possibility to navigate while rotating, in this example with a tethered system (image: [12]).

Fig. 2B: Easier life support/plant growth systems: **2.1** the NASA Passive Nutrient Delivery System (PONDS) on ISS in an attempt to solve the proper water and nutrient supply to crops (Canadian Space Agency astronaut David Saint-Jacques; image NASA). **2.1** Under microgravity plant growth is seriously hampered by the lack of convection near the root system (image: [13]). **2.2** In plant growth microgravity is also a limiting factor in proper function of leaves with respect to water and gas exchanges (image: [14]). **2.3** In an AG system plant can make use of their evolutionary developed gravitropism mechanism for proper growth (image from Seeds-in-Space experiment: [15]). **2.4** Fluid handling in µg is very cumbersome. Earth-based culturing techniques such as hydroponics/vertical farming can directly be applied in a large rotating space station (image: Imperial College, London, UK). **2.5/2.6** Growing crops in space is one thing but consuming them also involved cleaning before eating. In an Artificial Gravity environment cleaning of crops are much more efficient than in a microgravity environment (image: www:PipeWrenchPlumbing). **2.7** Pockets of water can form (unnoticed) when the dewpoint is locally reached above surfaces colder than the ambient air and condensation occurs. Especially in microgravity they might develop at difficult to reach locations that are cumbersome and time consuming to clean (image: Adobe stock).

Fig. 2C: 3.2 ISS/microgravity can easily be a cluttered working place with instruments all over and items sometimes floating away and even getting lost (image: Marcus Wandt/ESA). **3.3** In a Artificial Gravity environment no specific retaining instruments are needed to perform a certain procedure, like handling a 'patient' as seen in this activity (image ESA/CNES). **3.4** Extravehicular activities (EVA) would change in a rotating spacecraft and be more like related to a mountaineering activity (image: Adobe stock). **3.6** No or far less time is needed for in-fight countermeasure training (image ESA astronaut Alexander Gerst gets a workout on the Advanced Resistive Exercise Device, aRED (NASA)). **3.7** Size and distances acuity will reduce in a lower g environment. This might have an impact at landing or movement at Moon or Mars surface. (image: Apollo 8, NASA). **3.8** In AG one does not have to take into account the 1.5 times increase in time for in-flight/microgravity operation (image from crew procedure short-term plan (STP) [16]).

Fig. 2D: **4.1** The training as have been received on ground is more realistic when applied in an AG environment in flight so more "fly-as-you-have-been-trained" (Image from classroom training Exp 38/39 crew, NASA). **4.2** In an AG environment feet can now be used as a Man Machine Interface instead of being restraint in a microgravity environment and not causing skin issues as is reported from ISS (image: NASA). **4.4** In the framework of personal hygiene: taking a shower is one of the things that is very much missed while in orbit (image: Adobe stock), this also goes for washing hair (Karen Nyberg in ISS (image NASS). **4.5** In an AG environment one can make use of the products crops/fruits from the Biological Life Support System. **4.6** Training is an important aspect for a successful mission. To train in a similar (gravity) environment as in-flight provides a better preparation (image: NASA-JSC HERA facility: Houston, USA). **4.7** Crew also reports difficulties sleeping. Here astronaut ESA Luca Parmitano sleeps in his berth aboard the ISS (credit: ESA). **4.8** For long duration missions it is more advantageous to wash cloths instead of using disposables. In an AG environment washing is much more easy than having such a system under microgravity (image: [17]).

Fig. 2E: 5.1 Reduction in mineral content and bone strength in load bearing bones (image: NASA). Changes in brain morphology (image: [18]). **5.1** The relatively lately identified Spaceflight-Associated Neuro-ocular Syndrome, SANS, is (most likely) dependent on fluid shifts because of microgravity. Chronic AG will eliminate or at least reduce these shifts (image: [19]). **5.1** Muscle volume and strength is reduced due to immobilization (IM) (image: [20]) similar to space flight µg. **5.1** The cardiovascular (image: Frontiers) and immune system (image: [21]), and many other systems, are compromised in microgravity in physiological but also behavioral health. **5.2** Galactic and solar radiation is a major issue for long duration exploration missions. There are indications that microgravity and radiation have synergic effects (image: [22]). **5.3** Some 70 % of orbital crew report issues related to the space adaptation syndrome. Not a strong argument for space tourism (image: barfology.com).

Fig. 2F: 6.2 Flames behave differently in microgravity. We know much more how flames behave in a gravity environment (image: NASA). **6.3** Better/safer fluid control in an artificial gravity system. **6.4** Compared to 1 g, microgravity increases drug resistance in microorganisms (image: [23]). **6.5** Microgravity increases mold formation and growth of microbial life on surfaces and in fluid pockets. Shown is a molded-stained panel in the ISS hygiene area (image: [24]). **6.6** Surgical tools are developed to be used at 1 g. It is difficult to use such tools, and patients, in a microgravity environment (image: Univ. Louisville, USA). **6.7** Quite some drugs are used in flight but they are not always as effective as on ground and most drugs have side effects. This might create safety issues for both crew health as well as for operations and mission success (image: Adobe stock). **6.8** Traveling in a AG environment during the journey to another celestial body provides a better preparation for landing and early operations (image: Apollo 11 Commander Neil Armstrong: NASA).

Fig. 2G: 7.1 Based on ISS crew operations a minimum of 5.4 billion US dollars could be spared when (part of) a low Earth orbit station would have a chronic AG setting. (part of image: Samantha Cristoforetti in ISS training on the aRED system, NASA/ESA). **7.2** Money can be repurposed since investments in engineering, manufacturing and operational research for several microgravity countermeasure devices is not needed anymore (image: [25]. **7.4** A rotating spacecraft might increase the launch mass but current launch cost are only a fraction of what they were in the past (image: Falcon heavy, SpaceX). **7.5** Not having to spend time fighting microgravity related pathologies can save one crew member and related resources for a trip to Mars when the journey makes use of a chronic AG environment (image: Mars + edited SpaceX Crew-7: NASA).

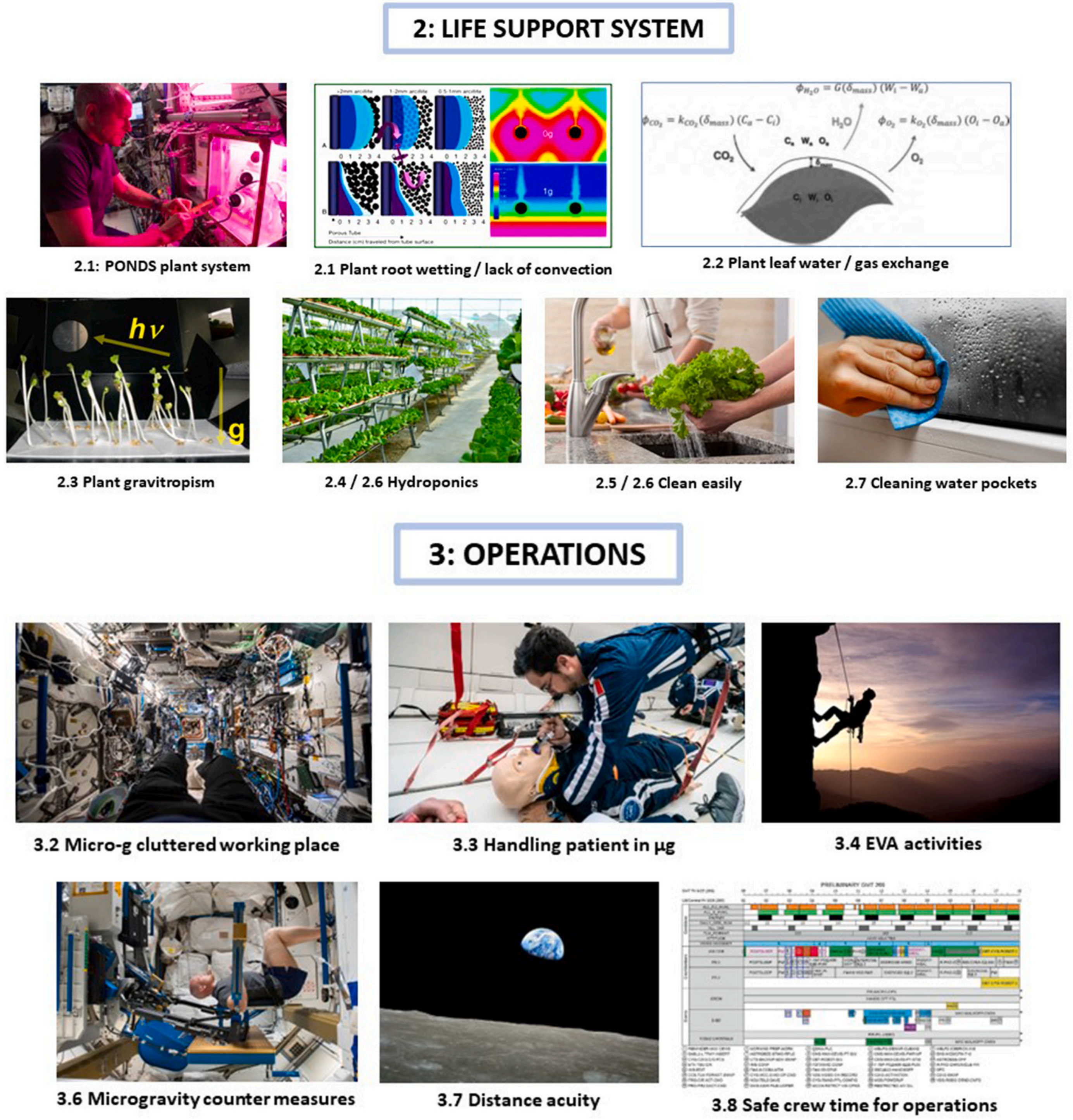
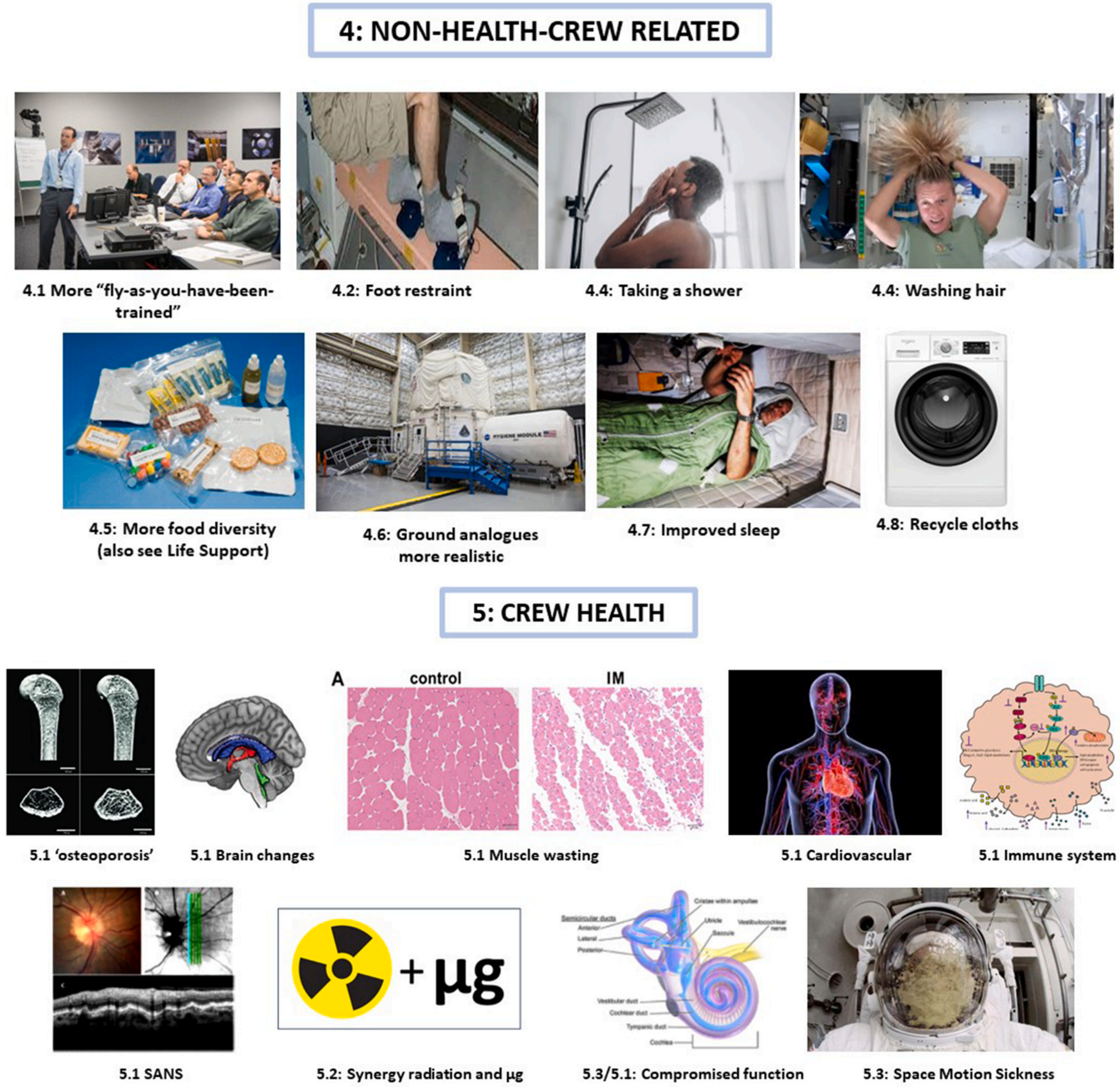


Fig. 2. (*continued*).

condensation and separation for atmosphere dehumidification, or degassing fluids. This could be applicable to propellant tanks [31], or heat transfer systems [32] etc. Also the more efficient immersion cooling systems [33] become more feasible when working in an AG environment.

One can also save on mass for obsolete micro-g typical sub-systems such as centrifuges, some exercise equipment (also see later), associated plug-ins and mobility aids.

The ‘natural’ convection of the air in a gravitational environment also simplifies the atmospheric management since there are no unvented stagnation areas. Natural convection when superimposed to forced convection will minimize air pockets, providing better mixing, more uniform temperature, relative humidity and gas concentrations which makes crew quarters ventilation easier but also helps in the temperature control of the various electronic systems used in a microgravity environment whereas forced convection needs to be applied when they are



4.1 More "fly-as-you-have-been-trained"
4.2: Foot restraint
4.4: Taking a shower
4.4: Washing hair
4.5: More food diversity (also see Life Support)
4.6: Ground analogues more realistic
4.7: Improved sleep
4.8: Recycle cloths
5.1 'osteoporosis'
5.1 Brain changes
5.1 Muscle wasting
5.1 Cardiovascular
5.1 Immune system
5.1 SANS
5.2: Synergy radiation and μg
5.3/5.1: Compromised function
5.3: Space Motion Sickness

Fig. 2. (*continued*).

used in a microgravity environment.

There is also growing interest in the application of additive manufacturing technologies in space [34,35]. In a 1 g or partial g environment in a rotating spacecraft the same printing set-up can be used as on Earth, and the use of various materials and printing technologies can be easily implemented.

The fact that a station is rotating might be challenging with respect to orbital and attitude control for such a system. Station orientation and manoeuvring is different from a non-rotating spacecraft although some studies have been published addressing the possibilities to control a large rotating spacecraft [36–38]. In the study for the Hyperion rotating space station the spin-up and spin-down is achieved by ion thrusters that can gradually increase rotation to the required outer ring rotation velocity [39], and ideas have been developed to manoeuvre a rotating spacecraft while not spinning down or spinning up thus avoiding using excessive fuel [12].

The designs and production of orbiting or transit Artificial Gravity modules could be reused as operable modules on Moon and Mars surface with only relatively minimal changes *e.g.* to cope with different mechanical, thermal, and ionizing radiation environment. See also Fig. 2A.

1.2. Life support systems

For the growth of plants as part of the atmospheric re-vitalisation and food chain one can use standard Earth-based techniques of using regular soil or hydroponics instead of complex materials to control macroscopic and microscopic fluid interface configurations and modeling in order to try to guide proper growth [40,41].

Fig. 2. (*continued*).

The complexity of Life Support Systems can be dramatically reduced when a system is operated in AG so we directly benefit from the current developments in vertical farming, and hydroponics could more easily be translated to in-flight use [42–44].

There is no need to apply one of the complex in-flight phase separation techniques [27] and more standard fluidics can be used. For biological elements in a Life Support System (LSS) such as growing crops, microgravity provides numerous challenges: from managing two phase flows and engineering proper growth substrates [45]. Also lack of roots oxygenation as well as loss of priming in fertigation lines are typical issues, still not completely solved for microgravity systems [46, 47]. In addition, at the level of the leaves and their heat management a gravitational field would be preferable compared to a microgravity environment [14], and in general plants are not developing as well in microgravity as compared to 1 g conditions [48].

In a gravitational environment plants can make use of their evolutionary well developed gravitropism where roots grow along the gravity vector and shoots grow against [49,50]

Also the cleaning and rinsing process of the cultured crops before consumption is easier to be performed in a rotating spacecraft.

As for spacecraft humidity control, the battle against unwanted condensation of the humid air inside the closed environment of a station is a time consuming task from the side of the crew aboard as well as from the ground control teams. Especially in the ISS there is no homogenous layout of the station walls and the rack constructions attached to them. So, pockets of water can form unnoticed when the dewpoint is locally reached above surfaces colder than the ambient air and condensation occurs. Natural gravity driven convection forces the exchange of colder and warmer air masses, leading to a more uniform dewpoint. See also Fig. 2B.

1.3. Operations

Performing tasks in a rotating spacecraft will not be that much different than performing the same tasks on Earth provided a person has been adapted to phenomena related to rotating systems such as Coriolis forces and cross-coupled illusions [51,52]. The often-used conversion factor of 1.5 for crew time necessities in microgravity, compared to Earth gravity, would not be applicable in the AG part of the station. Much crew time will be saved in those activities. More (science) activities could be integrated thanks to the time saved.

In a two-degrees-of-freedom gravitational setting, it could be expected that the spatial volume is less cluttered, with items resting naturally on horizontal surfaces without additional restraints, or pegged to vertical surfaces. In contrast, in a three-degrees-of-freedom microgravity environment as aboard the International Space Station, quite some time *c.q.* money is spent to locate particular items that may be lost due to them floating away. A 2D operational environment does not require specific tools and restrains to prevent crew themselves from floating away from their tasks and work benches can be exploited much more efficiently since no items need to be fixed and very small articles can be handled more effectively. Therefore, by analogy with a workshop on Earth, all the tools, spares and items will be more contained and organized. Astronauts training will have even more fidelity by implementing a reproduction of the rotating station on ground.

For a new rotating station external structures will be likely designed to be mostly repaired remotely from the pressurized environment, but some "outdoor" EVA (Extra Vehicular Activity) maintenance will be necessary. This will lead to the engineering of robotic systems (*e.g.* upgraded versions of the European Robotic Arm [53] or the Canadarm2 [54] currently used on the ISS) to perform such tasks. A rotating station would provide quite different conditions and challenges for astronauts' EVAs as compared to a non-rotating one in terms of crew safety. When EVAs are required, the crew will need to be firmly tethered to the station with similar safety tether technologies as used by terrestrial mountaineers. When working on the inner facing side of the ring structure less or no time would be needed to be trained in simulated microgravity of neutrally buoyant pools and such training might have to be converted to more climber-like skills. However, working on the outer rim would pose a new challenging as the centrifugal forces would constantly drive crew and tools away from the station' surface.

Also, quite differently from the current ISS experience, within a rotating spacecraft payloads will now have a weight which should be taken into account during systems development but again, basically the same procedures as during on-Earth training could be applied in-flight.

As an additional operational feature, an AG spacecraft in LEO could also be used for in-orbit servicing to satellites, avoiding issues such as propellant transfer that arise in a microgravity environment and are not yet fully under control [55,56]. Re-fuelling satellites in-orbit would extend their life and, therefore, could have a great impact in the fast-growing economy around satellites and constellations. See also Fig. 2C.

1.4. Non-health - crew related

From a crew member point of view, one might state that they could "fly-as-you-have-been-trained" and artificial gravity would ease the life of an astronaut.

In a gravity environment one can also make use of their own feet as a steadying machine interface in operations which is sometimes not possible in the current 'floating' mode.

Personal hygiene would also improve significantly in a rotating spacecraft [57]. Washing will become easier for crew because water containment is easier. One could take a regular shower instead of the cleaning with wetted towels as currently done, and doing away with the clumsy space showers used in the past [58]. Using the toilet is far less cumbersome and most likely does not require 23 million US dollars to develop [59]. Also, one could launder clothes with an adapted washing machine instead of being forced to waste textiles as expendable materials. Introducing washing rather than replacement seems to start to pay off with a mission duration of more than a year [17].

Food has become a very important factor in the metabolic balance of astronauts during a long-term mission [60]. Carefully devised experiments such as metabolic wards in space or measurements of the energy balance under flight conditions have even convinced the astronauts to pay more attention to a balanced diet despite the time it takes away from work to prepare a nutritious dinner. Food variety can be improved since food substances do not need to be composed 'semi-sticky' to be approved for flight [61]. Food items can be easier contained and debris and crumbs will not contaminate the whole spacecraft. But the perception, appreciation and taste of the food would also be improved. Exemplarily, this has already been demonstrated when the prototype espresso machine aboard the ISS found its congenial open surface cup co-invented by astronaut Don Petit, which used surface tensions to contain the fluid long enough to smell the aroma [62,63]. Concerns about neglect of a balanced diet might be less likely with the improved taste and smell experience [64,65].

In the process to prepare crews for their in-flight activities numerous on-ground 'analogues' have been tried and in some case are still used, like Concordia [66], HERA [67], NASA/CELSS [68], Russian Bios-3 [69,70] and the SIRIUS complex used in Mars-500 [71], CEEF [72], Chinese Yuegong-1 [73], ESA MELiSSA Pilot Plant [74], NEEMO, Biosphere-2 [75] etc., but none of these, with exception of the NEEMO to some extent, take into account the factor of microgravity. So, in the case of an AG spacecraft, the training analogues would more closely representing the actual flight conditions.

And of course, there is the very important aspect of crew health and safety. Since there is nearly no experience in human chronic exposure to large diameter rotations, we cannot take possible rotation effects into account. However, we do know that the human body responds with the development of various, sometimes maybe non-reversable, pathologies to a long duration exposure to near weightlessness such as the deterioration of visual acuity known as Spaceflight-Associated Neuro-ocular Syndrome SANS [76]. As compared to current efforts for countermeasure devices and protocols no elaborate in-flight research programs are needed to prevent these μg induced diseases and the NASA Evidence Report in Artificial Gravity states that: "*..chronic AG might be the most efficient countermeasure*" for SANS [77].

Man-machine interfaces (MMI) and space ergonomics [78,79] can be more easily implemented based on and ported from ground-based 1 g systems.

A 1 g or partial gravity environment could also be supportive to improve on the sleep deprivation issue often reported in the context of space missions [80].

Arriving in a gravitational field, as *e.g.* Mars, after a long period of near weightlessness might bring operational issues since it has been shown that such conditions affects visual spatial cognition, which is important to properly perceive size and distances, especially relevant during landing procedures [81]. See also Fig. 2D.

1.5. Crew health

From the more than five decades experience on the effects of near weightlessness in astronautical spaceflight we have learned that the human body requires gravity for a proper functioning. When not taking possible rotation effects into account, we do know how body responds at 1 g. It is, however, very well possible to remain in microgravity for a relatively long period of time but the body starts to develop all kinds of pathologies related to *e.g.* the immune system [82,83], muscle [84], brain [85,86], thrombosis [87], bone [88,89], back pain [90], vestibular malfunction [91], skin [92], eyes [93], sleep [94], anemia/hemolysis [95,96], cardiovascular deconditioning [97], energy balance disturbance [60], changed micro-biome [98], and maybe cartilage [99] and cognition [100], although some of these effects could also be, partially, attributed to issues like confinement and are not directly related to microgravity [101]. The purpose of this paper is not to elaborate on the various microgravity induced pathologies. For this please see for some overview papers by Refs. [102–104].

In the last decades of gradually longer spaceflight missions, but also already during the shorter Space Shuttle flights, crews made use of various countermeasure systems [105]. Conversely, when using 1 g AG no elaborate in-flight training programs would be needed as compared to current efforts with countermeasures. Research efforts can be shifted from more operational related science to more basic research oriented activities.

Resources for countermeasure devices seem to be systematically limited in volume and upload mass. This limits the capability for astronauts to exercise sufficiently during spaceflight from the early Vostok, Mercury or Gemini all the way to the current Orion [106], and one could argue whether long duration spaceflight with the development of various pathologies and the limited efficacy of countermeasure is an ethical modus operandi [107]. By providing chronic AG the whole spacecraft serves as the microgravity countermeasure device. Such a ‘long-arm’ AG is not to be confused with the current efforts to use Short-Arm Human Centrifuges (SAHC) *e.g.* Refs. [52,108,109]. SAHC countermeasure protocols are similar in term of application per run as current countermeasure systems. Also, their efficacy based on only a short duration/large gradient [110] gravity application is not sufficiently successful probably since the subjects only receive a few percent of the daily g-dose [111]. So with respect to the success regarding AG one should clearly state the diameter of the centrifuge used.

In addition an AG spacecraft would also reduce the possible synergistic effects of microgravity and space radiation [112].

An AG station could also be the basis for interplanetary vehicles transferring humans to Mars. The key issue for the crew of having to cope with gravity transitions during a Mars mission (1 g to micro-g to partial-g, and return) would be greatly mitigated. See also Fig. 2E.

1.6. Safety

There are numerous safety related advantages when using a rotating artificial gravity spacecraft. Besides the aforementioned technologies developed and verified for a long time in Earth’s gravity field there are also advantages directly related to crew or spacecraft safety.

Combustion processes and flames behave quite differently in microgravity compared to a partial or 1 g environment [113]. In a micro-g environment the interruption of forced ventilation in the area possibly affected by overheating and potential fire actually depletes the oxygen in the affected area, leading to self-suppression. On the other hand, in a 1-g environment natural convection brings oxygen to the overheated material, enhancing the probabilities of fire to spread. However, we have a better understanding of heat, fire and flame behavior at 1 g than at μg which provides proven procedures how to fight fires in a gravity environment [114]. Also, an AG environment make fires less likely to ignite, because natural convection will dissipate excess local heat better.

Working with free floating liquids, but also tools or other small items, can be quite dangerous since they could end up anywhere, including within electronic systems, in a free falling non-rotating spacecraft. In a gravity environment such items and free liquids would always move along the gravity vector, hence more predictably as well as safer to handle. Leakage of any kind of fluid will be more easily managed in a gravitational environment of the AG spacecraft. This implies fewer constraints in the interior design of the vehicle in comparison with current space vehicles.

For quite some time already we know that pathological microorganisms while in microgravity are less susceptible to antibiotics [115,116] while they also seem to become more virulent [117]. It may be expected that microbes in a 1 g AG spacecraft respond more as we know on Earth. However, we cannot exclude any possible impact of increased radiation in a Low Earth Orbit as well as possible synergistic effects of microgravity and space radiation [118]. In microgravity there might be health issues regarding humidity control (see the discussion concerning dew points above) and consequently contaminated areas prone to microbial development (fungi) or biofilm formation and molding [119,120] or even protozoa and dust mites located in condensates behind panels on Mir station [121].

Surgery in microgravity is quite challenging and, fortunately, as far as we know, no serious procedures have had to be performed in space until now. Although some procedures regarding capabilities on basic and advanced medical interventions have been tested in analogue short duration weightless environments, some critical aspects are still poorly investigated [122], while also the operator’s fine motor skills in microgravity seem to be reduced [123]. Already a basic procedure as drawing of liquids from vials containing drugs in space is a significant challenge because of surface-tension effects [124]. Also all required equipment and advanced procedures need to be microgravity compliant which is a challenging task [125]. Surgery in an artificial gravity environment can make use of already developed and widely used, ergo more reliable, surgical equipment and procedures which would greatly enhance the chances of a successful outcome of the treatment. One can wonder if specifically designed surgical μg instruments, with very limited practical use, comply with regulations and laws set for the use of medical devices for humans and proper medical standard to allow them into the market: Do these specifically space modified instruments comply with the various national and international regulations and medical equipment certification standards, developed to guarantee reliable and safe use, or do we need to enforce a specific waiver for such instruments to be used in-flight? Making use of reliable 1 g instruments and procedures complies with the Long Latency and No Vehicle Return principle [126].

Besides the use of medical instruments and procedures also the main subject in this context, the human body, undergoes significant alteration under microgravity conditions. The body will have an adapted fluid distribution and responds differently, endocrinologically, when in microgravity. This might change the function and likely the efficacy of various drugs [127]. While the knowledge on these pharmacodynamical and especially pharmacokinetic [128] processes is limited [129] but we do know how drugs will function in a 1 g environment.

There is also a crew and mission risk involved for long interplanetary travel of some seven to nine months [130] in microgravity going from Earth to Mars, when arriving crew is being exposed to descent/landing loads as well as the chronic gravity field on the surface. We know from a Shuttle Neurolab mission (STS-90) pilot study that when astronauts had been exposed to artificial gravity during the mission [131] they showed less or no signs of orthostatic intolerance when returning to Earth’s gravity compared to non-gravity loaded controls. One has to realize that this preliminary study included only a few subject and more research in this field is needed. Of course on Earth we have a welcoming party taking care of the crew after landing. There will be no such assistance for a Mars landing. However, post flight tests within the first few hours of landing might have an effect on earlier recovery after a six months flight [132]. On the other hand, a recent modeling study on orthostatic intolerance predicts no severe effects when landing in a 1/3 Earth gravity field like on Mars, although problems are to be expected when returning to Earth from such a long duration Mars mission [133]. See also Fig. 2F.

1.7. Commercial/business/other points

A slowly rotating spacecraft might also make orbital space tourism much more attractive. When reaching microgravity after launch, some 70 %–80 % of the space travelers suffer from space motion sickness or the Space Adaptation Syndrome [91]. This can last several days and is characterized by nausea, vomiting, headache, fatigue, general distress [134]. Such symptoms are also reported when returning into a gravitation load. Low Back Pain is another discomfort reported by some 70 % of the crew which remains for about a week [90]. Besides this there are also lesser discomforts such as nose congestions that leads to reduced smell and taste [135]. All these factors do not make it attractive to buy an expensive trip to an orbiting space hotel with microgravity modules throughout. It would make a better business model if one can experience a microgravity environment but with the option of a retreat to a 1 g or partial g part of a rotating station [37,136].

When having a gravity based outpost it would most likely interest new Small and Medium Sized (SME) companies to support the supply chain to allow a higher number of ground-based advanced and reliable solutions to be used on-orbit. This would simplify engaging new companies into the space business. Changing Electrical, Electronic, and Electromechanical (EEE) parts quality toward a more challenging radiation environment, or ruggedize hardware toward the launch loads will be less challenging than functionally rethinking solutions for an environment absent of gravity [137].

1.8. Budgets (money and mass)

The concept of a rotating spacecraft has for long been discarded due to, alleged, mass and cost reasons *e.g.* Refs. [126,138–140] although the arguments put forward by these authors are not substantiated with any real evaluations and numbers. One published study that did address this issue was by Joosten [141]. He estimated that the additional cost for the establishment of a rotating spacecraft is quite limited and would be around 5 % for supplementary structural and propellant mass although this was not a LEO-based AG facility but a deep-space vehicle design for a Mars mission, while an older study from 1988 for a mission to Mars estimated a cost increase of some 10 % [142]. Discussions where additional mass increase and associated launch costs were brought forward as a main issue are now much less applicable with the current very significant drop in launch cost [143] while masses can be greatly reduced making use of the 'tensegrity concept' for assembling various structural elements [36]. While launch costs for 1 kg payload were around \$65,000 for the Space Shuttle, this had now reduced to some \$1500 for a Falcon Heavy rocket [144]. With a reduction of nearly 45 times up-mass related launch costs are not such an important cost driver anymore.

An investment done in a rotating spacecraft is an investment in the wellbeing and health of the professional crew who are in space for prolonged periods of time and should be protected as much as possible against adverse working conditions [145,146]. Artificial gravity will also provide a comfortable environment for visiting commercial and non-commercial short-term visitors to such a LEO space platform.

Significant costs will be saved since various systems do not need to go through a lengthy development phase in order to adapt to be functional in a microgravity environment. We can make use of well-established systems already used in the Earth 1 g environment. However, one also has to evaluate that *e.g.* during parts of the assembly or in certain emergency situations the station might not be rotating and we might need to provide μg resistant back-up and redundant systems.

In-flight operational costs can be saved. Besides the reduced crew time related to the in-flight time increase factor of 1.5 for executing procedures in μg, one would also regain a very significant amount of crew time since there is no need for performing regular countermeasure training. Astronauts and cosmonauts are allotted 2.5 h per day for countermeasure training [147]. If we would make a rough calculation taking the ISS for a period of 20 years with an average permanent occupancy of four crew members exercising 2 h a day for five days a week with an hourly crew time rate of \$130,000 [148] this would come down to having spent some \$5.4 billion in trying to counteract microgravity pathologies. This conservative number is without the costs of development, launch and maintenance of the various countermeasure devices. There is also a significant cost in the research, at agency and national academic and industrial level, performed for exploring various countermeasure systems and their efficacy. Despite this effort a recent evaluation of aerobic and resistance exercise of 46 astronauts after long duration mission showed them not to be fully protective against multi-system deconditioning [149]. The significant amount of this \$5.4 billion+, which is more than 1.5 times the complete NASA annual budget for the whole ISS program [150], could be saved when there is a permanent 1 g environment in long duration missions. However, one has to evaluate what the additional (cost) effort would be to also have a microgravity/static part of such a rotating station as depicted in Figs. 1 and 2 although such a central part would not be needed for a mission to Mars.

The most fitting number of crewmembers going to Mars in first human missions is still to be defined but most likely between three to six persons [151] although there are also evaluations for two and four person crew [152]. A crew of six going to Mars performing countermeasure training similar as on ISS would spend some 60 h per week in fighting microgravity pathologies. This is more than the time for a full working week of one crew member. A rotating spacecraft therefor saves, at least, the equivalent of one crewmember and its associated resources required for a round trip to Mars. See also Fig. 2G.

2. Discussion and conclusion

It is obvious that an ultimate future goal is to establish a rotating artificial gravity space station. Such a system has several benefits as addressed above. In addition a rotating station can also be used to test the response of the human physiology for long duration missions on to Mars by setting the rotation to generate 0.37 g. The same could be done for Moon g where the effects of 0.16 g can be explored without the dangerous cosmic and solar radiation present on the Moon's surface. These studies can be done in the relatively safe LEO orbit without going to Mars, in addition the very same system could be used for later transits to Mars.

As stated in the NASA Cross-Cutting Evidence Report [77] regarding Artificial Gravity under '*Tests Needed to Close the Gaps*' it is stated that "*We do not know if increasing the intensity of the Gz stimulus actually reduces the time of exposure needed. Consequently, the effects of gravity levels higher than 1 g on physiological functions definitely need to be further investigated.*". One of the possibilities is to establish a large diameter ground-based centrifuge for people to be exposed to a mild hyper-gravity level for weeks or months. With such a Human Hypergravity Habitat (H^3) – like system [153] we can explore and address this knowledge gap, but also other knowledge gaps identified in that Evidence Report could very well be addressed with a H^3-like system.

We have identified in this paper the positive effects of having an Artificial Gravity platform. However, there are also drawbacks in having such a rotating spacecraft in comparison with the current microgravity stations. This paper provided a broad overview of several aspects with respect to technology and operations that benefits from a large rotating system. However future studies should go into more details what the pro and cons are for each of the various (sub-)systems. As mentioned in the study by Joosten and colleagues [141], some 5 % additional mass is needed for an AG system.

In the current microgravity stations the crew can make full use of the 3D environment to move, work and leisure. An AG system is basically a more 2D environment which might be experienced as less spacious.

Also if additional counter masses are required for tethered systems or structural elements for a von Braun like donut configuration [154], one could reconsider the planned decommissioning and dumping ISS into the Earth's atmosphere in favour of making use of its mass for future stations.

There should also be an evaluation how the station would respond if it had to stop rotating. Systems that are needed and couldn't be shutdown during despun operations would still need to be certified for microgravity operations [155].

When we continue to explore the application of an in-flight rotating system, we need to have a comprehensive study where not only the engineering possibilities and safety gains are addressed but we also need to address the possible disadvantages regarding costs and mass of such a rotating system. However, the most leading benefit of providing Artificial Gravity is to give the crew an improved healthy and safe working environment [107].

One of the main requirements for the consideration and application of a large radius rotating space station is a paradigm shift from the current thinking regarding long duration human spaceflight and the application of multi-system countermeasures to fight microgravity pathologies.

We should not blindly take for granted the often used arguments of increased mass and cost. As far as we know there are only a few studies that seriously addresses these points and from this it appears that the additional cost for a rotating spacecraft is marginal. On the other hand very significant costs can be saved when there is a 1 g or partial g environment since crew time can be saved, less crew might be needed on long duration missions and 1 g ground-based widely used technologies can be easily applied in-flight.

An investment made in a rotating spacecraft is an investment in the wellbeing and health of the professional crew who are in space for prolonged periods of time and should be protected as much as possible against adverse working conditions [145,146]. Artificial gravity will also provide a pleasant environment for visiting commercial and non-commercial short-term visitors to such a LEO space platform not suffering from issues like space motion sickness or lower back pain etc. typical for initial periods in microgravity.

This paper is a first attempt of identifying the beneficial effects of permanent Artificial Gravity in a large rotating spacecraft including other aspects besides the crew health. However, additional detailed studies are required to specifically address the various more hardware related systems as well as the impact on *e.g.* crew time and operations but also on time and costs that could be saved in preparation of space.

CRediT authorship contribution statement

Jack J.W.A. van Loon: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Cesare Lobascio:** Methodology, Supervision, Writing – review & editing. **Giorgio Boscheri:** Methodology, Supervision, Writing – review & editing. **Clement Goujon:** Methodology, Supervision, Writing – review & editing. **Stefano Voglino:** Methodology, Supervision, Writing – review & editing. **Eleonora Zeminiani:** Methodology, Supervision, Writing – review & editing. **Ricard González-Cinca:** Methodology, Supervision, Writing – review & editing. **Reinhold Ewald:** Methodology, Supervision, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not make use of any AI assisted writing tool.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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