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ORIGINAL ARTICLE

The challenges and opportunities of designing pervasive systems for deep-space colonies

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1 Introduction

Space exploration is at an exciting yet challenging chapter in its history, with plans and preparations for the first human flight to Mars well underway. Our space flight capability has dramatically improved as a result of consistent technological advances coupled with a better understanding of the psychological and physiological effects of prolonged space flight on individuals and groups. Despite these advances, the usefulness and applicability of pervasive technologies (which is a mix of embedded, fixed and mobile networked interactive technologies) to space exploration is still limited, mostly restricted to tracking items onboard spaceships. While this situation is not likely to change in the near future, there still exists much potential for pervasive systems in the context of space exploration by humans.

In this paper, we consider how, in the future, pervasive technologies can assist humans in deep-space colonies when space flight becomes commonplace. By considering today's pervasive technologies in the context of deep space colonisation we make two contributions: (1) identify issues that future research should consider and (2) provide a shift in perspective which challenges the way we think about pervasive systems here on Earth. These two contributions are the challenges and opportunities of designing pervasive systems for deep-space colonies.

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In this paper, we draw on recent developments in large-scale pervasive systems that consider whole cities as systems, and consider how such systems can be developed for and used in deep-space. We highlight these differences by discussing three topics:

- environmental conditions
- infrastructure
- applications

For each topic, we analyse the impact of moving from Earth-bound to deep-space systems, and describe how existing technologies can be adapted appropriately.

2 State of the art

The next major milestone in deep-space exploration will be a human flight to Mars. Consequently, current HCI research in this area relates to the design issues arising in such a mission. Crews of long-duration space missions are exposed to numerous habitability, psychological, and interpersonal stressors, which are the results of the harsh living conditions, limited environmental cues, the amount of workload, lack of privacy, enforced social contacts, and separation from friends and family [1]. Research has begun to consider the effects of microgravity, confinement and isolation on cognitive and psychomotor performance [2–5], mood and well-being [6–8], and crew interactions [9–11]. A number of psychological countermeasures have been proposed, including remote monitoring of the mental and emotional state of the crew, and support to avoid feelings of monotony and boredom [12, 13].

In addition, substantial HCI and design research in the context of deep-space exploration has focused on developing expert tools to assist crews in troubleshooting operational issues and to provide psychological support. For example, extending the TRIZ approach (Russian acronym for Theory of the Solution of Creative Problems) [14], Whiteley et al. [15] propose the generation of a contradiction matrix as a structured approach to generate scenarios for the design of crew expert and assistance tools. This approach, used by the European Space Agency [16], relies on identifying physical and technical contradictions that can result in psychological challenges that crews must overcome during long-duration missions. Such structured techniques complement experience gained from the International Space Station and Mir Space Station, typically accumulated in mission reports but also in academic publications e.g. [17, 18].

Whiteley et al. [19] present a more concrete design, which outlines the development of a tool to support human crew in long-duration missions. To assist crew autonomy, this tool embodies a number of problem-solving techniques to assist with various operational aspects of a mission. The main design consideration is to reduce the number of instances where help from Earth is sought, as such requests may take up to months to complete depending on the distance to Earth. To achieve this objective, the proposed tool takes the form of a multifunction handheld device. This device can help the crew troubleshoot unforeseen circumstances, mitigate problems until help from Earth is provided, and help the crew locate items—a common problem on the International Space Station.

In considering and analysing physical space, literature in the domain of space exploration typically considers systems of components and their role in shielding the crew from hazards. For instance, the design of the Columbus laboratory, Europe's principal contribution to the International Space Station, is considered as a hierarchy of layers of protective shells that guard the crew from hostile external environments [20]. This approach helps to isolate and resolve problems with any component or shell. On the other hand, the literature for analysing urban space typically focuses on the relationships between spaces and how structure gives rise to various phenomena such as flow of pedestrian movement and land use [21, 22]. Finally, regarding the actual use of physical space on planetary surfaces, feasibility reports considering human flight to Mars envision a crew of six astronauts travelling to Mars in a habitat of 300–400 sq.m. and the potential of enlarging this space on the Martian surface using inflatable materials [1, 23, 24].

While current research focuses on the technological and psychological aspects of human flight to Mars and beyond, we now consider the use of pervasive technologies in a scenario where long-duration space flights are commonplace, and deep space has been colonised by humans. Our analysis evolves around three topics: environmental conditions, infrastructure, and applications.

For the purposes of this paper, we make certain assumptions, or predictions, about the colonisation of space. We assume that space colonies will consist of both planet-based and orbit-based structures. In both cases, those structures might support from a few dozen up to thousands of residents. Additionally, we assume that very few of the natural resources will be usable and that each colony will act as a resource and energy recycling unit. Thus, space colonisation will entail a number of self-sufficient units, some of which will be mobile (e.g. spacecrafts), while others will be static (e.g. a planetary-based).

While our assumptions may not fully reflect the actual state of space colonisation in the future, the basic premise of our analysis is that the pervasive systems used in space colonisation will eventually be derived from today's technology and knowledge.

3 Environmental conditions

Space colonies will face radically new and different environmental conditions and natural resources compared to Earth. For example, there is lack of water, wind, and atmosphere in the Earth-bound sense, yet space has to offer intense electron and gamma ray storms. Another notable difference is the presence of microgravity. Furthermore, energy efficiency and recycling becomes a key role in our colonies' ability to be self-sufficient. Finally, space becomes a luxury: colonies cannot simply extend their perimeter, or build more rooms, to "make more space". Let us now consider the afore mentioned issues in more detail.

In the traditional HCI sense, the lack of an Earth-like atmosphere has only one important consequence: humans cannot survive. This means that any human travelling "outdoors" will require a special suit simply to remain alive. In turn, the presence of this suit means that fixed and mobile devices are harder to use and operate. Additionally, devices that are usable indoors (such as a mobile phone) will not necessarily be usable outdoors due to the potentially cumbersome protection suit. While today's assumption is that mobile devices are usable both indoors and outdoors, this is not necessarily the case in deep space. Indoors and outdoors have completely different usability requirements when considering space colonies. In the rest of this section we consider "indoor" technology, unless otherwise stated.

An interesting issue to explore is the lack of gravity and microgravity. While this poses certain limitations to existing technologies, it certainly opens up numerous possibilities. A technology likely to suffer from microgravity is the mouse, whose operation in zero gravity becomes a completely new experience. Similarly, wearable technologies relying on accelerometers, touch, pressure, and human movement in relation to the physical environment (such as motion-sensitive tablets or touch screens) [e.g. 25] also become hindered. Other interaction techniques, however, should not be affected by the lack of gravity. For example, input methods utilising voice or hand gestures [e.g. 26, 27] generally do not rely on gravity.

On the other hand, microgravity opens up an array of possibilities. For example, rooms can utilise the floor and ceiling as additional surfaces for displays, information projection and input by humans. Additionally, the lack of gravity allows for really large interactive displays, for example 10 m by 10 m displays. Such displays are not possible on Earth because users physically cannot reach all parts of such a display. A further interesting property of microgravity is that users interacting with the same artefact do not need to be aligned in the same direction. On Earth, for example, multiple users operating a touch-screen need to have their feet on the floor, thus information needs to be rendered in an appropriate way (i.e. orthogonal to the direction of gravity). In the absence of gravity, however, spherical displays become a conceivable solution, as users can rotate themselves in order to interact with the object (as opposed to rotating the object itself). Such displays, which allow an arbitrary number of users to interact with them simultaneously, are currently tested on Earth [28].

Another natural resource that colonies and spacecraft need to carefully utilise is space. While open space is “free” on Earth, this is not the case in spacecraft since maintaining a human atmosphere in space is expensive. Therefore, space that is seldom used becomes a luxury and waste of resources. Hence, while on Earth we have public urban spaces such as parks and plazas, such concepts are unsustainable in a space colony. A most likely candidate for replacing parks and plazas is the notion of a shared recreational space that can be utilised for other purposes as well. It is certainly interesting to explore the impact of long-term deprivation of open public spaces, especially in terms of the culture of privacy of these spaces. For instance, the perceived privacy of bedrooms has progressed through a number of different stages on Earth [29], and we can expect the same to happen with shared entertainment recreational spaces in the absence of open spaces. Additionally, it would be interesting to explore the impact on pedestrian movement and encounter [30], and to study whether current models hold or break down. Research in virtual reality and immersive environments is considering redirected walking [31] and other compression techniques to minimise visual-proprioceptive conflicts when decoupling walking in physical space to the position in the digital space or immersive environment [32]. Such effects relating to the use of space need to be considered in designing pervasive systems for public and private use in a space colony.

The final natural resource we consider is energy. Currently, governments and organisations on Earth debate on global warming and the effect of human technology on the climate. A by-product of this debate is the focus on energy conservation and recycling, a concept that businesses are beginning to take adopt. In the context of deep space colonies, energy efficiency becomes crucial in the survival of the colony itself. In this sense, we can start thinking about energy-efficient interaction techniques. For instance, flat-panel displays consume more energy than speakers or headphones, and thus we should consider situations where it might be appropriate to replace screens with speakers. In addition to energy conservation, interaction techniques bear great potential for energy recycling. For instance, a user requires about 430 Joules to type an average of 1500 words per day,[1] while on average we expend 300 Joules a day on mouse usage.[2] In the absence of gravity, part of this energy expenditure could be recycled, for instance by recharging an energy unit attached to the computer. Similarly, interaction techniques relying on user movement, e.g. hand gestures and wearable computing, are another source of energy conservation, by converting part of users’ kinetic energy to electricity. Such energy-preserving interaction techniques should be considered orthogonal to conventional approaches to recycling energy, including harvesting energy from exercise equipment or normal human motion. Figure 1 provides some examples of the impact that scarce energy and weak or zero gravity can have on using interactive technology.

Finally, the use of the sun as a power source becomes crucial, and efficient ways of power sharing between users and mobile devices should be explored. With this in mind, we need to revisit an old chestnut of HCI design: hiding the infrastructure. A recent design approach, seamful design [33], suggests that there are benefits to revealing the underlying technology and its limitations, and highlighting the situations where it breaks down, i.e. the ‘seams’. We can consider applying this design paradigm to deep-space pervasive systems, given that users are accustomed and expect the wall sockets to behave in a certain, reliable, way. In addition to the energy aspects of infrastructure, we must also consider the technological aspects of the infrastructure for deep-space pervasive systems and how it is likely to be different from the Earth’s infrastructure. We explore these issues in the following section.

4 Infrastructure

In moving from Earth-bound to space-bound pervasive systems, we can expect network delays to get longer and

[1] See http://search.cpan.org/~mndrix/, last accessed 4 May 2007.

[2] Assuming a 100-g mouse, and a daily mouse movement distance of 30 m.

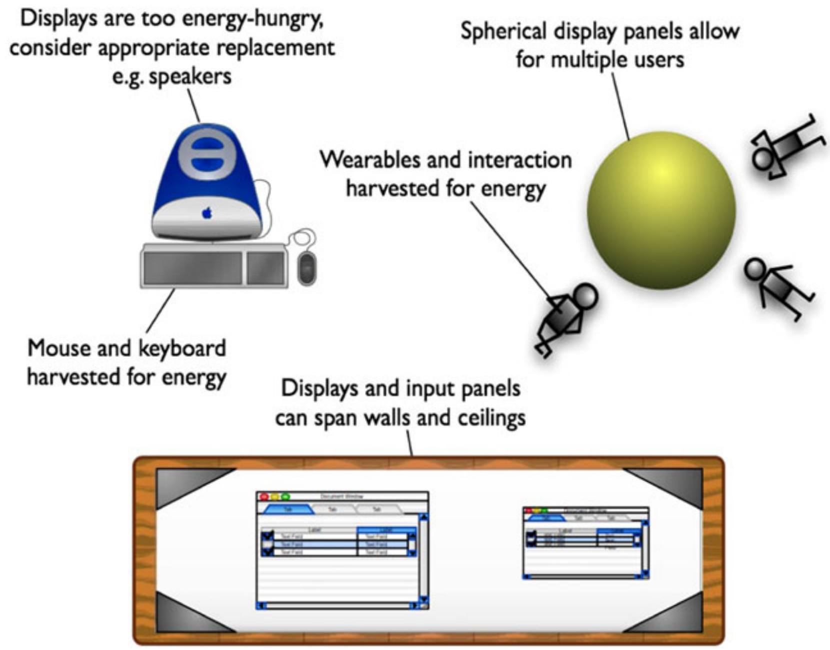

Fig. 1 Examples of how energy considerations and zero gravity can affect interaction techniques

shorter at the same time. The vast transplanet distances introduce delays in the order of minutes and hours, assuming that our communication cannot travel faster than the speed of light. At the same time, however, we can expect technologies deployed within planets or orbiting stations to become much more efficient and thus reduce the delays locally. The resulting effect on the use of interactive communication technologies profound.

While on Earth the telephone, instant messaging, chat rooms and online gaming bring users closers, it is challenging to fully grasp the longitudinal effects of introducing significant delays (e.g. 1-h delays) to all means of communication. To begin with, conversations are simply impossible to have, regardless of the medium used. While email is designed to cope with long delays, we need to consider how other communication technologies can adopt an "email approach" to communication. For example, are voice recordings a viable alternative to telephone communication? Although today we have the capability of sending voice messages via email, we still prefer written email. Similarly, mobile phones are increasingly being used for text messaging. Plain text is, effectively, a truly pervasive "technology", as it is easy to transfer, store, process, and represent. Hence, we can hypothesise that text is the best candidate technology to be used in transplanetary, delay-prone, human to human communications.

The issue of delays at the infrastructure level can be addressed technically with the use of Delay-Tolerant Networks (DTN),[3] which are conceptually quite similar to the FidoNet[4] used mainly by Bulletin Board Systems in the 1980s. Such systems embrace delays and offer a layer of abstraction to conceal unavoidable hold-ups. Thus, DTNs can be utilised as a backbone for connecting deep space colonies with Earth, while at each colony a local "Internet" can be deployed (see Fig. 2). A further technology, caching, can be used to counter delays in communication. With the use of caching and duplication, information can appear to travel faster than the speed of light. Systems such as Google's caching[5] or the Internet archive[6] are ways in which information browsing and accessing can overcome delays. An approach would be to have multiple "Google" archives serving different parts of our deep-space network. This means that interactive systems, such as online shopping, real-time searching or any other systems that rely on real time transactions, must reconsider their operation by embracing caching and delays.

Another infrastructure issue closely related to delays and caching is coordination. Pervasive technologies, object tagging, and real-time system adaptation rely on minimal delay between computational entities and the ability to coordinate actions at multiple locations. Due to transplanetary distances, the relativistic nature of time becomes crucial, and we are forced to seek appropriate ways of synchronising our systems and communications. From a user perspective, whether walking, sleeping or eating, other users are always on the move—in relation to Earth, other planets, and other spaceships. Thus, while location retains its locative importance, proximity becomes a key concept

[3] See http://www.dtnrg.org, last accessed 22 January 2007.

[4] See http://www.fidonet.org, last accessed 22 January 2007.

[5] See http://www.google.com, last accessed 13 May 2007.

[6] See http://www.archive.org, last accessed 13 May 2007.

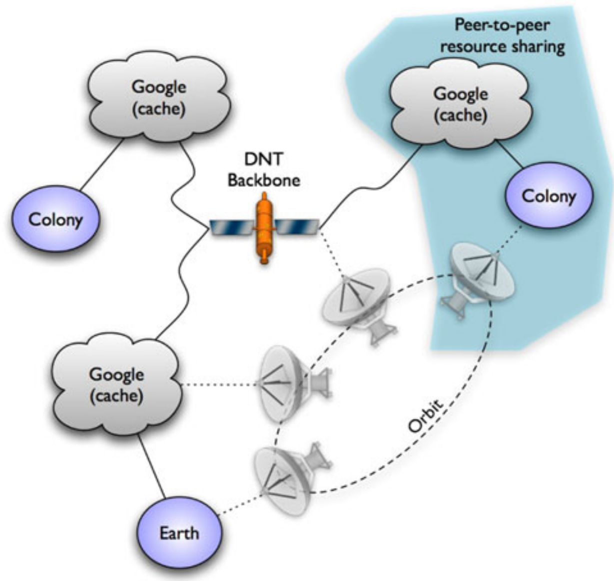

Fig. 2 Sample architecture for transplanetary communication. The orbiting station's proximal entities change over time. Resource sharing happens in a peer-to-peer fashion. Also, a DTN backbone can be utilised to connect remote sites

that also needs to be conveyed (e.g. "John is at home, which today is 1 light hour away"). Since location is relative, as any arbitrary frame of reference cannot deal with relativistic time and distance, proximity is an appropriate alternative concept since users are already familiar with it. Users already have experience in "being within range" of WiFi or a cell phone tower, "out of range" for Bluetooth connectivity, line of sight, and interference, relating to the availability and operation of technology. Therefore, we can hypothesise that the concept of proximity is an appropriate abstraction to presenting to users of transplanetary communication and interactive systems.

If proximity becomes the defacto communication abstraction, then all systems can be considered to operate in a peer-to-peer fashion. To carry on from the earlier example of multiple (Google) archives serving different parts of deep-space colonies, users would use the system nearest to them—the one in closest proximity. In addition to the "local" systems—the ones that users can reach with minimal delays—users can also link with systems further away using peer-to-peer, proximity-based mechanisms. Thus, the metaphor of "online navigation" becomes indeed a search through space, such as attempting to logon to the nearest transplanetary email server. As a peer-to-peer system, resources cannot be taken for granted, but rather depend on the proximal entities at any given moment. Thus, a most mundane task such as checking one's Hotmail account—historically advertised as "email everywhere"—becomes an almost impossible task when considering distances of the order of 1 light hour.

5 Applications

While it can be premature to begin considering killer apps for deep-space exploration and orbiting stations, we can begin to explore the novel aspects of those communities and the effect of these aspects on interactive technology. Based on such an analysis, we can reflect on how our current applications can be adapted or extended. Certain novelty points to keep in mind are the ones we presented in the previous sections, which include the following:

- Differences in gravity
- Energy-aware and energy efficient interaction techniques and techniques
- Introducing delay and caching to interactive systems
- Shift from location-based to proximity-based models of interaction
- Replacing client–server infrastructure with peer resource sharing

In addition, there are certain social parameters we can consider, which effectively define the domain of our potential applications. One such aspect is the purpose of deep-space colonies. Will those communities be similar to military bases or will they be more like neighbourhoods? This distinction does not necessarily reflect the physical structure and layout but rather social structure. A characteristic of military-like colony is that personnel act as a unit, with well-defined structure in people's behaviour, encounter, and movement. Alternatively, a neighbourhood-like colony involves much more entropy in people's movement, encounter and behaviour.

Another shift we must consider is that travelling becomes expensive for humans. Today, on Earth, many meetings take place in person because flying by plane and travelling has become affordable and efficient. If this is not the case in deep-space communities, the implication is a necessary move towards transpatial technologies for collaboration. Thus, it is conceivable that people spend their whole lives interacting with colleagues whom they have never met in person. Therefore, the existing collaborative tools need to be adapted for use by space inhabitants and their requirements.

In addition to the issues we have highlighted so far in this section, we consider two potential applications, or rather, potential systems. These are the smart home, and the smart city. Here, we briefly sketch how the requirements of deep space colonies affect the design decisions to be made for each of these types of systems.

6 The smart home

Deploying our existing systems and understanding for building smart homes in deep space is a major challenge.

By smart homes, we refer to homes that can sense and react to their residents' actions. The main obstacle in deploying such systems in outer space is the lack of gravity, or microgravity. Currently, our systems for detecting users' activities in the home rely on motion sensing using accelerometers worn by the users [34]. The models we have developed assume the presence of gravity and its effect on people's movement and actions while carrying out any given activity in the home. Without gravity, our activity detection models become invalid. This, however, does not nullify our understanding but rather requires us to carry out extensive data collection on people's movement while in zero gravity.

A further effect of zero gravity is its impact on people's mobility throughout the home. Consequently, our systems are likely to suffer if they rely on users' movement between different spaces, in the home or the effect of people's movements on various household objects. For instance, many systems rely on pressure sensors for detecting the inhabitants' location and subsequently activating nearby devices or screens [35]. Such systems cannot operate without gravity and therefore must be adapted in order to incorporate technology that can detect people's presence when they are hovering in space. Similarly, the longitudinal patterns of movement between the different rooms in a home may be affected by the lack of gravity. For instance, inhabitants of deep-space colony smart homes might be inclined to minimise their movements, as opposed to "wonder around the house", or the opposite. Once more, this implies that extensive data gathering would be required to build accurate models of user behaviour in a zero gravity home.

In terms of domestic interaction techniques, an interesting technology to consider is the "everywhere" technology, consisting of a wall-mounted projector with a rotary motor [36]. Such technology is quite appropriate for displaying information in any part of the room or any orientation. This would work quite well in environments where people are not aligned in the same direction but rather all use different surfaces of a room for work or play. We should also note that because smart homes will be built from scratch, it would be much easier to embed in them the required sensors and actuators. This will require a collaboration effort between computer scientists, engineers, and architects in order to produce fully functional yet inhabitable homes.

7 The smart city

While homes, whether smart or not, act as a city's building blocks, city planning begins at a much higher level. Typically, city planning involves generating adequate public spaces, ensuring the shops, malls, schools, and hospitals are distributed appropriately and considering the effectiveness of the street network. The architectural community has long been involved in producing the perfect city, the classic example of such an attempt being Brasília, which implemented the "Athens Charter".[7] This charter, dating back to 1938, lays out the foundations for planning and construction of rational cities, addressing topics such as high-rise residential blocks, strict zoning, the separation of residential areas and transportation arteries, and the preservation of historic districts and buildings. The key underlying concept of the charter was the creation of independent zones for the four "functions": living, working, recreation, and circulation.

While the Athens charter has received criticism about its lack of appreciation for the richness of social aspects of cities,[8] it still highlights the fact that architects and urban planners have long considered the design of perfect cities. We can expect urban designers to adopt a similar approach when designing the cities for deeps-space colonies, attempting to provide both a functional and socially viable design.

In this context, there are at least two possible scenarios in which we can consider the differences between deep-space cities and Earth cities. First, we can consider orbiting cities characterised by weak gravity, limited public spaces, and having a specific purpose or operation such as acting as a refuelling station or telecoms provider. Alternatively, we can consider cities that have been established on planets and gradually grow to accommodate the functionality and requirements of its inhabitants. In both cases, there are a number of ways in which pervasive technologies can be embedded in the city in order to make it a "smart" city. By smart cities, we mean cities that can sense what its residents are doing and also react to better accommodate the specific needs of residents.

An ideal use for pervasive technologies in smart cities is to maintain living conditions throughout the urban environment. This involves monitoring for oxygen levels, toxic levels, atmospheric pressure, as well as detecting atmospheric leaks. Also, actuators can utilise environmental sensing information and intervene whenever is needed. In addition to maintaining living conditions, smart cities can also utilise energy more efficiently. This can be done in a number of ways. For instance, technologies can be activated only in the presence of people—a concept quite similar to the motion activated lights in certain buildings on Earth. In addition to the on/off states, however, technologies can operate in intermediate modes of energy consumption, based on various parameters such as the

[7] http://en.wikipedia.org/wiki/C.I.A.M, last accessed 20 May 2007.

[8] http://www.team10online.org/, last accessed 20 May 2007.

number of people within vicinity or time of "day". For instance, a public display might operate in sound-only mode when fewer than 10 people are within its range, while for more people it can also activate the visual aspect of the display. Moreover, publicly usable technologies can be adapted so that they become energy efficient themselves, as discussed in the earlier sections.

Further efficiency gains can be realised by adequate and accurate modelling of pedestrian movement and behaviour. Developing such models gives us the additional ability to effectively manage the movement of people across the city. Pedestrian management can be guided by a number of objectives, including minimising wear and tear of the city's infrastructure and optimising the flows of people. With appropriate interactive technologies, including public and personal devices, pedestrians can be advised of the routes to follow for any specific destination.

Beyond the management of people, pervasive technologies can be utilised to manage the flow of information across a smart city [37]. In the context of space colonisation, cities act as self-sustained units, similar to the concept of city-states in ancient times. Thus, a city will require the infrastructure that today can be found spread throughout multiple cities or even countries. Such infrastructure includes energy and resource management, waste management, transportation, defence and security, telecoms, health, and education. The informational requirements for maintaining such an infrastructure are complex, considering that numerous networks of people require varying access to information about the smart city's infrastructure. To address these requirements, urban sensing technology such as Bluetooth sensing [38] allowing for the sustained operation of this infrastructure can also be used for decision-making by central authorities, as well as decision-making by the inhabitants of the city.

8 Epilogue

We conclude by turning our attention back to the human and considering the implications for the quality of life of inhabitants of space colonies. A debate that needs to take place must explore the tension between two conflicting sets of requirements in the development of space colonies: engineering and civic requirements.

As we have described so far in this paper, we need to build colonies that are sound from an engineering perspective, functionally efficient, robust, adaptive, and to a certain extent capable of self-healing. These requirements prescribe the use of numerous sensing technologies, scanning technologies, security measures and countermeasures, as well as control and management systems. On the other hand, civic requirements include freedom, choice, and privacy. These are rights that modern cultures value extensively to the extent that wars and revolutions have been fought to gain or preserve them.

While the engineering requirements of space colonies aim to sustain and protect life, at the same time they appear to take away certain high-valued qualities of life such as privacy. In fact, space colonies are prone to becoming miniature Orwellian societies. However, a crucial point we need to consider is that the technology in space colonies is in place to protect life; in Orwellian societies, the technology is used to control life. We must therefore aim to develop technologies, both interactive and non-interactive, that preserve life and at the same time distribute control. This is not an easy task, given the vast differences between Earth and deep space colonies, both in terms of natural resources (see Sect. 2) and infrastructure requirements (see Sect. 3).

In this paper, we have highlighted some of the challenges, as well as opportunities that space colonisation offers for pervasive technologies. While we are still far from building orbiting cities that can accommodate thousands of people, we can still consider how today's technologies need to be adapted in order to achieve such a feat. Here, we provide an overview of these issues, focusing on environmental conditions and infrastructure requirements. In terms of applications, we consider the smart home and smart city, and draw on certain issues for research and debate. While there is great potential for building deep-space colonies, ultimately our technology and systems need to provide enough benefit so that people can positively answer the question 'do you want to live in a space colony?'

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