30 Sensors to Mars: Toward Distributed Support Systems for Astronauts in Space Habitats

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***Abstract*—In October 2017, an international crew participated in an emulated Mars colonization mission. For two weeks, they stayed confined in a special complex, a so-called analog habitat, where they were isolated from the outside world, including a lack of natural lighting and exterior noises, and lived on particularly adjusted Martian time. The mission followed a strict schedule, involving actual scientific work and activities envisioned as necessary for survival and exploration of the red planet. The main objective was to study the behavior and group dynamics of the crew in conditions recreating colonization of Mars, albeit under some unique circumstances compared to previous similar experiments. What was also special about the mission was the use of sociometric methods utilizing custom pervasive sensing solutions that we had built and deployed to complement classic methods based on self-reports and interviews.**

Based on that experiment, in this paper we contribute twofold. First, we share our deployment experiences to highlight the potential of pervasive distributed sensing systems in sociometric studies of habitat-based missions. The examples presented to this end include quantitative results that we obtained, among others, on social interactions between the astronauts, the impact of atypical situations on the crew, and the ergonomics of the habitat. Second, drawing from the experiences, in cooperation with the astronauts we attempt to highlight some unique challenges that space habitats pose for distributed support systems, such as ours. Among others, the challenges pertain to system deployment, autonomy, resilience, and flexibility. We believe that these challenges and, in general, space colonization constitute exciting research opportunities for the distributed systems community.

***Index Terms*—space colonization, astronaut, habitat, analog mission, behavioral study, sociometric system, distributed sensing**

I. Introduction

For many years, our civilization has aspired to becoming multiplanetary [1], [2], [3] but it has been only recently that ventures aiming to reach this goal, notably by colonizing Mars, have attracted a lot of interest and support. Such ongoing colonization initiatives [4], [5], [6] inherently put an emphasis on technologies that would ensure safe and efficient transportation to the red planet and survival in its hostile environment. Nevertheless, a potential manned mission to Mars has to face also different types of challenges: ones that are not of a technical but sociopsychological nature.

More specifically, while on the red planet, the first astronauts will likely be forced to stay in an isolated and confined environment, a so-called *habitat*, which will maintain atmosphere, radiation, temperature, and other life-critical parameters at levels tolerable by humans. Such living conditions raise concerns about the behavioral health and performance of the crew [7], [8], especially since similar settings, like space flights [9], [10], [11], polar missions [12], or submarine expeditions [13], have already proved to be problematic from the sociopsychological perspective. What is more, apart from the inconveniences of the habitat, homesickness, and stress, the crew may themselves be a source of behavioral tensions. In particular, different objectives and cultural backgrounds of astronauts have already been known to contribute to group conflicts or individual mental issues [14], [10]. Consequently, the enormous impact that a manned mission on Mars will have on humanity, not to mention its huge costs, requires minimizing the risks posed by such sociopsychological factors.

This is done by emulating extraterrestrial missions on Earth to collect relevant sociopsychological data, analyze them, and develop appropriate procedures and practices. In such a mission, referred to as an *analog mission*, a crew of astronauts is deployed in an Earth-based habitat to perform real tasks envisioned as necessary during the actual colonization, and various behavioral parameters of the crew members are regularly monitored [15], [16], [17]. As we elaborate in the next section, to date such monitoring has been conducted mainly through diverse surveys or medical examination, for instance, daily interviews or frequent blood tests. However, these classic methods exhibit numerous shortcomings, which we believe can be addressed by additionally employing sociometric technologies based on distributed sensing systems. Although such technologies have already been utilized for different studies in social sciences, missions in habitats pose unique challenges, including the isolation, small subject populations, peculiar activities the subjects engage into, and a need to focus not only on large-scale trends but also individual events. At the same time, to the best of our knowledge, little work has been done on developing and deploying distributed sensing systems for behavioral studies of astronauts in habitats.

In this paper, we make a step toward bridging this gap and argue that distributed sensing systems for behavioral monitoring of astronauts as well as for supporting them in other aspects of their missions may be a cornerstone of successful colonization of Mars. Our contributions are twofold. First, we share our experiences from one of the analog habitat missions conducted with a distributed sociometric system that we had developed. Second, based on these experiences (as well as those from an earlier mission), we highlight the challenges and research opportunities that habitat-based settings and colonization missions offer for distributed systems.

The considered mission involved a commonly-sized international crew of six astronauts. It was conducted for a period of two (terrestrial) weeks within a professional habitat, in which we were allowed to deploy 30+ wireless sensors, notably our custom wearable sociometric badges [18] that had been utilized in a few earlier successful sociopsychological studies in different settings. Apart from the use of this technology, some aspects of the mission were unprecedented also from the astronautical perspective, especially participation of a physically impaired crew member, which all in all gives a lot of unique insights that we believe are worth sharing.

After surveying related work in Section II, we start by presenting the most relevant details of the mission in Section III. In Section IV, we explain our sociometric methods and technology, followed in Section V by examples of results from the mission. In Section VI, we outline some of the research challenges that we learned space habitats offer for distributed systems. Finally, in Section VII, we conclude.

II. Related Work

Being primary opportunities for research on Martian habitats, analog missions emulate numerous known aspects of real missions: their crews are formed of carefully selected candidates, the habitats feature professional infrastructure envisioned as suitable for colonization, and the crew members perform tasks and follow rigorous astronautical procedures that are known as necessary for survival on the red planet and exploration thereof. This faithful reproduction of Martian missions and use of state-of-the-art technologies in habitats is in stark contrast with the methods that have been employed to date to understand behavioral dynamics of the crew: in a great majority of past analog missions, classic methods based on self-reports, surveys, and interviews were adopted [8].

The classic methods exhibit limitations and various forms of bias that have been widely recognized [19], [20]. Consequently, modern sociopsychological studies increasingly combine them with quantitative approaches based on sensing and computing technologies, even to the extent that warrants creation of new fields of science [21]. In the context of pervasive sensing technologies, especially computer vision, smartphones, and wearable multi-modal sensing devices, often custom ones, have become popular. Among others, such technologies enable analyzing the appearance, voice, movement, orientation, and proximity of the experiment participants, and such analyses often yield compelling quantitative results regarding not only individuals but also groups of people.

To illustrate, it was demonstrated that interpersonal relationships can be inferred from phone call logs and proximity data [22], and social activities of individuals can be classified by means of smartphones [23]. Correlation values were computed between behavioral metrics and personality traits [24], and it was quantitatively assessed to what degree different cultures shape contact patterns [25]. A new concept of communication richness was showed to be a key factor influencing productivity of software engineers [26], and it was measured how multitasking and social interactions affect employees' concentration [27] and moods [28]. Moreover, by quantifying social contacts, infection transmissions were investigated [29], and terms that had been abstract before, like "trust" [30], were operationalized in terms of computational models. Finally, quantitative data was presented on how work performance is influenced by factors such as physical space design [31], schedule of work breaks [32], [33], or temperature and noise [34]. All in all, these few selected examples already show the potential results that sociometric methods based on pervasive sensing could yield during missions in habitats.

Yet, while to date these methods have been utilized in numerous settings, including offices [26], [33], social events [35], schools [36], hospitals [37], and museums [38], to name just a few applications, analog missions in habitats have hardly been targeted. A major problem is the very nature of such missions.

On the one hand, the absolute confinement ensured by habitats precludes any intrusive on-demand observations, involving real-time communication with astronauts or their advanced examinations. As a result, only the astronauts themselves can be trained to conduct certain procedures and only with the equipment available in the habitat. Moreover, these procedures and equipment must not impair the core mission activities the astronauts engage into. To illustrate, in recent missions, some crew members were specifically trained and equipped to perform on-site blood tests [39] or analyses of saliva, urine, breathed air, and ECG and EEG measurements [40], which aimed to enable assessing individual levels of stress hormones and emotional reactions to various stimuli [41].

On the other hand, automated continuous monitoring of astronauts must not violate their privacy. Consequently, certain types of effective sensors, like cameras, often cannot be deployed in a way that would enable drawing meaningful conclusions. To be concrete, we are aware of only one attempt to using video recording and automated visual recognition for detecting the emotions of the crew members [42]. Nevertheless, even in that case, the settings were rather peculiar.

Analog missions in habitats thus indeed present unique challenges for developers of sociometric technologies based on pervasive sensing. To the best of our knowledge, just a single recent study independent of our work has started quantitatively analyzing social activity and teamwork of astronauts by means of custom wearable sensing devices [43]. However, there have been no published sociopsychological results nor data on technical aspects of this project, apart from a presentation with general information on the executed and planned experiments [44]. What is more, as mentioned previously, the mission presented here was unprecedented in several aspects, which to some extent was dictated by the need to evaluate our technology in scenarios that diverge from the hoped-for ones.

This paper is thus arguably the first to highlight the possibilities that pervasive sensing technologies offer for sociometric studies of analog missions and to discuss the concerns that have to be addressed when turning such technologies into future systems dedicated for behavioral monitoring of astronauts in habitats. We focus mainly on technical aspects of such monitoring, leaving detailed analyses of sociopsychological phenomena during the mission for separate papers. Nevertheless, to support our claims, we do present examples of such phenomena observed thanks to our solutions.

III. Mission ICAres-1

The selected mission, ICAres-1, was organized in 2017 and received considerable local media attention. It started on October 8 and lasted until the early morning of October 22. For these two full weeks a crew of six astronauts lived in an isolated and confined habitat that emulates conditions expected during Mars colonization. The participants behaved as though the mission had been real, while the situations they were put into had been directed by a group of researchers. The study aimed at gaining insight into perception of time in response to clock shifts, finding potential impact of delays in communication between Mars and Earth, and, above all, verifying if state-of-the-art technologies and standardized procedures remain effective in case of potential accidents. Next, we give details on the habitat, the activities involved in the mission, and the crew, as well as highlight unique aspects.

A. Habitat

ICAres-1 took place in Lunares [45], a professional habitat in Pila, Poland, combining an emulated space base with a research laboratory. Its location and construction made the astronauts absolutely isolated from the outside world. There were no intruders, no urban noises, and no light other than artificial lighting that corresponded to Martian time of day. The only people who were able to exchange messages with the crew was the so-called *mission control*, that is, a group of professionals who supervised the experiment from a facility almost $200\,\mathrm{km}$ away. Moreover, the communication was delayed by $20\,\mathrm{min}$, reflecting a possible Earth-Mars latencies.

The habitat itself consists of separate modules of distinct kinds and purposes: a bedroom, kitchen, office, biological and analytical laboratories, an equipment storage, gym, and bathroom, which are all arranged in a semicircle with a place to rest in the middle. During the mission the only available exit led via an airlock to an isolated hangar, where Martian regolith, with sand, rocks, and other irregularities, was imitated.

B. Activities

Each of the 14 days in the habitat was filled with demanding tasks. Most of them, like conducting experiments on potentially useful parasitic species, taking care of an indoor hydroponic garden, or designing and 3D-printing specialized equipment, required skills and expertise in certain fields. Another challenging kind of tasks was extravehicular activities (EVAs), performed on the artificial Martian surface in an outdoor outfit imitating an actual space suit. For the faithfulness of EVA emulation, meticulous preparations and post-EVA procedures were adopted, lasting approximately $30\,\mathrm{min}$ each. EVAs themselves involved in turn steering semi-autonomous rovers and testing a lightweight electric wheelchair, adjusted to possible use cases on Mars.

All of the activities had been determined a priori and organized into a strict and precise plan, divided into $30\,\mathrm{min}$ slots. Each crew member was expected to follow their own schedule for a given day, which regulated $14\,\mathrm{h}$ of daytime and included only two $30\,\mathrm{min}$-long breaks. While $1.5\,\mathrm{h}$ in total was spent on eating meals, for the remaining $11.5\,\mathrm{h}$ the astronauts were supposed to work on their tasks in full seriousness: the experiments and tests were not merely a mean to emulate Martian expedition, but had their own scientific purpose. Consequently, hard work of astronauts could potentially lead to novel publications in their respective fields, which presumably improved engagement and discipline of the crew. On the other hand, the pressure to complete individual tasks on time as well as their high level of difficulty severely constrained the opportunities in which the crew members were able to socialize. These circumstances and the fact that the astronauts had barely known each other before the mission let us expect occurrences of relevant sociopsychological phenomena, which our sociometric solutions aimed to help detect.

C. Crew

The crew was international and consisted of 3 women and 3 men. This is a representative crew size envisioned for the colonization as well as adopted during many previous analog missions. A major reason is the amount of resources (e.g., space, oxygen, food, equipment) that can be secured during a flight to Mars and later in a habitat. Moreover, in large teams the performance of individuals declines [46], partially because of the surging number of links managed among the team members, which make cooperation impractical to handle [47]. Consequently, even though such a subject population seems small compared to previous sociometric research in different settings, it is to be expected in Martian habitats.

Attracting tens of volunteers per position, recruitments for analog missions are multi-stage and extremely selective, and the considered mission was no exception. In particular, the crew members had second-class medical certificates for pilots or professional drivers (apart from one person, as we explain shortly). They had undergone additional medical and psychological examination, as well as various types of training, such as aerodynamic tunnel training, outdoor survival, advanced medical emergency techniques training, or helicopter underwater escape training, to name a few examples.

Each of the participants was then given a position in accordance with their competences and experience. For instance, Commander of the mission had already spent more than a year on similar projects, Chief Medical Officer had graduated in both Astronomy and Medicine, while Structural Material Scientist was pursuing a doctoral degree in Engineering. The astronauts, aside from performing their duties, formally agreed to undergo all necessary procedures dictated by the mission targets. Their commitment to stay in the habitat and complete the goals is worth even more respect considering the unique nature of the mission, as discussed next.

D. Extraordinary Aspects

Before ICAres-1, analog missions were based on the assumption that astronauts were perfectly fit and healthy, which would likely be the case on their launch day. However, a space flight and the hostile environment of Mars pose a high risk of situations that may lead to serious injuries or even casualties among the crew. Space agencies have to prepare for such scenarios, and ICAres-1 provided opportunities to attempt to answer some relevant questions, like: Would disability of an astronaut stop them from participation in daily activities? Would it become a burden for the group? How would a sudden death of an astronaut impact the performance of the crew? What impact a food shortage may have on the astronauts?

Investigation of these and related issues made the mission unique. First, one of the astronauts, referred to as astronaut *A*, was visually impaired and had no left hand nor three fingers in the other palm. Nevertheless, no allowances were made for them: *A* attended all team activities and followed the schedule of tasks that was demanding even for someone with no disabilities. Another astronaut, astronaut *C*, left the habitat on the fourth day of the mission as virtually dead. Despite this emulated tragic event, the crew had to continue and take over the responsibilities of astronaut *C*. Finally, on the eleventh day of the experiment, an extreme shortage of resources was announced, in particular resulting in meagre rations of food: under $500\,\mathrm{kcal}$ per day for each person.

E. Summarizing Remarks

In summary, analog missions are costly and intricate to organize. Habitats have specific arrangements and equipment, matching as closely as possible the settings they emulate. Astronauts are carefully selected and trained to maximize their performance and dedication, not only individually but also as a team. The activities they engage into are of a specific nature, which requires meticulous planning and often strict safety measures. In this light, deploying extra technologies and adopting further procedures is typically considered as a huge risk. In the case of ICAres-1, the risk was further aggravated by those aspects of the mission that had been unprecedented also from the astronautical perspective, and hence aroused great expectations. Therefore, we believe that our sociometric experiences from the mission are indeed of value.

Fig. 1: A crew of analog astronauts wearing our badges during an earlier mission in Lunares, Lunar Expedition 1 (photo by Mariusz Słonina).

IV. Sociometric Methods and Technologies

Since video and audio recording in the habitat was prohibited for legal, privacy, and other reasons, at the heart of our sociometric methods lay multi-modal sensing badges [18], which we had designed, built, and earlier deployed in a range of different settings. A prominent example of those deployments was a couple of commercial companies, where the badges had allowed us to distinguish formal and informal meetings and describe their dynamics, detect communities formed among employees, quantify significant differences between working styles on different positions, and identify the impact of environmental conditions and workplace arrangement on employee performance, to name just a few findings. Among others, it was such compelling results—and the new possibilities they offered for the company managers—that made the organizers of the mission decide to adopt our solutions for ICAres-1.

Our badge is designed as an unobtrusive wearable device (cf. Fig. 1). Its dimensions are $140\,\mathrm{mm} \times 84\,\mathrm{mm} \times 10\,\mathrm{mm}$ and its weight, including all electronics, a battery, a 3D-printed casing, and a cord, is just $111\,\mathrm{g}$, which makes it suitable to be worn on a neck of an astronaut without severely constraining the activities the bearer is expected to perform. This well-defined on-body position also facilitates interpreting the readings of the badge sensors, and hence monitoring the bearer and their environment. A detailed technical specification of a badge and more information on its sociometric capabilities can be found in the aforementioned paper [18]. Here, in turn, we just give a brief overview.

In a nutshell, the basic sensors of a badge include an accelerometer, magnetometer, gyroscope, thermometer, barometer, light sensor, and microphone. Because of the aforementioned constraints, especially the microphone is worth elaborating on: we used it to detect the presence of human speech, its loudness, and frequency, notably for identifying the speaker during a multi-person conversation and distinguishing between male and female speakers; we did *not*, however, record raw data from conversations.

Apart from these local sensors, a badge incorporates three wireless communication interfaces, which also act as sensors of interactions with other badges: an $868\,\mathrm{MHz}$ radio, a 2.4 GHz Bluetooth Low Energy (BLE) radio, and an infrared transceiver. The two radios, with omnidirectional antennas and different signal attenuation properties, serve as proximity sensors, used for detecting nearby badges and for indoor localization. The infrared transceiver, with a well-defined directional communication cone, enables in turn assessing whether two badges are truly close and face each other, so that it is likely that their bearers may be having a conversation.

A badge also has a few input-output interfaces, which, however, we barely used during the deployment. Similarly, although it is operated by a relatively powerful ARM-based microcontroller, its computational power was hardly utilized. Instead, because of the novelty and unpredictability of the deployment, we decided to collect frequently sampled raw data and store them on an on-board SD card for offline analyses. Since this decision inherently led to increased energy consumption, we required each badge to be charged overnight.

We assigned one badge to each astronaut and asked them to wear the device for the whole time they were on duty, that is, for about 13 hours. For the remaining time, the badges were expected to be connected to a charging station. At the station, we also deployed an additional reference badge, which was permanently being charged, sampled environmental sensors, and served for the other badges as a time source, with which they communicated opportunistically. In effect, we were able to compute clock shifts between distinct devices and compare their sensor readings to the reference ones. Since after the start of the mission nobody was able to access the astronauts, we also provided them with 6 redundant backup badges, in case their assigned ones failed. We did not replicate the reference badge because the risk of its failure did not warrant the effort necessary for implementing failover software and procedures.

Apart from the badges, we were also allowed to deploy in the habitat 27 BLE beacons (cf. Fig. 3), each of which broadcast a message announcing its presence approximately three times per second. Every badge recorded these messages together with the received signal strength indicators, which later was fed into a positioning algorithm based on triangulation. As we learned in preliminary experiments, because of the construction of the habitat and the carefully selected placement of the beacons, the accuracy was high even without employing the inertial sensors of a badge. In particular, the room the badge located in was detected perfectly.

What is more, we considered deploying several additional types of wearable sensors. They would have integrated well with the system through the BLE interfaces of the badges. However, ultimately they did not find their way into the habitat, mainly because they matched poorly the specific nature of the mission. For example, galvanic skin response and optical heart rate sensors we had access to would have impaired many activities the astronauts were expected to perform, particularly in the laboratories. Other medical sensors were even more inconvenient or violated the privacy regulations of the mission. Apart from that, any extra devices would have necessitated additional procedures governing their usage and charging, thereby putting yet more load on the astronauts. In any case, however, in line with our prior experiences in other settings, the results from the missions confirmed that, even on their own, the badges are a powerful sociometric technology.

Finally, to complement our technical solutions, we also made use of classic surveys. They were prepared so as to minimize the overhead necessary to complete them while delivering information that was important from our perspective. More specifically, they were filled in by each astronaut every evening and questioned their levels of satisfaction, well-being, comfort, productivity, and distraction. Among others, the answers allowed us to interpret and verify the findings obtained through multi-modal sensing. Our conclusions were also cross-checked with the reports from astronauts on unusual events and the detailed schedule of the mission. In other words, we strove to verify every single result we obtained with our sociometric technologies, which was a laborious process.

V. Sample Results

The astronauts started wearing their badges on the second day of the mission since on the first day they needed time to get accustomed to the habitat and its equipment. For the remaining 13 days, we secured 150 GiB of data. An average badge was worn for 63% of daytime and for 84% of daytime it was active but not necessarily worn on the neck. The reasons for this were mostly of a technical nature: the crew was not allowed to wear our badges during EVAs—when dressed in an outdoor suit; neither were the devices worn in restrooms and during physical exercises. Nevertheless, the amount of the collected data was more than sufficient to make statistically meaningful observations on the participants and the habitat.

Overall, the application of our technology was a success, yielding many novel results. Detailed analyses of the results relevant from the sociopsychological and astronautical perspective have been and will be subject to separate publications. Here in turn we present only a few samples of them, to exemplify the kinds of observed phenomena and substantiate our claims about the potential of the technology.

Let us start with the ergonomics of the habitat. To this end, we derived room occupancy based on localization information from the badges, which was accurate because the metal walls of any room perfectly shielded the signal from the beacons in other rooms. To find out whether the habitat was arranged in an optimal manner, for each pair of rooms (X, Y), we measured how many times an astronaut moved from X to Y and spent in Y at least $10\,\mathrm{s}$.[1] It turned out that the kitchen should have been situated close to the office and the workshop: from these two rooms, especially the office, most astronauts went directly to the kitchen and the other way round (cf. Fig. 2).

Initially, we presumed the kind of activities performed in the office was more conducive to distractions in contrast to working in the biolab. However, the astronauts tended to stay at the biolab mostly about $2.5\,\mathrm{h}$ while the majority of stays at the office and the workshop lasted twice as much. Hence, another

[1]This minimal interval was necessary to filter out situations when occasional beacon signals from another room slipped through open doors.

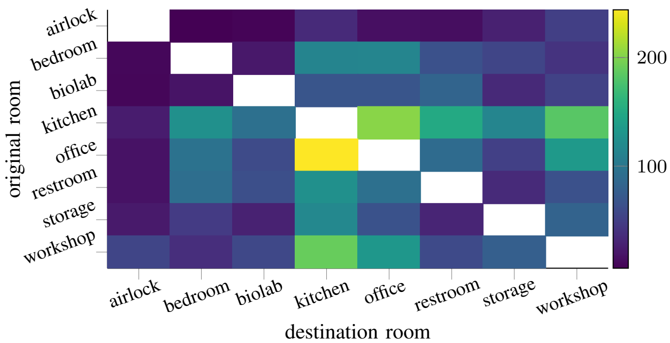

Fig. 2: Total number of passages from one room to another (the main room adjacent to all other rooms is not considered).

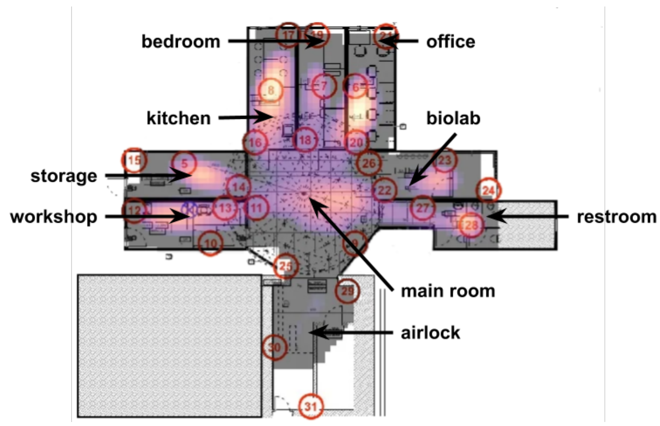

Fig. 3: The more vivid the color is the more time was spent by astronaut *A* at a certain location (with a granularity of 28 cmx28 cm squares) during the whole mission. Circles with IDs denote beacons.

explanation, confirmed by the astronauts' experiences, is that people used to be absorbed in their office/workshop work, forgot about breaks, and in the end had to quickly supplement water in the kitchen to avoid dehydration. The kitchen was also favored by the crew as the cosiest room with the highest temperatures and atmosphere supporting socializing.

In-room localization, in turn, allowed us to determine the dominant position of an astronaut within a 1 s-frame. These data can be transformed into heatmaps: histograms with a logarithmic scale that present how much time in total a given astronaut spent in a given area (cf. Fig. 3).

Heatmaps created for all participants allowed us to notice that the physically impaired astronaut, *A*, in comparison to the others, tended to stay in the middle of a room, usually did not approach corners, nor wandered around places that did not require their specific attention. This could have resulted partially from *A*'s schedule, hampered access to certain areas, and particular caution in moving around the unknown place. Most probably, over a longer period, the astronaut would have acquainted themselves with the habitat so that this difference in behavior would have become less noticeable.

To further analyze the mobility of the crew, we plotted fractions of recorded time that were spent on walking for all astronauts on consecutive days. Fig. 4 confirms the expectations that *A* was more passive than others. Moreover, there were two distinct pairs of different levels of mobility: *D* and *F* were walking significantly more than *B* and *E*. We got similar results regarding the average daily acceleration and sought the explanation in the differences between the astronauts' tasks and personalities: *D* and *F* were described as energetic, *E* was more reserved while *B*, as Mission Commander, had to spend more time on paperwork in the office.

Using localization and data from accelerometers we also aimed to verify if the emulated death of *C* on the fourth day influenced mobility of the whole crew, that is, whether the astronauts were forced to move between different rooms in a more hectic, rapid way to complete tasks of the deceased. Prior to the incident, the third day of the mission was relatively calm (with a low rate of location changes and low acceleration), which seems to support our hypothesis. Yet, since *C* left at the beginning of the mission and the difference was subtle, the observed irregularity cannot be a conclusive evidence. The incident itself was, however, visible in the collected data, especially after we analyzed group meetings and compared them with the schedule. As shown in Fig. 5, shortly after *C* passed away, the crew organized an unplanned consolation meeting in the kitchen at about 15:20 PM of local time: everyone was in the same room and the conversation was clearly quieter than, for instance, during lunch at 12:30 PM.

As we learned after the mission, losing *C* was a serious blow to the rest of the crew: *C* had already taken part in a two-week mission in Lunares, knew the place perfectly, and shared his knowledge with others. This again can arguably be explained with the collected data, which reveals that *C* was an energetic conversationalist (cf. Fig. 4 and Table I): *C*'s voice dominated during meetings while the fraction of time *C* spent on talking daily was the highest among the crew (cf. Fig. 6).

Fig. 6 illustrates also one more noticeable trend common for all participants: they talked less the closer the mission end was. Their conversations became rarer even in the kitchen, during lunches, and briefings. On the eleventh day, when food rations were extremely limited, and on the following day, when the mission control reprimanded the crew for performing invalid tasks, the astronauts barely talked to each other and, apart from speech, there was much less other noise recorded.

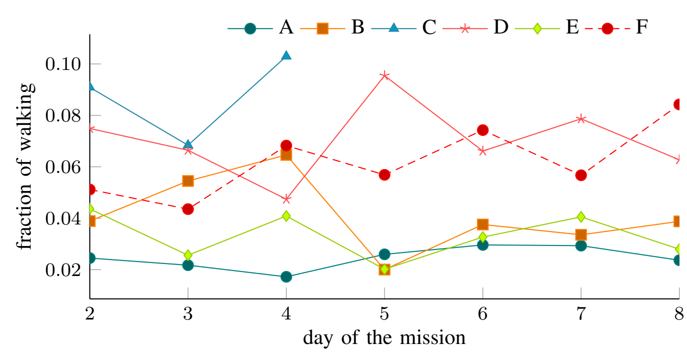

Fig. 4: Fraction of recorded time spent on walking during the initial days.

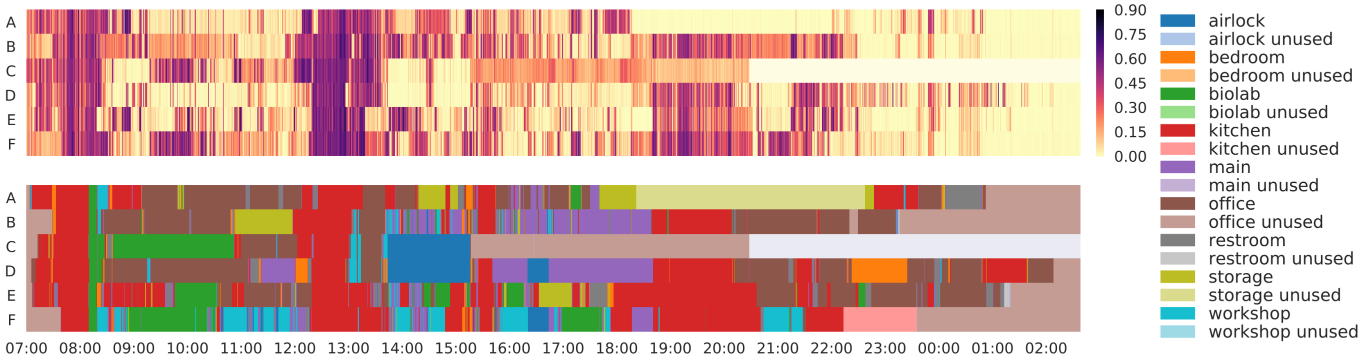

Fig. 5: Fraction of time with detected speech and location: timeline for all astronauts, for the day when *C* left the habitat. With these two kinds of information, we detect when the astronauts were in the same room and analyze the dynamics of their meetings based on speech parameters.

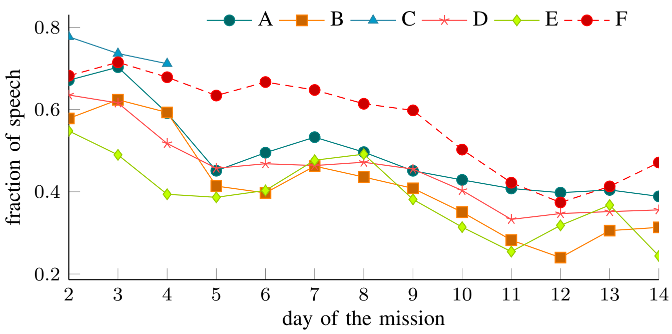

Fig. 6: Fraction of recorded time intervals when the badges detected speech. A $15\,\mathrm{s}$ interval is considered as speech if there are voice frequencies detected of at least $60\,\mathrm{dB}$ and for at least 20% of the interval. The boundary values were determined experimentally and correspond to a conversation at a distance of at most $2.5\,\mathrm{m}$.

The number, duration, and intensity of conversations are crucial sociometric parameters. By observing them, we learned about the atmosphere in the habitat and the group structure. For instance, our data shows that there were significant disproportions with regard to person-to-person relations: *A* and *F* talked privately with each other for about $5\,\mathrm{h}$ more than *D* and *E* during the mission. In addition, *A* and *F* spent together $10\,\mathrm{h}$ more on all meetings, both private and group ones, than the latter pair. Another finding confirms *B*'s social skills as Mission Commander, who cooperated, supervised, and kept company with the crew: *B* dominated being the person who was the most central and available to the others (cf. Table I).

In summary, some of the presented results confirmed the subconscious impressions of the astronauts, while others revealed to them surprising correlations. What is important is that the great majority of the results, for instance, regarding the popular locations in the habitat or changes in the time spent on conversations or walking, would not be reliably obtainable using solely the classic methods. Likewise, although the other findings on the behavior of the crew, for example, concerning social centrality or individual reticence, could potentially be recreated with detailed surveys, they would be only qualitative and far less reliable. All in all, delivering such compelling results, the experiment was an undeniable success, which strongly encouraged the ICAres-1 organizers to herald the utility of sociometric technologies for analog missions.

VI. Distributed Systems and Martian Habitats

A natural consequence of the success of the experiment was our continued collaboration with the astronauts, in particular, to sketch a future research agenda relevant for both communities. As stated previously, our system delivered important data about the course of ICAres-1, notably behavioral aspects of the crew. Some of the data would have been extremely difficult, if not impossible, to obtain with classic methods. The results of the performed post-mortem analyses of the data, such as those exemplified here, can thus be invaluable when designing and conducting subsequent missions. However, what we learned would be even more desirable is real-time feedback to the astronauts on the results of the analyses. In other words, there is a need for what we refer to as a *mission support system*.

The goal of such a system would be assisting astronauts in as many aspects as possible, informing them about relevant phenomena and allowing for reacting appropriately. One such aspect is broadly understood health: the system could measure fatigue, stress, and mood, help prevent injuries and avoid conflicts, maximize performance and minimize diseases through environmental control (e.g., air, sound, light). Another aspect is optimizing utilization of scarce resources, such as power, water, oxygen, food, especially during critical periods (e.g.,

TABLE I: Average and normalized parameters measured for the crew during the mission. Subtable (a): centrality measured as amount of time spent accompanied and, based on this score, Kleinberg centrality (authority). Subtable (b): fraction of recorded time with detected speech. Subtable (c): fraction of time spent on walking.

id	company	authority	talking	walking
A	0.79	0.86	0.63	0.39
B	1.00	1.00	0.60	0.45
C	n/a	n/a	1.00	1.00
D	0.94	0.96	0.63	0.70
E	0.74	0.83	0.57	0.49
F	0.89	0.96	0.76	0.75
	(a)		(b)	(c)

sandstorms). Warning about and predicting such events, not only due to external factors but also human error, is itself another important aspect. So is even merely offloading the astronauts from the need for logging their every activity.

Such a mission support system would inherently be a *distributed system*. A habitat itself consists of many modules and pieces of equipment, which are independent but have to be orchestrated to deliver certain functionality. The distributed nature also comes from the fact that components of the habitat, and hence the system, may fail and thus have to be replicated so that a partial failure or unavailability of some functionality does not hinder the success of the entire mission. Finally, from a purely organizational perspective, a space mission is normally supervised by a mission control on Earth, which is itself an extreme form of distribution considering the distance.

Although some requirements of such a distributed support system overlap with the vision of the Internet of Things (IoT), and notably industrial IoT [48], extraterrestrial habitats pose a number of unique challenges. Because of space constraints, here we highlight only a tiny fraction of these challenges, which we personally find most interesting.

A. Uniqueness of Extraterrestrial Deployment

The main reasons behind the peculiarity of the considered setting can be tracked down to the *dramatic reduction in available resources* that will occur throughout the extraterrestrial deployment. In the initial phase, to accomplish a grand-scale goal of human settlements beyond Earth we rely (directly or indirectly) on virtually all resources available to our civilization. Preparations consume efforts of most knowledgeable people, hi-tech solutions, and gigantic financial budgets. Nevertheless, in the final stage, crossing the frontiers of space exploration will ultimately be left entirely in hands of a small group of people. These de facto representatives of humankind will have to face two serious limitations: (1) they will need to rely only on supplies provided in, most probably, just a single spaceship and (2) in time-critical situations they will need to make judgments based solely on their own expertise. This is how the immense preparations for the expedition will be juxtaposed with extreme constraints set by the venture itself.

B. Limited Cargo of Spaceships

With regard to equipment in habitats, limited cargo of a spaceship enforces designed distributed systems to integrate elements of high versatility. Since no unnecessarily redundant equipment should be allowed (due to cargo volume limits and launch costs, i.e. thousands of dollars per kg of payload [49]), boundaries between distinct support systems cannot be strict, that is, it should be possible for a system to reuse data and results originally collected by other supporting modules. To exemplify how tight integration of various support systems can be realized we consider a urine processor assembly (already used to recycle water in space [50]) combined with an identification system (e.g., provided by wearable sociometric badges) and smart drinking mugs. These three modules together allow for tracking fluid loss and intake to warn astronauts against dehydration, one of common physiological issues resulting from, among others, low gravity [51]. Many similar ideas induce a vision of a global sensing system, which utilizes wearables, smart devices and servers, for a whole habitat. Such an *uber-system* would collect all kinds of information and provide it to specialized system units for separate or cooperative data processing. Consequently, it would be possible to monitor and regulate virtually all aspects of the mission, including resource management, living conditions, and human factors, without duplicating the infrastructure.

Elimination of redundant equipment should be carried out on all fronts. Since sensing infrastructure and support technologies (e.g., sociometric or medical ones) would be useful already during a spaceship flight and since it should be possible to 3D-print replacements for their most fragile elements, software and hardware architectures of designed distributed systems need to be modular and easily configurable. These features, albeit general, imply a number of concrete, practical problems. First, what could be physically challenging for astronauts is transporting necessary devices from the spaceship to the newly built habitat. Secondly, the crew would be responsible for a correct initialization of the systems, which often deviate from the plug-and-play specification, like, for instance, state-of-art solutions for indoor localization, based on initial input with a map of monitored area. Finally, while addressing these requirements can be reduced to specific engineering issues, there is still one problem that can be solved only with significant uncertainty: finding a balance between a spaceship overloaded with devices of same functionalities and a sufficient number of backups.

C. Limited Number of People

Just like we cannot send to Mars at once all useful devices invented up to the day of flight, pioneer expeditions beyond Earth are limited in the number of their crew members (as already discussed in Section III-C). Although space ventures are monitored round-the-clock by a mission control, the latency of communication and physical challenges conduce circumstances where the mission success depends mainly on certain qualifications of astronauts. Therefore, candidates for spaceflights have to meet extremely high expectations: while tens of thousands apply to NASA for the astronaut status, no more than 1% of applicants is accepted for the second phase of the recruitment process [52]. Nevertheless, even such a rigorous selection does not guarantee that first steps on Mars will be made by experts in all fields needed for survival. It is then important to adjust engineering visions of distributed systems in habitats to realistic competencies and abilities of the crew as well as put a greater emphasis on potential emergencies when no help from a mission control may be available.

1) System Deployment: As mentioned before, initialization of a distributed system in habitat could be both physically and technically troublesome. With regard to problems of technical nature, not only should the deploying process be maximally automated (with a manual mode supported as well), but also it should output enough diagnostic information to control whether installed devices function as expected. In case of any system failures, provided details, possibly along with instructions of a supervising system unit, could allow the crew to repair broken components on their own.

While physical efforts to settle large computing machines in a habitat might be challenging, it is even more necessary to consider issues arising around wearables, deployed everyday and by every astronaut. We learned how important it is to design comfortable personal sensing devices the hard way. The participants of ICAres-1 complained about the badge hanging on their neck in the laboratory or workshop, where our devices turned out to be a burden. This inconvenience was probably one of the reasons for which the fraction of daytime when the analog astronauts wore our badges dropped from about 80% to about 50% throughout the mission. Hence, for future deployments, we propose to integrate personal sensors with astronautic outfits, including spacesuits. With similar solutions [53], [54] already paving the way for industrial applications, we expect that such smart clothing for astronauts is within the reach of today's technology, despite many more requirements set by extreme conditions in space.

2) System Autonomy: The deployment and operational issues are further exacerbated by the fact that communication between a Martian habitat and Earth involves a high latency and is occasionally impossible. Even if there were an immediate and flawless interplanetary connection, the estimated amount of information collected by a sensor network similar to the one deployed in ICAres-1 might be prohibitively large to transfer in time. Thus, support technology cannot be designed merely as a local monitoring system steered by a mission control. It should rather function autonomously and, in addition, mitigate disruptions resulting from imperfect contact with a terrestrial station.

That communication problems can indeed put a space venture at risk was confirmed by events on the twelfth day of ICAres-1, when delayed instructions from the mission control contradicted the course of action already taken by the crew. Although negative consequences of the incident were mostly limited to surging stress levels of the participants, a similar situation could produce a far more perilous outcome in case of a real expedition. Accordingly, a habitat cannot be considered reasonably safe nor reliable without a distributed system that monitors the surroundings, immediately alerts of any anomalies and instructs the crew if needed. Further assured by remarks from the ICAres-1 team, we envision that the autonomous technology, apart from its critical functions of protecting human life, should also help the astronauts with their everyday duties. What exemplifies this idea is a mechanism detecting fatigue or distraction among the crew and suggesting how to reschedule the tasks. A more universal solution could be designed solely as a source of real-time feedback, claimed to be one of most desirable features of a habitat support system. Indeed, rising awareness (e.g. of risks, the quality of performance or chances for progress) in time is a significant aid to develop self-consciousness and to make more informed decisions as well. For instance, familiarity with current sociometric indicators could have motivated the ICAres-1 crew to give extra attention during group meetings to the most passive astronaut, *D*.

Being indispensable, the autonomy of a distributed system comes with serious difficulties that need to be faced by engineers. Naturally it involves instant data processing performed entirely on-site: with local resources only and without any contributions from a mission control. Hence ample supply of computational power needs to go in pair with efficient algorithms for data analysis. These, in turn, would likely be based on machine learning: the programming paradigm able to match dynamic, unpredictable environment of space habitats with its flexibility and almost unlimited potential for self-improvement. Provided that the artificial intelligence is fed with enough information beforehand.

To collect such amounts of data, including astronauts' personalized profiles, that could result in acceptable accuracy of the envisioned software, analog missions need to become an even more important part of preparations for future space colonization. Due to global limits of resources (number of volunteers, habitats, and funds), there are, however, open questions that should be soon addressed in the context of creating training datasets: Are many short-term analog missions more useful than fewer but longer experiments? Should we deploy the system in similarly extreme and confined places, like mines or submarines, to enhance the collected data? How much time is needed to train software of sufficient maturity to serve as powerful support for first people on Mars?

3) System Resilience: Advantages of the system's autonomy seem unquestionable. However, extremity of space expeditions calls for equally extreme cautiousness that requires granting control over any technology deployed in space to a human supervisor. Just like overseeing the condition of astronauts and administering their actions belongs to responsibilities of a mission control, the support system could be governed remotely from Earth as well. However, while expertise and technical resources would allow space agencies to successfully manage the habitat in typical circumstances, for aforementioned communication-related reasons, terrestrial assistance is not sufficient in time-critical cases.

For the sake of safety, the support technology needs to be supervised also by the astronauts. Such design offers an opportunity to extend the crew's competencies further and allow for adjusting the system to their own needs. For example, the astronauts may intensify sensor measurements when they are alarmed by anything unusual or temporarily disable some functionalities in privacy-sensitive situations. The habitat system, which is inherently ubiquitous and intruding, could be then perceived as more acceptable by the crew themselves.

On the negative side, taking care of the deployed devices could strain already tight schedules of astronauts. Hence, available customization and the need of emergency interventions should not invalidate a vital property of the technology: being an out-of-the-box solution. It is also important to acknowledge that the additional responsibility of the crew necessitates thorough training of the astronauts, both in using the system and being an expert on its inner workings. ICAres-1 serves as a tangible proof that incomplete information on how data is collected and processed can lead to serious misunderstandings. For example, astronaut F reused a badge that had belonged to deceased astronaut C whereas the algorithms assumed that each device can be assigned to one owner only.

However, not all mistakes are unintended. The astronauts may be tempted to abuse their power and disrupt proper functioning of the deployed devices, especially if their actions are impacted by sociopsychological problems. Hence, to protect the system from harmful changes introduced by disobedient individuals, it might be worthwhile to require approvals from all the teammates and the mission control before any significant change to the system is applied. While reaching a consensus may be sometimes impossible for objective reasons, other cases of escalated personal disagreements can and should be avoided. The system needs to carefully monitor social relations between the crew members, react to incidents of miscommunication, arbitrate conflicts, and coordinate teamwork to prevent long-lasting, disruptive phenomena such as alienation or forming of coalitions.

The common denominator of the presented risks is the problem of trust. Unprecedented conditions of a Martian habitat call everyone and everything into doubt: Is the system truly reliable? Are the astronauts competent and stress-resistant? Are decisions of the mission control informed and well-communicated? Do space agencies intend to protect lives of the crew unconditionally? This train of thought leads to a distributed support system based on multilevel firewalls and authorization methods. Its challenging design should create perfectly balanced entanglement, in which all three actors, a mission control, astronauts and the support system, can get in two-way partnership interactions with each other as well as gain domination if needed.

4) System Flexibility: The possibility of spectacular dangers should not overshadow apparently less problematic nuisances that could just as effectively hamper space colonization. One of those important though relatively neglected aspects is adjusting the deployed technology to abilities of the the crew, in general known as *ability-based design* [55]. Even if all astronauts are required to pass demanding physical tests and be classified as strong and healthy, their fitness might get limited during the mission. It may be either permanent due to an unfortunate accident or temporal, for example during EVAs, when the ability to see or speak is sometimes impeded by difficult conditions (e.g., no light source) or unforeseen problems like spacesuit water leak [56].

Acknowledging diverse capabilities of users, is one of the main lessons learned during ICAres-1: unanticipated needs of the impaired astronaut A resulted in various inconveniences and errors. For instance, since the badges were identified with numbers displayed on their e-ink screens, astronaut A accidentally swapped their badge for one day with B. It was also difficult for A to make sure their microphone on the front side was properly exposed. This, in turn, resulted in occasionally muffled recordings. A further examination of collected data was not straightforward either: we had to modify the algorithm for conversation analysis to not be misled by a computer program reading out texts for A.

Enriched with these experiences, we recommend that the whole habitat technology provides accessibility support aimed at diverse human senses, with informative light signals complemented by sounds, buttons corresponding to voice commands and other solutions of this kind. To take care of increasing power consumption, already troublesome in wireless solutions, these additional interfaces should be embedded into wearable elements of the system as detachable modules, optimizing energy use and weight of devices, similarly to some recent approaches [57].

VII. Conclusions

To sum up, this paper contributes twofold. First, the deployment of our distributed sociometric system during an analog habitat-based mission illustrates that today's technologies can yield quantitative results of unprecedented granularity, thereby leading to a far deeper understanding of the mission dynamics compared to what has been possible to date. The volume of positive reactions from the astronauts makes us believe that similar systems will likely become a standard during future missions. Second, our experiences from the deployment let us highlight some of the challenges that will likely drive the design of future distributed systems for supporting habitats. These problems, as well as the preliminary ideas and suggestions are only a tiny fraction of the insights that we gained through the participation in ICAres-1 and subsequent collaboration. In general, we believe that space colonization involves exciting research opportunities also for the distributed systems community, with potential outcomes impacting multiple sciences.

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