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Development of an AI assistant for supervising the future Moon and Mars surface operations

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Abstract

Following the Global Exploration Roadmap defined by the International Space Exploration Coordination Group, ISECG, the Spaceship FR team at CNES, the French Space Agency, wishes to contribute to the development of technologies extending human reach toward space, notably for the development of habitats, first on the Moon and then transposed on the Mars surface. The Moon is used as a test bench for future bases on Mars. The operational concept takes into account the long distance between bases and Earth. On the one hand, the operations and sustainability of such structures in stressful isolation conditions constitute a high level technological and human challenge. To relieve the high mental load of the astronauts, the solution could be an artificial intelligence assistant that would supervise the automation of the base as well as monitor and maintain the mental health of the crew through a cognitive approach of human-computer interaction. On the other hand, habitats will be regularly inhabited and real time operations are impossible due to the high distance from the Earth control centers. That leads to redefining the command and control concepts and transferring most of the actual control center tasks to an autonomous digital supervisor that will command and control all the habitat systems.

AI4U, developed by Spaceship FR, is the system at the crossroad between computer sciences and human factors, aspiring to take on the task. Besides its organization and automation skills, this artificial intelligence interacts with the astronauts with an intuitive and natural interface. It can support their work and leisure activities with a sympathetic approach, recognizing their current mental state by using face and voice recognition. AI4U is the entry door to the operational systems. It can manage basic sub-systems tasks and discharge the crew from basic activities. It gathers the systems' information and displays them to the crew and Earth control centers. It also executes and distributes commands from the crew and Earth control centers.

This paper will present the new concepts of command and control adapted to the Moon and Mars habitats, and how AI4U will interact with the different systems in order to increase the autonomy level of operations and become a real astronaut assistant.

Keywords: Spaceship FR, AI4U, Autonomous Supervision, Artificial Intelligence, Astronaut Assistant.

Acronyms/Abbreviations

AI	Artificial Intelligence
AI4U	Artificial Intelligence for you
API	Application Programming Interface
ASR	Automatic Speech Recognition
CNES	Centre Nationale d'Etudes Spatiales (French Space Agency)
E3P	European Exploration Envelope Programme (Terra Novae)
EDF	Electricité de France (French national energy company
ESA	European Space Agency
ExPeRT	Exploration Preparation Research and Technology Team
GER	Global Exploration Roadmap
HAB	Habitat (of MDRS facilities)
ISAE	Institut Supérieur de l'Aéronautique et de l'Espace (Higher Institute of Aeronautics and Space)

ISECG	International Space Exploration Coordination Group
ISRU	In Situ Resource Utilization
ISS	International Space Station
MDR	Mars Desert Research Station
ML	Machine Learning
NASA	National Aeronautics and Space Administration
NLI	Natural Language Interpretation
R&T	Research and Technology
RAM	Repair and Maintenance Module
SSH	Secure Shell
USOC	User Support and Operation Centers

1. Introduction, context and problematic

Humanity is getting ready to go back to the Moon and use it as a testbed for future travels to Mars. These goals have been listed by the International Space Exploration Group (ISECG) in the Global Exploration Roadmap (GER) in 2018 [1].

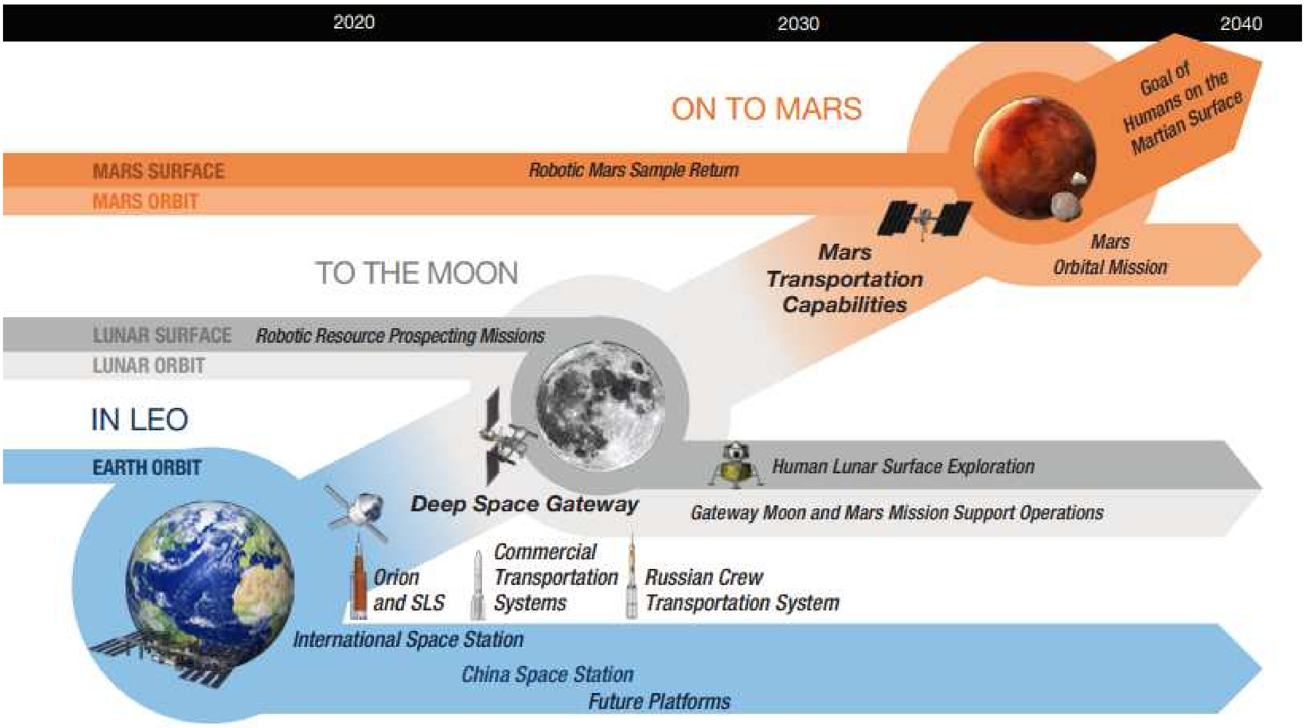

Fig. 1: The GER 2018. Credit: ISECG [1].

The GER identifies the 47 technological bricks – see Appendix A - that are currently unavailable or underdeveloped but that are critical for the success of the missions. The European Space Agency (ESA) put in place the ExPeRT program to work on Space Exploration in different domains [2]. One of its initiatives is the Spaceship network. The goal is to work on innovative solutions for human space exploration.

Fig. 2: The three Spaceships under the European Exploration Envelope Programme (E3P) [3].

After the creation of Spaceship EAC [4] and Spaceship ECSAT, [5], the French Space Agency, Centre National des Études Spatiales (CNES), decided to create the Spaceship FR project [6][7] in 2018 to contribute to the common effort and work on 27 of the critical technologies ordered in 7 categories, which include "Digital and Supervision". Through collaboration with industry and academia, including student activities, internships and projects, Spaceship FR carries this mission to "Inspire, federate and support".

1.1 Problematic

In the International Space Station (ISS), astronauts are assisted by different Control Centers and User Support and Operation Centers (USOC) with nearly instant communication via a satellite network. The control centers command and control the different systems of ISS continuously. And they give procedures for the multiple experiments and operational activities that the astronauts on the ISS perform and can support the crew with any problem, either medical or technical. For future operations on the Moon, the delay of communication will already increase to 2.7s, which stays manageable, even in case of emergencies. The Moon is also considered to be a testbed for Mars, and on Mars things will start to be difficult. The delay of communication with Mars can go up to 42 min for a round-trip exchange which would be a real time communication impossible.

The big communication delay with Earth will imply the role of the control centers will change. The command and control will not be performed in real time. That means astronauts and systems to be more autonomous. One solution is to transfer the knowledge and the work of the control centers in the Mars base. Thanks to computer technologies, we can imagine expert systems to support the crew to supervise the base and support the operations.

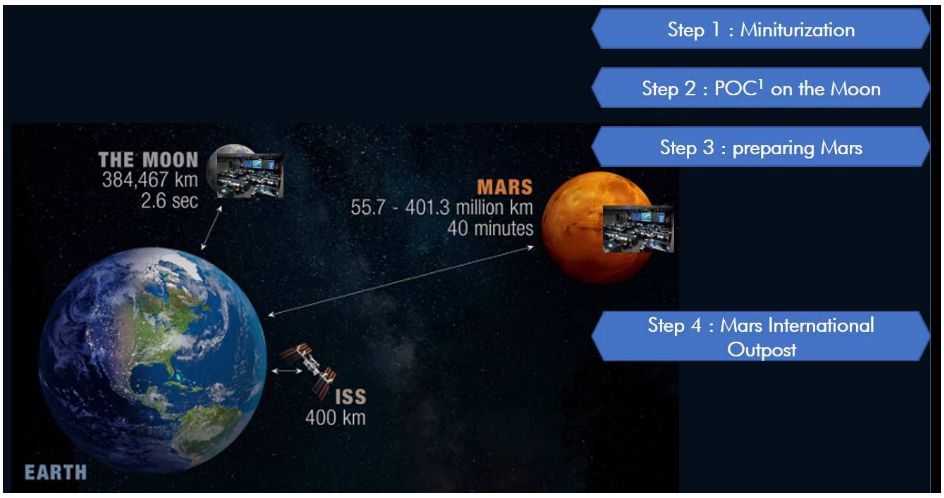

Fig. 3: control centre knowledge and operations transfer strategy.

Importantly, the difficult isolation conditions might lead to stress and mental load, which can affect the physiological and mental health, and behavior of the crew [8]. To decrease the risk on these scopes, digital solutions could support the astronaut during his work and provide pleasant company during his leisure and rest time.

1.2 Virtual assistants

A virtual assistant could be a solution to these problems. A virtual assistant is a software based on Artificial Intelligence (AI) able to converse with the user to provide a service. Indeed, in the last few years, multiple virtual assistants have been developed and are used daily by companies, websites, and families in their homes. We can cite as an example Siri developed by Apple and IBM Watson in 2010, then Windows and Amazon followed in 2014 with respectfully Cortana and Alexa, and then Google Assistant in 2016. In February 2022, Alexa has even visited space for the first time and is going back to the Moon with the first launch for Artemis in September 2022 [9].

But she was not the first Earth virtual assistant to get there, IBM Watson was sent in 2018 with the assistant for astronauts CIMON, developed in cooperation with the DLR, Airbus and IBM [10]. Otherwise, the idea of a robotic assistant already appears many times, especially in science-fiction with, to cite a few, Jarvis, the very helpful Iron-Man butler, TARS and CASE in Interstellar, and even HAL 9000 from 2001: A Space Odyssey. NASA took on this idea in 2000, by imagining the first of the kind, the Personal Satellite Assistant (PSA) [11]. Japan on their side sent Kirobo to the ISS [12] in 2013 and Int-Ball [13] in 2017.

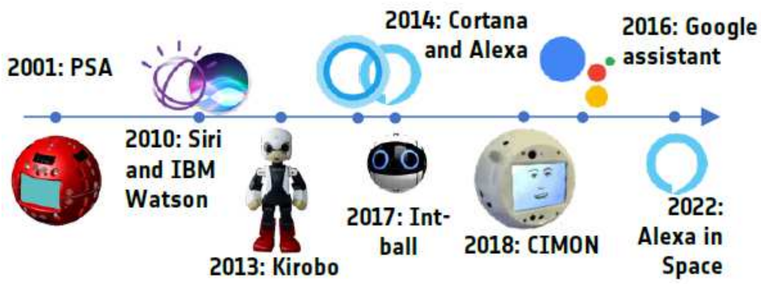

Fig. 4: Virtual assistants developed for space applications.

2. AI4U to assist the astronauts

In 2022, the Spaceship FR team imagined AI4U, a virtual assistant to support astronauts on their journey to the Moon and Mars.

Fig. 5: AI4U avatar.

The main functionalities to be developed are:

- Supervising autonomously the habitat, especially relieving the astronauts from repetitive and unpleasant tasks;
- Supporting the operations, optimizing them and increasing the efficiency while also enhancing the crew's autonomy from the Earth;
- Supporting the mission by feeding a knowledge database and developing its skills;
- Supporting the astronaut being a companion and a countermeasure against the stressful and isolative conditions of space settlement.

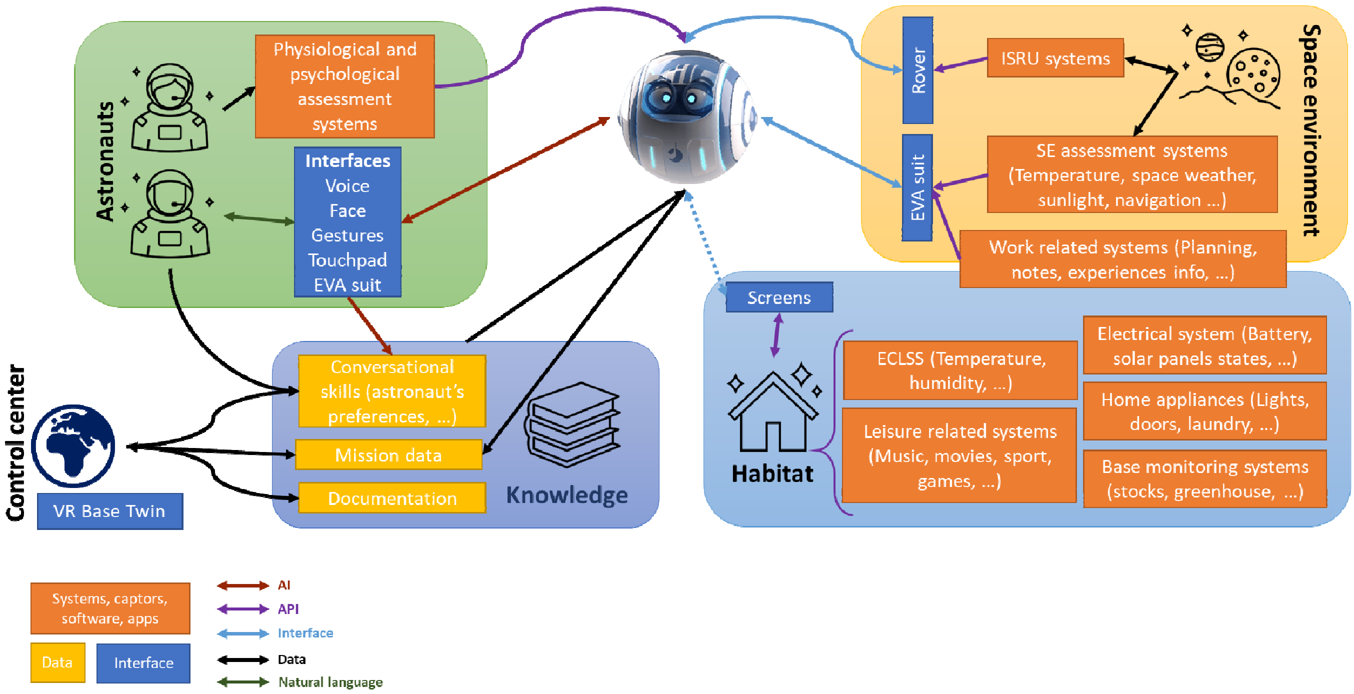

Fig. 6: Interfaces of AI4U with its environment.

Spoon company developed the first terrestrial version of AI4U in 2022 for CNES to interact with students and present topics relative to the space domain. The main skill of the digital entity is to mimic human emotions to facilitate communication.

The Spaceship France project has based the development of AI4U on this skill with the objective of eventually providing a virtual crewmember.

2.1 AI4 for supervising autonomously the habitat

As planned in the GER [1], the future Moon and Mars habitats will be as autonomous as possible with onboard systems monitoring and controlling functions for each subsystem.

- Power: Battery state and charge, solar panels output, intelligent power distribution.
- Life support: Temperature, air composition, water, and gas storage, waste management.
- Greenhouse: Food production monitoring, storage, nutrition management.
- Home appliances: Light, kitchen, bathroom, laundry, cleaning station, etc.
- Leisure systems: Music, television, e-books, workout machines, etc.
- Maintenance of the habitat subsystems: scheduling, repair guides, replacement parts storage, etc.

The functions automatically controlling these subsystems will be connected to AI4U through Application Programming Interfaces (API). It will allow the astronauts to access the information that they provide as well as give commands through voice, touch, or gesture thanks to AI4U's interface anywhere in the habitat. Indeed, it could be present on multiple supports in every room of the habitat:

- On screens, with a camera and microphone on the workstation;
- In the kitchen and leisure room, with the microphone and cameras that can be turned on with a keyword;
- In the bathroom and personal quarters, only with a microphone that can also be turned on only on request, to respect the astronauts' privacy;
- In personal quarters, each astronaut could have a pad for leisure activities on which they can also have access to AI4U.

Besides the indoor systems, it could also have access to the outdoor sensors used for example to assess space weather (e.g. sand storms on Mars, solar flares) and the status of the In Situ Resource Utilization (ISRU) system for monitoring and control. AI4U would be able to perform simple maintenance tasks.

2.2 AI4U for supporting the operations

For the habitat maintenance tasks that automatic functions cannot perform without the astronaut's input, AI4U would establish a schedule for the crew. Combined with the work activities schedule, AI4U will be able to reschedule in the event of an unforeseen activity such as an urgent repair or for the good mental and physical health of the astronauts. If there is an urgent repair, it should also warn the crew instantaneously using the according signals and after running the diagnostic provide advice, guidance, and operation procedures on how to handle the situation.

While performing the operations, AI4U would offer assistance in reading procedures and completing the astronaut's logbook. It would use its emotional skills to detect if the astronaut needs help and suggest giving more explanations. AI4U would also perform some operational tasks in parallel with the astronaut's activities in coordination with the crew.

2.3 AI4 for supporting the mission

Currently, the different ISS ground control centres are responsible for numerous experiments running simultaneously. They elaborate procedures and training for the astronauts and then provide support to them during the experiments. Communications, monitoring and control can be done in (quasi) real time with the ISS.

It is reasonable to assess that the number of experiments will not decrease on the Moon and on Mars. Because of the distance, especially for Mars, a real-time support is impossible. The solution is using computer technologies to "miniaturize" these control centres and to transfer their knowledge and control activities in the habitat.

AI4U could take on this role, using the documentation provided to coordinate the mission, the operations and run the experiments. For that, AI4U would have access to a knowledge database. This knowledge will be constituted by the information related to:

- General knowledge and cultural references;
- The mission database, containing all the parameters and data to build the operational procedures and the automatic activities;
- The operational database, containing all the parameters and data used to read and exploit the data collected during operations;
- The data prepared on Earth, and then augmented by all the data gathered during the mission;
- The data provided by different expert systems like the habitat supervision;
- The computer tools, to make calculations, summaries and predictions;
- The crewmembers, to interact in the right way with everyone.

2.4 AI4U for supporting the astronaut

AI4U is an emotional metabot acting as an interface between the astronauts and their environment. First, it is a character with a look, a voice, mannerisms, a personality, and a story all designed for it to fit as well as possible in the astronauts' team. This digital entity can be declined on multiple supports. A touch screen, a microphone, and a camera constitute the interface with which astronauts can communicate. In order to interact with astronauts, AI4U uses multiple AI technologies combined with a microphone and a camera:

- An Automatic Speech Recognition (ASR) that allows it to transform astronaut's words into text in a natural language;
- A Natural Language Interpretation (NLI) to understand the intent of the astronaut based on machine learning (ML);
- A speech synthesis to be able to answer accordingly;
- A human face recognition to be able to detect humans and mimic facial expressions in order to execute non-verbal communications (inspired by large mammals' interaction codes).

For AI4U to be able to help the crew in the habitat supervision and their work, it must be trusted and appreciated, even more, to fulfill its companion role. For that, it must become a real character with a story and a personality. A character design approach, similar to what is used in fiction writing for books, movies, or video games, served as a basis for defining AI4U's story and personality.

Besides the core principles of helpfulness, trustworthiness, and humility, it will also display different traits of character. It will have some humor, which makes it more entertaining and is also considered as a mark of intelligence if used at appropriate moments, and at some times, can even show enviousness or a lack of tact. Indeed, humans are not perfect creatures, and it is easier to get attached to a character that displays some weaknesses. However, AI4U will not try to pass as a human to avoid any "uncanny valley effect" [14], an eerie unease feeling that humans can experience when something, a robot for example, has a human-like appearance. Its look is very robotic as well as its voice.

Besides, it is "aware" of its difference and even a bit conscious about it. For example, it might regret not being able to eat any of the delicious space food, and by expressing that bringing some comic relief. However, it must be professional and will display the different personality traits based on the situations, with different operative modes for work and for leisure. It also has cursors for different emotions and inclinations based on circadian cycles, the moods of the crew and the events of the day.

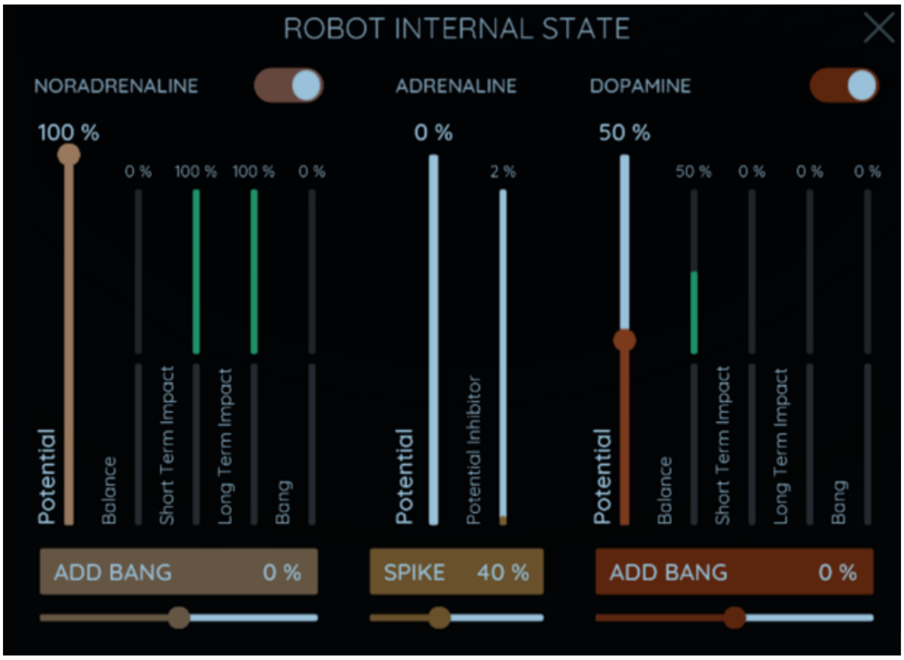

Fig. 7: Cursors for AI4U's hormonal levels.

These feelings and personality traits can be seen in the facial expressions of the character, its gestures and of course in conversation with the tone of its voice or its choice of words. Besides, as it gets to know the astronauts better, its conversation style could evolve from polite and professional to less formal and friendlier.

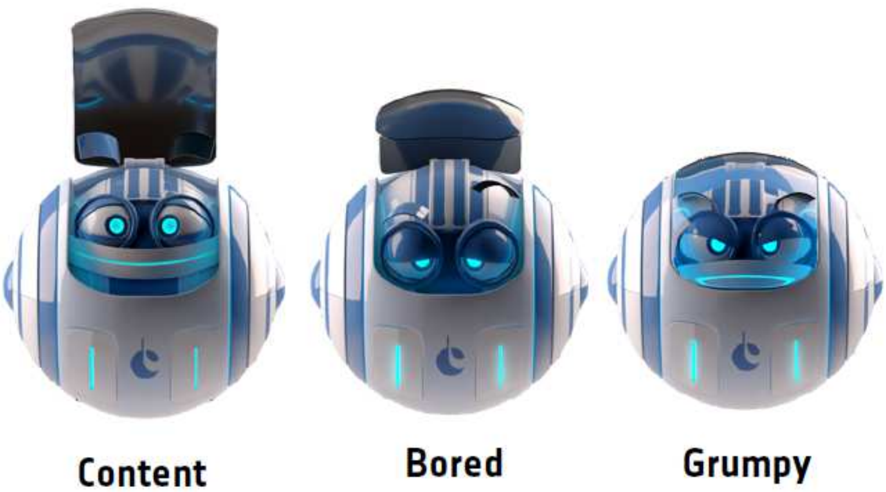

Fig. 8: Examples of AI4U expressions.

3. A first version for an analog mission

A student team from SUPAERO engineering school (ISAE, Toulouse, France) will execute a 4-week analog mission in MDRS facilities in February 2023. That was the opportunity for a first test of AI4U in operational conditions.

Another student team of SUPAERO school has developed two operational scenarios for AI4U:

- Simulate the triggering of an alarm linked to the malfunction of a module element to train the MDRS team to react in the event of an emergency,
- Facilitate data retrieval from environmental sensors to allow initial monitoring of the base.

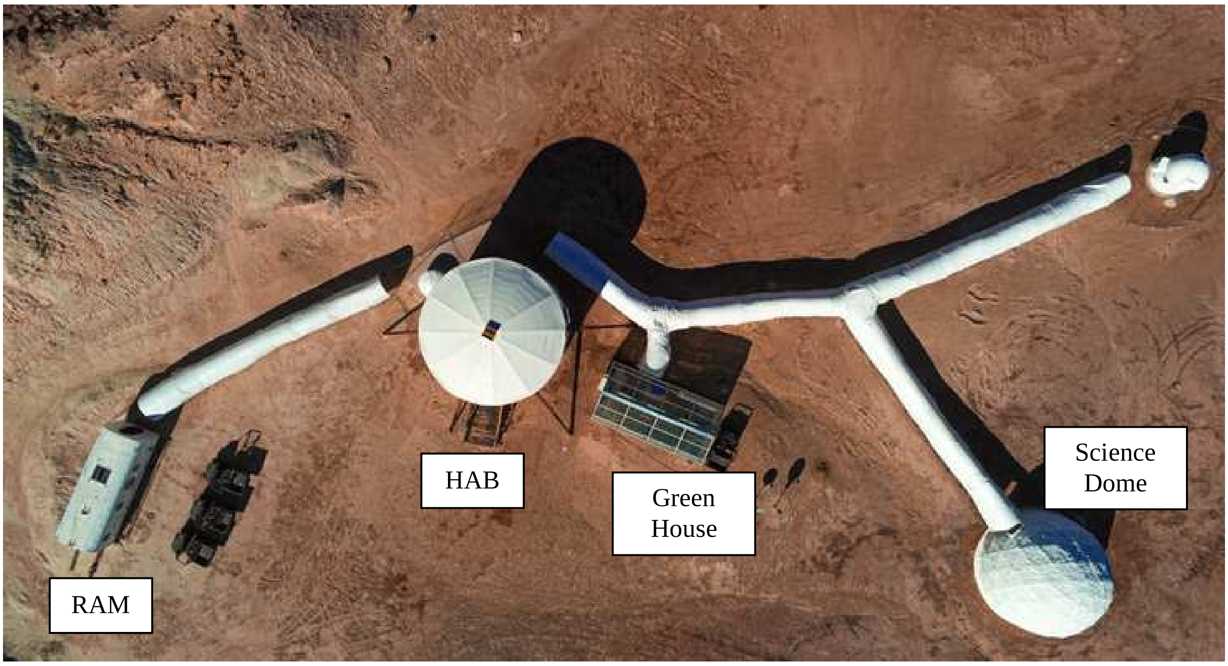

Fig. 9: MDRS facilities.

This simple first implementation and deployment of AI4U in an operational context gives us the opportunity to understand the difficulties of implementation and operational use, to list the improvements to be made to the system and to define the development priorities, in particular regarding the human-computer interaction.

During and after the different tests, the crewmembers will fill out a form with their feedback.

CREW MEMBER	MODE	Conversation DURATION	Number of REPETITIONS in average	Overall satisfaction LEVEL	If encountered problem, add a COMMENT

Fig. 10: Feedback form.

3.1 Alarm simulation

For the alarm simulation, AI4U will be used mainly in its conversational software role. Due to the repetition of tasks, the sentences spoken by the user must differ as much as possible from each other. The objective is to have first feedback from the crewmembers regarding their interaction with the digital entity, especially its character, voice and conversational behavior.

The system will start the alarm randomly. The crew can also start the alarm intentionally. Then the crewmembers have to execute the emergency procedure deciding whether they need support from AI4U or not.

REQUIREMENTS
R1:The system shall launch an alarm training R11: The system shall launch the training once or twice during the mission R12: The system shall launch the training randomly during permitted slots (specific working hours slots) R13: The system shall provide an immersive experience *R14: The system shall be able to launch different scenarios* R2: The system shall help the user in case of need R21: The system shall provide help with interactive actions R22: The system shall provide different levels of help

Fig. 11: Requirements for the alarm simulation tests.

Step 1 : Preparation	• Everyone should gather in the main hab
	  • « Everyone is in the main hab »
	• Get into 3 different groups
	  • « Groups are defined »
	• Get one radio per group
	  • « Radios are taken »

Step 2 : Initial checks	• A group of 2 people goes downstairs to prepare the EVA suits
	  • « EVA suits are ready »
	• A group of 2 people check every sensor
	  • « Hole detected »
	• A group of 2 people closes every door
	  • « Doors closed »

Step 3 : Sensor checks	• 2 people put the suits on + 2 people help them
	  • « Ready for EVA »
	• A group of 2 people check every sensor
	  • « Sensor check is over »

Step 4 : Repair groups	• 5 people get in a safe place and prepare 2 others for EVA
	  • « Repair group ready »
	• 2 people in EVA go in the low pressured room detect the precise hole location
	  • « Hole in view »

Step 5 : Repairs	• 5 people stay in a safe space
	  • « Everyone is safe »
	• 2 people in EVA repair the hole
	  • « Hole repaired »

Fig. 12: Alarm simulation procedure steps.

The architecture is simple and focused on the human-AI4U interaction.

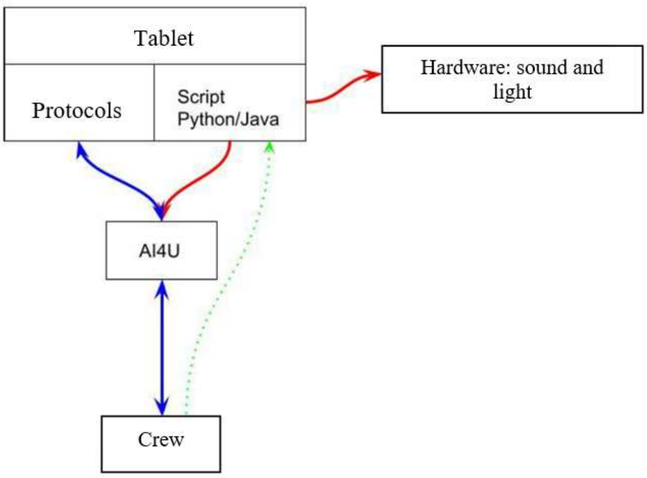

Fig. 13: Architecture involving the alarm simulation.

The scenario developed for AI4U gives crewmembers the choice of requesting support from the digital entity for the execution of the procedure.

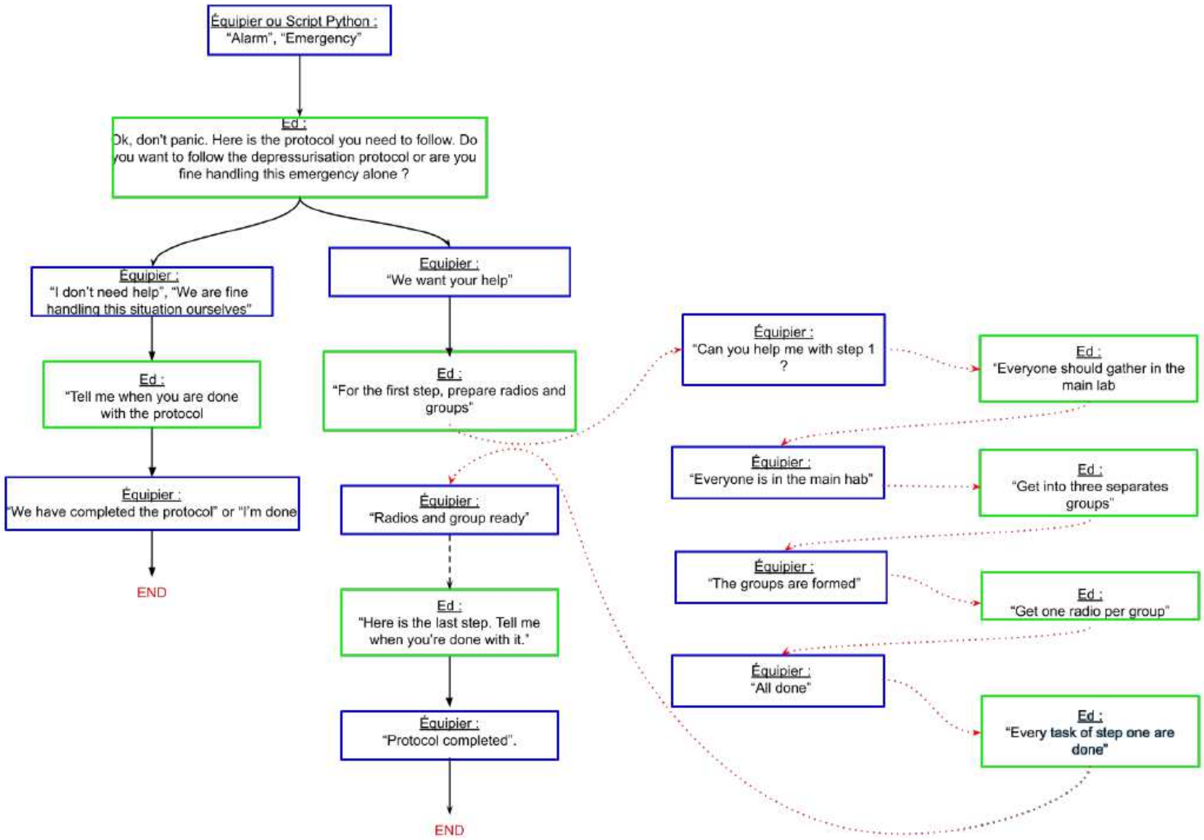

Fig. 14: Dialog choices *("Equipier" = crewmember; "Ed" = AI4U).*

The implementation in DialogFlow is done for each step of the procedure. DialogFlow is a tool developped by Google to facilitate the developement of vocal assistants.

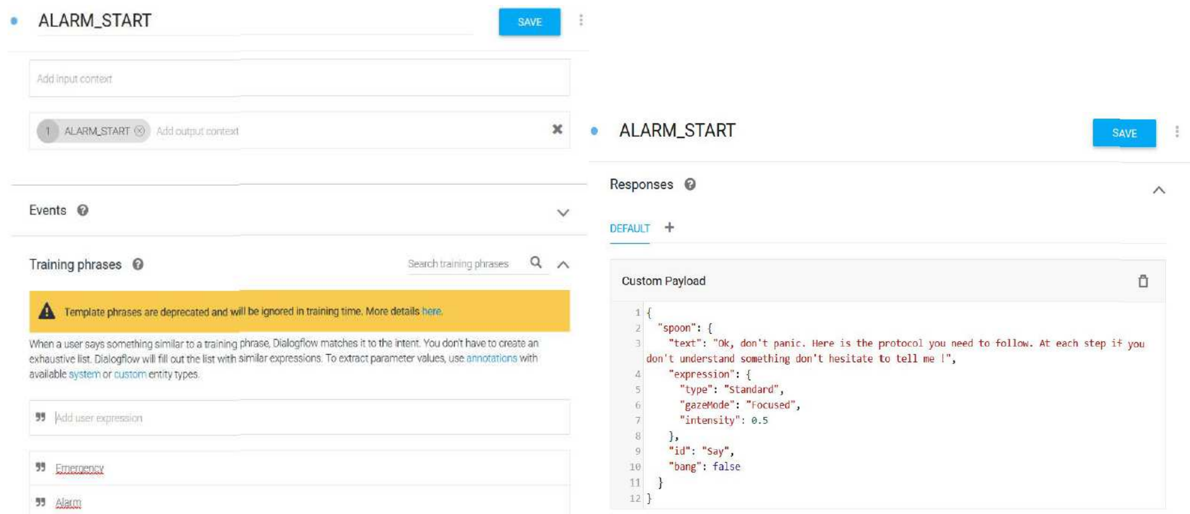

Fig. 15: DialogFlow screenshots.

3.2 Data retrieval

For the data retrieval function, AI4U will be used in its conversational software role and interaction with a simplified life support system. Here again, the objective is to have initial feedbacks from the crewmembers regarding their interaction with the digital entity. That was also the opportunity to test the development of interfaces between AI4U and a hardware subsystem.

For each test, the crew will ask AI4U for information about the environmental data. Two modes are available, the crew can request updated data, or to store data for a period of time.

REQUIREMENTS
R1:The system shall automatically retrieve data from sensors R11: The system shall retrieve measures from different locations R12: The system shall retrieve with a 10 measures/hour frequency for each sensor R13: The system shall provide an orderly storage for measures (--> by date, ...) R2: The system shall facilitate data access for users R21: The system shall give data points from chosen measure type R22: The system shall give a chosen number of data points R23: The system shall give data points between two dates R24: The system shall share the latest data in near real time (→ speaking) R25: The system shall share a large amount of data for further analysis (→ Copy the requested data in the users' hard disk) R251: The system shall store the data in different csv for each day R26: The system shall provide an interactive interface

Fig. 16: Requirements for the data retrieval tests.

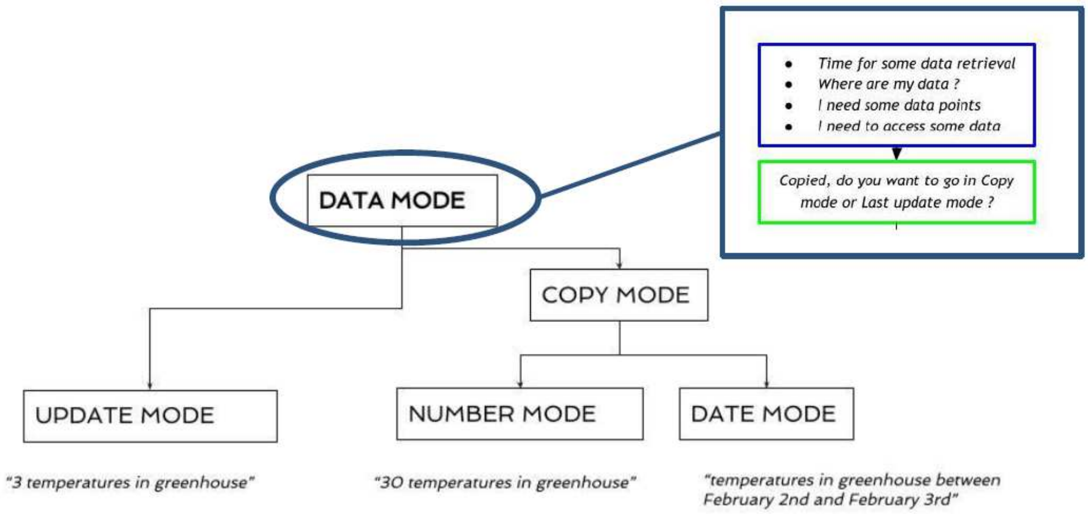

Fig. 17: Modes for the data retrieval tests.

For the Update Mode, the crew can ask up to 10 last measurements for one type of parameter for one place. After giving the data, AI4U will ask the user if he needs other data.

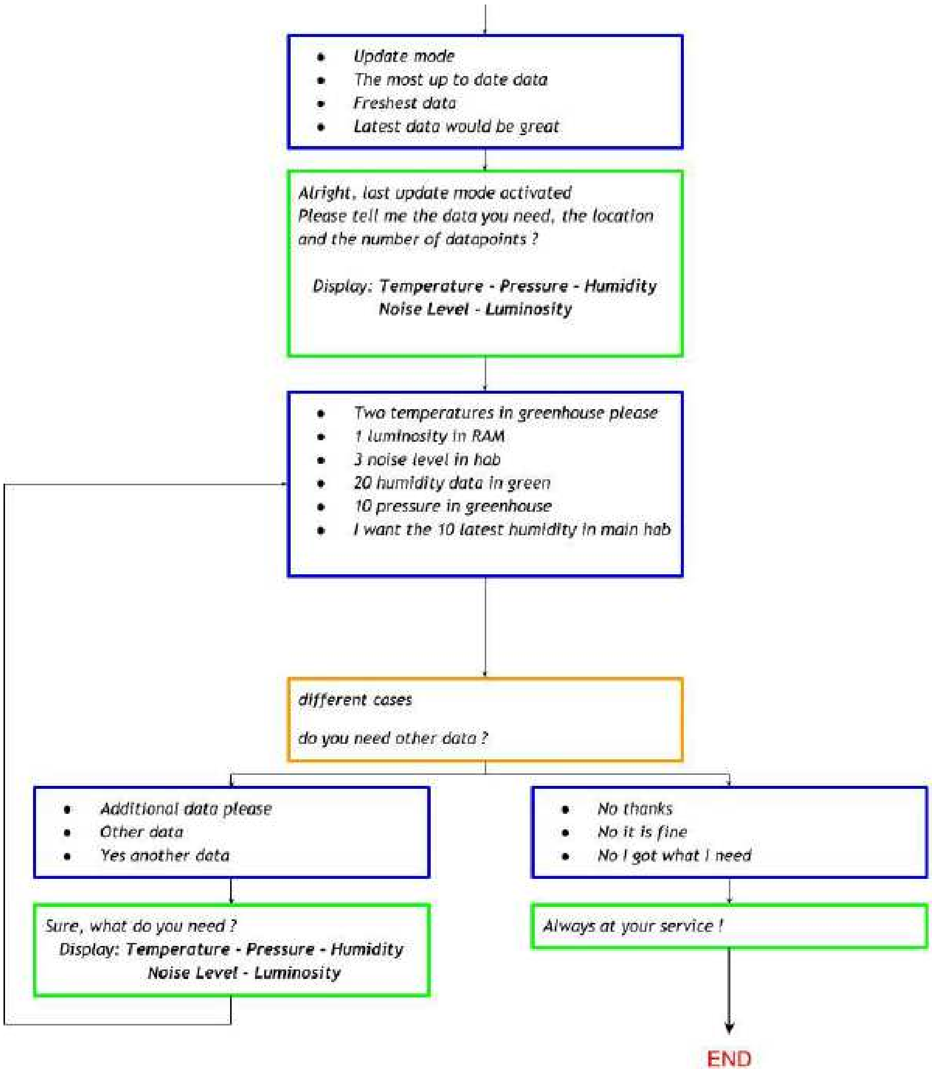

Fig. 18: Update Mode dialog steps for the data retrieval tests.

In the Copy Mode, the crew can store environmental data in a .csv file. The crew can choose to enter either the Number Mode or the Date Mode. In the Number Mode, the crew can request the storage of several measurements for one type of parameter for one place. In the Date Mode, the crew can request the storage of measurements for a period of time for one type of parameter for one location. After storing the data, AI4U will ask the user if he needs other data.

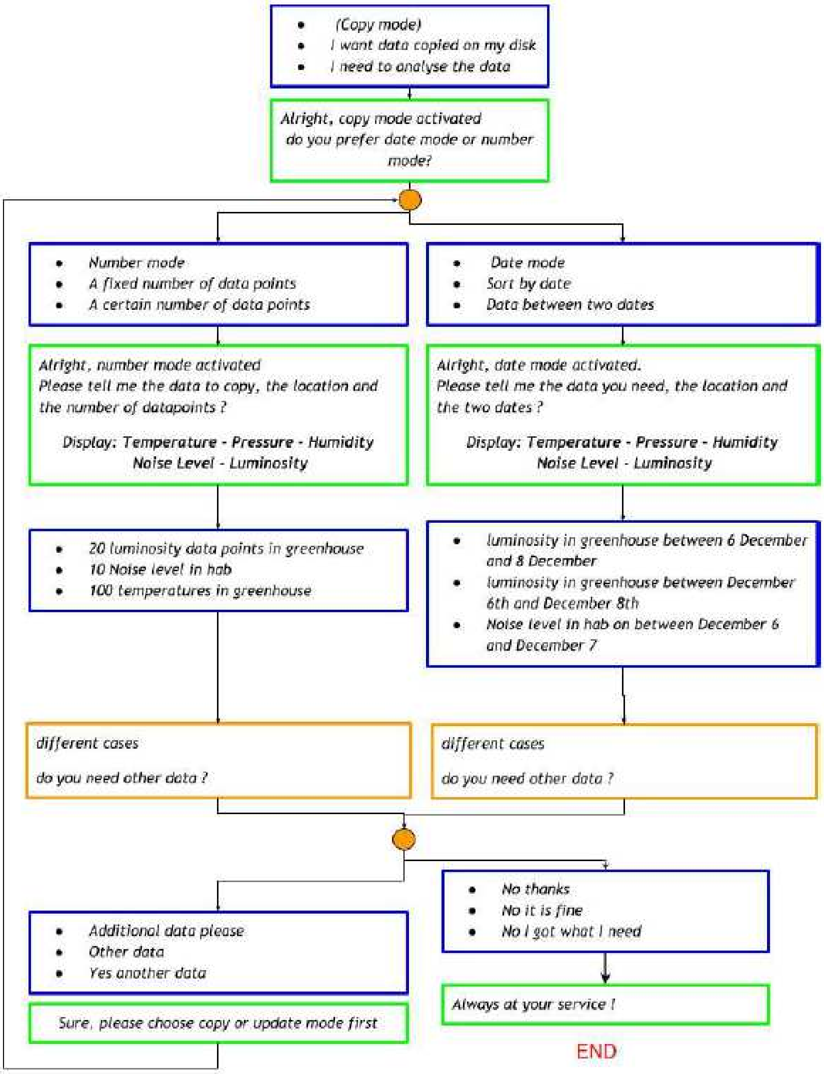

Fig. 19: Copy Mode dialog steps for the data retrieval tests.

To have a fluent conversation, the heart of development consists in listing the keywords that will trigger the intervention of AI4U. For example, to start the Update Mode, the crew can say "*update*", "*updates*", "*last*", "*latest*", "*up-to-date*", "*freshest*".

Similarly, non-nominal requests must be taken into account and AI4U must question its interlocutor so that he reformulates his request. For example, if the crewmember does not mention the location in his request, AI4U will ask "*Please mention the location*". This error management works for one mistake but if there are multiple errors, AI4U will be unable to recognize the relevant information. The user can kill the process and restart the copy mode by saying the keywords "*kill*", "*leave*", "*stop*", "*finish*".

At the beginning of the mission, the MDRS Supaero student team will install several sensors in the different buildings of the base.

Table 1. Distribution of the sensors in MDRS facilities.

Sensors \ Place	Green House	HAB	RAM	Science Dome
BME280 (Temperature, pressure, humidity)	1	5	1	1
TSL25911FN (Light)	1	5	1	1
SPH0645LM4H (Sound) optional	1	5	1	1

These sensors are connected to uPesy ESP32 Wroom cards to collect and store the data. These cards are connected to the local network thanks to a Wi-Fi link. A python code is used to gather automatically the data in a .csv file and send it periodically to the server.

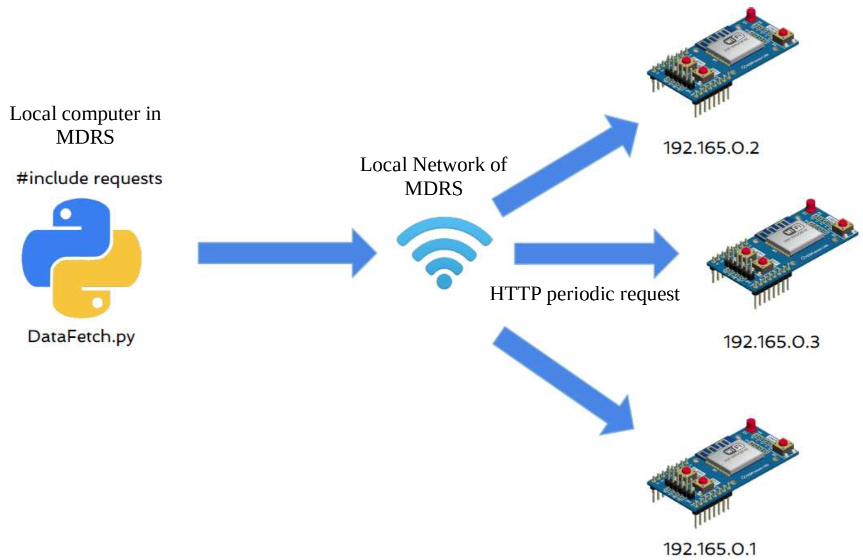

Fig. 20: Architecture to retrieve environmental data.

The use of the Dialogflow tool requires a webhook server to transfer the data between the local computer and AI4U. This prevents the project from running everything locally but it is representative enough for the first tests.

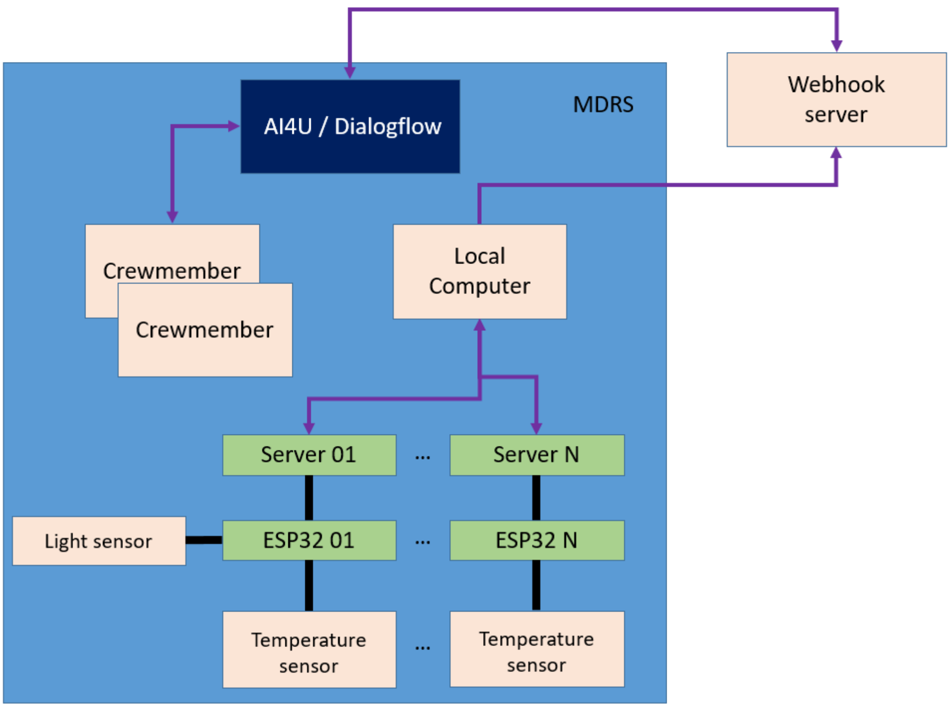

Fig. 21: Architecture involving the data retrieval tests.

At each request of an astronaut of the crew to AI4U in Copy Mode, the data concerned are automatically extracted and transferred via an automated SSH connection to a dedicated server and are easily recoverable/usable.

```
def store_data(type, number=False, loc = 'greenhouse', begin_date= False, end_date=False):
    path = './test.csv'
    path_copy = './extracted_data/' + loc

    if not os.path.isdir(path_copy):
        os.makedirs(path_copy)

    df = pd.read_csv(path)
    df.date = df.date.apply(lambda x : pd.to_datetime(x))
    df = df[(df['type']==type) & (df['location']==loc)].sort_values(by='date', ascending=True)
    if number:
        df = df.tail(number)
        df.to_csv(path_copy + '/' + type + '_' + number + '.csv', index=False)
    elif (begin_date and end_date):
        beg = pd.to_datetime(begin_date, format='%Y-%m-%d')
        beg = beg.replace(year=beg.year-1) #Dialogflow provides 1-year shifted dates
        end = pd.to_datetime(end_date, format='%Y-%m-%d')
        end = end.replace(year=beg.year-1) #Dialogflow provides 1-year shifted dates
        df = df[(df.date>beg) & (df.date<end)]
        df.to_csv(path_copy + '/' + type + '_' + begin_date + '_' + end_date + '.csv', index=False)
    else :
        df.to_csv(path_copy + '/' + type + '.csv', index=False)
```

Fig. 22: Storing data function.

4. Results and first improvements considered

The first developments show the ease of use of Dialogflow in terms of coding thanks to the predefined parameters, the .json format allows intuitive data manipulation and the graphical interface is clear and user-friendly.

However, the functionalities provided by Dialogflow are limited and the need for an Internet connection, and the use of the webhook server for python functions execution, are not representative of the future Martian bases. This tool also implies that offline migration and interaction with local sensors are complex.

Moreover, the first checks show the discussion with AI4U has some shortcomings in voice recognition depending on the accent of the interlocutor, and the use of plurals, numbers and certain words (for example, AI4U can understand "*cookie*" instead of "*copy*").

Finally, the AI4U character can disturb its interlocutor because of its behavior. It does not remember the crewmembers (this skill is not yet implemented) and his interjections are not always adapted to the context.

The goal for AI4U is to blend as a member of the space crew, its interaction with the astronauts shall be as natural as possible. This is enabled by multiple means. The most important one is a fluid communication that relies on an efficient design of the chatbot and a powerful embedded server. A Research and Technology (R&T) activity has demonstrated the technical feasibility of embedding AI4U in the space habitat thanks to the Tock chatbot solution. This solution deployment is ongoing.

AI4U's interaction with humans, its expressions, mimicking, and reflexes are based on the ones observed in the interactions of big mammals, humans included. This aims to make the conversation more familiar and instinctive [15]. To start the improvements, AI4U should be able to recognize the astronauts. Combining face and voice recognition, it would be able to remember astronauts' preferences in their work and casual interactions. This facial recognition skill will be developed in 2023.

To improve itself and create a stronger link with the astronauts, AI4U, after interacting with the crew members for some time, will increase its vocabulary and semantic expressions knowledge, ending up occasionally mimicking the talking habits of its interlocutors, as humans usually do. Also, when it doesn't understand the intent of the user or mistakes it and observes that it did, it will directly ask what it should have understood and if it's the appropriate time, if it could have a short teaching session on this topic. Through the conversation, it will automatically add its discoveries to its knowledge base, which the astronauts and the development crew on Earth can always access and modify at any time. This learning skill will be developed in 2023.

All these improvements will be tested during the next MDRS Supaero team analog mission in 2024.

An agreement signed in 2022 between EDF (Electricité de France, the French national energy company) and CNES sets up a partnership to work on connected habitats. Among several solutions, AI4U will be tested in the future terrestrial demonstrator.

These hands-on experiments test and improve the user experience when using AI4U. They make it possible to quickly identify the developments to be carried out as a priority in order to drastically improve the behavior of AI4U and its acceptability by the user.

A work to determine the roadmap for the development of AI4U is in progress. A team of different experts in operations, software development, Artificial Intelligence, human behavior, neurology and health has listed the different skills to develop for the digital entity during a workshop at the end of 2022. Future work will aim at organizing the development tasks for the next years to make AI4U a real virtual crewmember.

Table 2. List of the skills to develop for AI4U (in brackets is how often the idea appeared).

Subject	Human-Machine Interaction	System supervision	Help with work	Ethical and legal aspects
Nominal	Mental and physical health countermeasures (Sport class, news from the family, nutritional recommendations, rescheduling, etc)	Access the information at different levels of abstraction, being able to give a general overview as well as being an interface with the specialized systems giving the details from the captors and being able to control it	Tasks optimization with priorities, allocation, scheduling and rescheduling, random activities suggestion, maintenance scheduling (6)	Privacy and personal space for the astronauts, right to deconnect (4)
	Means of interaction with AI4U (Vocal, Touch, Gestures, Expressions)	Information collection for virtual twin of the base and astronauts to anticipate problems and countermeasures advice (3)	Regular training (in VR?) of the crew on new and old tasks and have to know how to do without AI4U (3)	Acceptability of AI4U by the crew
	Interaction adaptability to crew members and situations VS AI4U's Personnality (2)	Monitoring and repair if problem or schedule a repair (4), equipment environement,	Note taking, photos, videos, reports summarizing, operational support with experiments	Secure data storage
	Communication hub between astronauts and the control center	Communication with Earth, give and transmit information (2)	Localisation of crew members and equipment (4)	
	Mental and physical health supervision (3)	Monitoring the the food production and food stock	Help with teleoperation	
	Multiple characters for different tasks (2)	Energy monitoring (storage, production batteries)	EVA	
	Collective life facilitator (5)	Monitoring of the stock	Medical assistant (2)	
	Black sheep	Domotic (5)		
Urgency	Define a decision chain between AI4U, the crew and the ground center, authority (6)	Manual mode (2)	Pilot monitoring (call-out, cross check,...)	Fiability and certification of the AI, avoid biased learning (5)
	Efficient and adaptable information on the processes in case of urgency (1)	If problem in the base or medical alert and send message to ground control and give procedure (6)	Tasks priorities, allocation, rescheduling, optimisation	Security against hack, secure personal data storage (2)
	Avoid automation surprise (WAI) and be predictable (4)			A crew member is not all-knowing
	Possibility to stop the AI in case of problem (Safe word, unplug) (6)			Being able to admit its limits (2)
	Reassurance in case of stress			

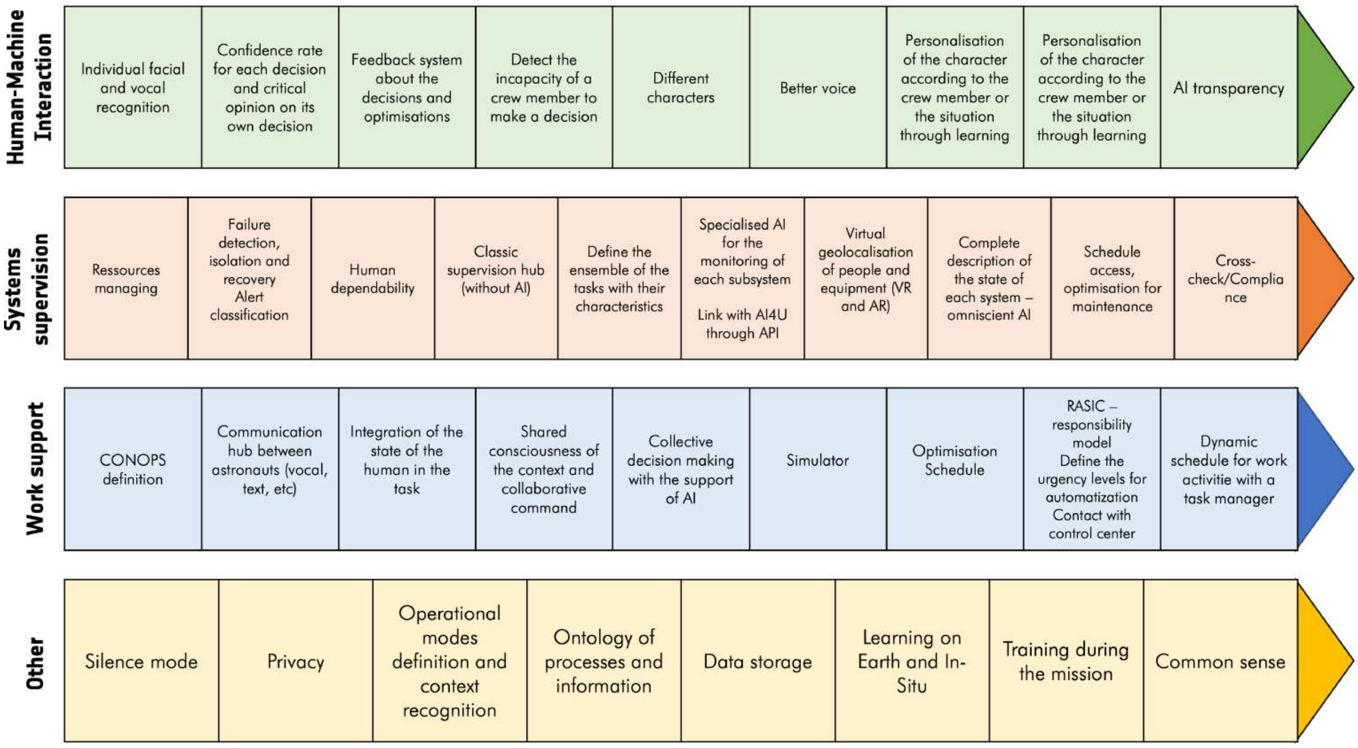

Fig. 23: Development tasks for the next years.

6. Conclusions

The need for crew autonomy in future lunar and Martian missions can be solved thanks to computer science applications and digital assistants. Several tests and studies were realized in this domain for terrestrial and space applications. CNES Spaceship France project has chosen to develop AI4U, a digital entity which main skill is to communicate verbally and non-verbally based on the recognition of emotions.

As a virtual crewmember, AI4U will take the role of supervisor, butler and companion.

A multitude of technologies developed in the computer science domains can be used to build AI4U.

The Spaceship France team set up the first developments and rapid tests in an analog mission in 2022 and 2023. The first operational deployment will take place in February 2023 but the next development priorities are already identified: using AI4U in standalone mode without an Internet connection to be representative of lunar and Martian conditions, facial recognition and voice learning to improve the interaction experience and the user acceptance.

In parallel, the project team works with different experts in operations, software development, Artificial Intelligence, human behavior, neurology and health to build a roadmap to develop AI4U through three domains: Man-Machine Interface, autonomous supervision and operational work support.

The Spaceship France team is also working in cooperation with CNES operational teams to imagine a potential use of AI4U in satellite control centers. This solution could introduce the notion of an augmented operator and open the door to its use in a digital twin to predict space system behaviors and anomalies.

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Appendix A The GER Critical Technologies within AI4U [1]

Global Exploration Roadmap Critical Technologies (Summary Table)

Global Exploration Roadmap Critical Technologies	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
Propulsion, Landing, Return			
In-Space Cryogenic Acquisition & Propellant Storage	Spacecraft: CPST/eCryo demo	u-G vapor free liquid tank to propulsion transfer, Efficient low-power LOx & H_2 storage >1 Yr (Mars)	
Liquid Oxygen/Methane Cryogenic Propulsion		Throttleable Regen Cooled Engine for Landing (Lunar Scale)	Throttleable Regen Cooled Engine for Landing (Mars Scale)
Mars Entry, Descent, and Landing (EDL)	Spacecraft: MSL class (~900 kg)	Demonstration of advanced technology in deep space environment	Large Robotics >1000 kg; Human ~40,000 kg
Precision Landing & Hazard Avoidance	Spacecraft: Lunar & Mars Landers State-of-the-Art	~100 m accuracy, 10's cm hazard recognition, Support all lighting conditions	
Robust Ablative Heat Shield Thermal Protection	Spacecraft: Orion Heatshield test flight (EFT-1)	~1000 W/cm2 under 1.0 atmospheric pressure	~2,500 W/cm2 under 0.8 atmospheric pressure
Electric Propulsion & Power Processing	Spacecraft: 2.5 kW thruster (Dawn)	~10 kW per thruster, High Isp (2000 s) (for some mission options)	~30-50 kW per thruster (for some mission options)
Mid & High Class Solar Arrays	ISS: 7.5 kW/Panel	High Strength/Stiffness Deployable, 10-100 kW Class (for some mission options)	Autonomously Deployable, 300+kW Class (for some mission options)
Autonomous Systems			
Autonomous Vehicle System Management	ISS: Limited On-Board Mgmt functions, < 5 s comm delay	On-Board Systems Mgmt functions (handles > 5 s comm delay)	On-Board Systems Mgmt functions (handles > 40 min comm delay)
AR&D, Proximity Operations, Target Relative Navigation	ISS: Autonomous docking	High-reliability, All-lighting conditions, Loiter w/ zero relative velocity	
Beyond-LEO Crew Autonomy	ISS: Limited Autonomy	Automate 90% of nominal ops Tools for crew real-time off-nom decisions	
Life Support			
Enhanced Reliability Life Support	ISS: MTBF <10 E-6, Monitored/operated by GC	More robust & reliable components (eliminate dependence on Earth supply logistics) Increased systems autonomy, failure detection capabilities, and in-flight repairability	
Closed-Loop Life Support	ISS: 42% O_2 Recovery from CO_2, 90% H_2O Recovery	Demonstration of advanced technology in deep space environment	O_2/CO_2 Loop closure; H_2O Recovery further closure; Solid Waste, reduce volume/storage
In-Flight Environmental Monitoring	ISS: Samples to Earth	On-Board Analysis for Air, Water, Contaminants	
Crew Health & Performance			
Long-Duration Spaceflight Medical Care	ISS: First Aid+, return home	Demonstration of advanced technology in deep space environment	Training (pre & in-flight) for medical aspects Continuous monitoring & decision support
Long-Duration Behavioral Health & Performance	ISS: Monitoring by Ground	Demonstration of advanced technology in deep space environment	Cognitive performance monitoring Behavioral health indicators & sensory stim.
Microgravity Counter-Measures	ISS: Large treadmills, other exercise equipment	Demonstration of advanced technology in deep space environment	Compact devices to assess/limit disorders Reduced weight/vol. aerobic & resistive eqpt.
Deep Space Mission Human Factors & Habitability	ISS: Large crew volume, food & consumables regular resupply	Demonstration of advanced technology in deep space environment	Assess human cognitive load, fatigue, health Optimized human systems factors/interfaces
Space Radiation Protection (GCR & SPE)	ISS: Partially protected by Earth Apollo: (accepted risk)	Advanced detection & shielding New biomedical countermeasures	
Infrastructure & Support Systems			
High Data Rate (Forward & Return Links)	Ground (DSN): 256 kbs Forward, 10 Mbs Return Link	Demonstration of advanced technology in deep space environment	Forward: 10's Mbps; Return: Optical > 1Gb/s
Adaptive, Internetworked Proximity Communications	ISS: Limited capabilities	Demonstration of advanced technology in deep space environment	>10's of Mbps simultaneously between users Multiple Modes; Store, Forward & Relay
In-Space Timing & Navigation	ISS: Limited to GPS range Spacecraft: DSN Ranging	Demonstration of advanced technology in deep space environment	Provide high-spec Absolute & Relative pos'n Space-Qualified clocks 10x-100x beyond SOA
Low Temperature & Long-Life Batteries	ISS: Lithium-ion (-156 C short duration), ~167 Wh/Kg	Lunar night temperatures and duration	
Comprehensive Dust Mitigation	Apollo: limited 3 day crew ops Rovers: limited mitigation	Multiple Active & Passive technologies required Significant advances in Life cycle	
Low-Temperature Mechatronics	ISS: +121 to -157 C	Operations to -230 C (cryo compatible); multi-year life	
ISRU: Mars In-Situ Resources		Potential Test-Bed for Mars Forward, and enhance lunar missions	O_2/CH_4 generation from atmosphere LOX/LH_2 generation from soil
Fission Power (Surface Missions)		Potential Test-Bed for Mars Forward, and enhance lunar missions	Fission Reactor (10's of kWe)
EVA/Mobility/Robotic			
Deep-Space Suit	ISS: EVA Ops at 0.3 Bar (4.3 Psid)	EVA Ops at 0.55 Bar (~8 Psid), extended EVA lifecycle On-Back regen CO_2 & humidity control, High Specific-Energy Batteries	
Surface Suit (Moon & Mars)	Apollo: 3 day max (Lunar)	30 day min duration, improved lower torso mobility, dust tolerant	1 year+ duration, thermal insulation (CO_2 atmosphere)
Next Generation Surface Mobility	Spacecraft: Lunar and Mars Rovers State-of-the-Art	Autonomous & Crewed capability, less Ground Control Extended range, speed, payload; navigate soft/steep varying soils	
Tele-robotic Control of Robotic Systems with Time Delay	ISS: <1-10 Sec delay for GC Ops Spacecraft: Lunar/Mars Rovers	Few seconds to 10's of seconds Dynamic environments w/variable delays & LOC	Up to 40 Minutes
Robots working side-by-side w/ crew	ISS: Limited (Robotic support to EVA)	EVA control robots w/ no reliance on Ground Control International standard & protocols	

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