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Spacecraft Anomaly Handling made accessible – Development and Testing of a Board Game based Trainings Tool using Gamification for a broader Audience.

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Abstract

Traditional training methods for satellite operations engineers, such as studying documentation, using spacecraft (S/C) simulators, participating in control room simulations, and engaging in hands-on activities with the spacecraft, often face challenges such as limited engagement, accessibility, and availability. To address these challenges, a board game was developed that incorporates gamification aspects to create an engaging, accessible, and motivating learning experience for all aspects of spacecraft anomaly handling.

The board game covers all major subsystems of a satellite, including Attitude and Orbit Control System (AOCS), Thermal Control System (THM), Chemical Propulsion System and Electrical Propulsion System (CPPS/EPPS), Payload, OnBoard Data Handling (OBDH), Electrical Power System (EPS), and Ground Segment operations. The game is designed to simulate real-life scenarios and anomalies that engineers might encounter, providing a risk-free environment for players to learn and practice anomaly handling. Key gamification elements such as peer interaction, immediate gratification, decision making, and low entry barriers are integrated into the game to enhance its educational value and player engagement.

The new board game, including all used methods of gamification and serious elements are discussed. The study aimed to determine whether the use of the game leads to an increase in the participants knowledge of satellite anomaly handling and general subsystem knowledge.

The results of the study indicate that the board game provides a increase in the knowledge of the participants. Improving the participants knowledge and their understanding of satellite subsystems and anomaly handling procedures after engaging with the game, regarding general knowledge as well as applicable skills for real satellite missions.

In conclusion, the development and implementation of a serious board game for training satellite subsystem engineers in anomaly handling represent a promising supplement to traditional training methods. The game's ability to increase knowledge memorization, enhance engagement, and provide an accessible learning tool suggests that it can be a valuable addition to the training programs for satellite operations engineers.

Keywords: training, gamification, decision making, cooperation

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control System
CPPS	Chemical Propulsion System
DSS	Dynamic Spacecraft Simulator
EDRS	European Data Relay System
EoL	End of Life
EPPS	Electronic Propulsion System
EPS	Electrical Power System
ESA	European Space Agency
FLD	Flight Director
FOP	Flight Operations Procedure
GOP	Ground Operations Procedure
GRD	Ground
GSOC	German Space Operations Center
LEOP	Launch and Early Orbit Phase

MCS	Mission Control System
NASA	National Aeronautics and Space Administration
OBDH	OnBoard Data Handling
PLD	Payload
S/C	Spacecraft
SCOS	Satellite Control and Operation System
TC	Telecommand
THM	Thermal Control System
TM	Telemetry
VOCS	Voice over Console System
XP	Experience Points

1. Introduction

Spacecraft Operations is a complex discipline involving many different systems, some of which need to operate in a hostile environment, mostly without the possibility of direct human maintenance or intervention. With only remote monitoring and commanding capabilities to diagnose and handle anomalies on the spacecraft, it is of the upmost importance that the subsystem engineers operating the spacecraft are well trained. As with most complex systems, the training required is long, tedious and includes few practical experiences. Besides that, the training of subsystem engineers consisting mostly of reading the documentation and some training sessions on the dynamic spacecraft simulator (DSS) towards the end of the training. Often the time on the DSS is limited, as the number of simulators is limited as well. For some missions the simulator is a dedicated hardware component that can not easily be replicated. Even if the simulator consists solely of software components, they typically run on dedicated simulation chains that in theory could be replicated but only with significant effort and dedicated computational power. Especially during the preparation of a spacecraft mission, the validation of flight operations procedures (FOP) on the DSS takes precedence over training.

While a high level of technical aptitude is required in spacecraft operations, social skills especially in regards to cooperation is another key ability. In addition, a general knowledge of other systems interfacing with once own helps in discussing and solving complex anomalies that often effect multiple systems on the spacecraft.

In order to break up the classical training and shorten the time needed for training new subsystem engineers as well as increase their motivation, this paper discusses an added innovative gamification approach to facilitate the spacecraft operations training with a goal of giving a general overview to spacecraft systems, typical anomalies and requests coming from the customer. Taking the concept of a board game, designed to train payload engineers proposed by [1], this paper aims for a more general approach. As the cooperation aspect of spacecraft operations is seldom trained directly, the focus of the game is on the interaction with the other players. A secondary focus was put on providing a broad but not very in-depth knowledge of satellite systems and processes using serious game elements to train the players during the game.

The term of "serious games" was first coined by Clark C. Abt in 1970 in his identically named book [2]. This form of gamification is not a new approach, but so far isn't used in many application or trainings in the space sector. While gamification methods such as serious games are meant to be fun, their main focus is the transfer of knowledge and not on providing entertainment [3]. Serious games have proven to be effective tools in enhancing the learning experience while increasing the motivation [4].

Since the introduction of serious games in the aerospace sector, a wide range of game-based approaches has been developed to facilitate learning and reduce entry barriers of complex or repetitive subjects. These include interactive training modules used in air traffic control simulations [5], National Aeronautics and Space Administration (NASA) virtual reality environments for extravehicular activity (EVA) rehearsal [6], and high-fidelity flight simulators like NASA's X-Plane-based systems, which are employed to train pilots and astronauts in realistic aerospace scenarios as well as software applications like "A Portable Learning Application" for astronaut training of long duration missions [7].

2. Serious Game "Operation Luna"

Taking the serious game "Operation Payload" [1], later called "Flight Team - A serious game" (see Fig. 1), that was developed for the training of payload engineers for the European Data Relay System (EDRS), Operation Luna tries to go one step further and teach the basics of S/C operations on a general level. Opening the game up to a wider audience by having a higher degree of abstraction than its predecessor and making it easier for people outside the field of satellite operations to interact with it, ”Operation Luna” aims to have an low entry barrier. It puts the players in the role of the subsystem engineering team of a fictional science and relay satellite orbiting around the moon. In addition to the payload (PLD), players have to take on the roles of AOCS, OBDH, THM, EPS, Ground (GRD), and the Flight Director (FLD).

A fictional lunar mission scenario was selected as the basis for this board game training tool due to its greater

Fig. 1. Flight Team - A serious game.

perceived engagement potential in the public compared to Earth-centered missions, while also offering the opportunity to introduce the operational complexities and scenarios associated with future lunar satellite missions. This approach enables trainees to familiarize themselves with unique challenges to cis-lunar operations.

Given the renewed international focus on lunar exploration missions by initiatives such as NASA’s Artemis program, the development of the Lunar Gateway space station, and corresponding efforts by the European Space Agency (ESA) , the choice of a lunar based training context is both timely and strategically aligned with current aerospace priorities.

In parallel, the German Space Operations Center (GSOC) is actively preparing to support upcoming lunar missions, highlighting a growing need for mission control personnel to gain experience with lunar specific missions their corresponding constraints and potential anomalies. Consequently, the development of an in-house training tool developed to simulate lunar mission scenarios offers additional value to the existing training efforts.

Similarly to the predecessor ”Flight Team - A serious game”, ”Operation Luna” introduces anomalies and operational requests into the game space for the players to solve. A solution has to be found before the number of anomalies and open requests stack up too high and exceeds the tolerated amount. The game is played in rounds separated by different phases. In the first phase a certain number of cards are drawn from the anomaly deck. This deck contains the red anomaly cards, describing certain unexpected behaviors of the S/C illustrated by a picture that, in some cases, might give additional information to the experienced player. In addition to the anomaly cards, the anomaly deck also contains gray request cards that represent external requests from the customer of the S/C services, as well as reoccurring tasks that the operational team needs to fulfill.

To solve these anomalies and requests, each player has a number of green action cards corresponding to activities and telecommands (TCs) of their chosen subsystem. The players have to discuss their approach to solving the open anomaly and request cards and play their action cards in the order they want them resolved. To get a hint what the problem is with the S/C, the players can use a ”Check TM” card to get more information on the current status of the S/C regarding a singular anomaly card. It allows them to compare a yellow bar code on the anomaly card to the bars of the blue system cards, representing the S/C status. This simulates checking the telemetry (TM) of the S/C to investigate the root cause of an anomaly. If all bars on the system card match to bars on the anomaly card, the system is most likely affected by the anomaly and tells the players in which status this component is right now, including a little description text giving insides into possible root causes (see Fig. 2). After the players played all their action cards, the anomaly cards are turned over. On their backside a description of the anomaly root cause can be found, including all actions that need to be played to solve this particular anomaly. If the corresponding actions were played, the anomaly is solved. The players take an amount of XP stated on the anomaly card and discard it.

The number of action cards that can be played in a single round are restricted by two factors. First, there is a maximum number of actions that are allowed to be played per player each round. Second, all action cards that

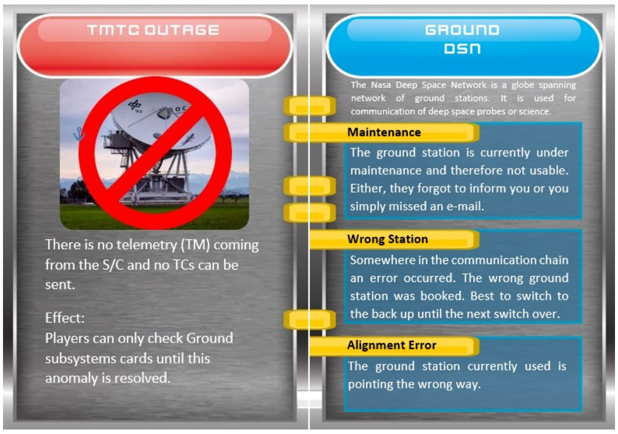

Fig. 2. Barcode comparison between an anomaly card on the left (red) and a system card on the right (blue). Indicating an ongoing maintenance on the ground station.

represent TCs send to the S/C require the players to spent a certain amount of bandwidth. If not enough bandwidth is available, the action card cannot be played.

Besides bandwidth, the players have to manage a number of other resources on the S/C. The available power on the S/C is needed to power the systems and payload of the satellite. This is represented by the players spending their available power at the end of each round on so called end-of-round-actions, modeled after the payloads on-board. For this game a generic relay payload was chosen as well as a multi-spectral camera, a radiation sensor and a gas sensor of the early mission phase. Fuel is needed to move the S/C along the track on the game board as long as no anomaly prevents it, representing the orbit of the mission (see Fig. 4). Finally the satellite has a resource called redundancy. Without the ability to track which component has failed, a generic redundancy resource is introduced. Each time a component fails this resource is reduced. If no redundancy is left on the S/C, the game ends. The same is true if the fuel runs out.

Resource management constitutes a core mechanic of the board game, serving as an analogue to the complex decision-making process a mission planning team typically undertakes. The resources are represented by little plastic cubes which are stored on a stylized two-dimensional model of the satellite (see Fig. 3). By solving anoma-

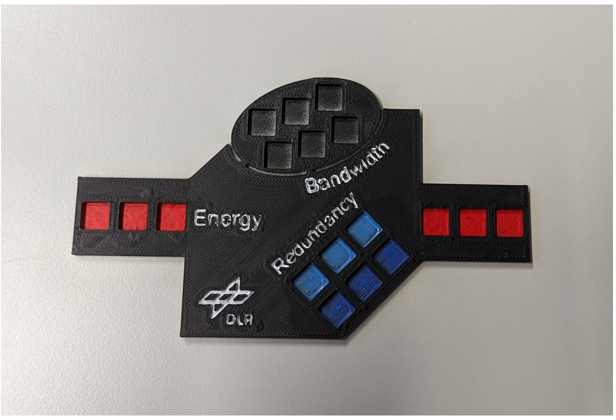

Fig. 3. Stylized 2D S/C Model.

lies and requests, the players are awarded with experience points (XP) . Those can be used to buy advanced action cards or permanent upgrades for the current game. Advanced action cards represent an assortment of multiple telecommands in one card, taking the place of FOPs for satellite commanding, while permanent upgrade cards are representative for software updates either on the ground system or the S/C itself.

The in-game objective is to reach the moons orbit with the S/C and collect as many science points as possible by using energy to power the payload actions. A high score of science points can be tracked between games to motivate the players in replaying the game and while the game being of a cooperative nature, it still appeals to the players competitive side.

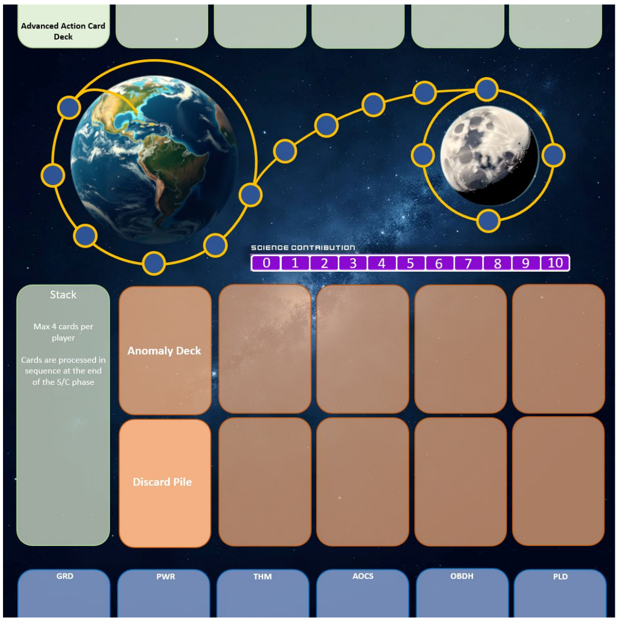

Fig. 4. Board Operation Luna.

3. Lessons Learned

Compared to its predecessor "Flight Team - A serious game", multiple improvements to the design have been included in "Operation Luna". For an easy access to the game rules and mechanics, reminder cards were created to quickly look up the core elements of the game, improving game flow and reducing over all game time required to finish a game, especially for inexperienced players. In addition to that, a lookup card was created with a list of the most important acronyms. The fractured nature of a game that uses cards as a vehicle to transport all knowledge, such an approach reduced frustration in players in a rate that made it preferable over the small gain in remembrance rate of acronyms without it.
The digits of the bar code used to compare anomaly cards with system cards were increased from eleven to twelve plus an additional calibration bar in white. While it is sufficient to just align the cards based on their size, this new approach decouples the bar code from the exact position on the card during the printing process, making it more robust against small alignment errors. The other additional digit in the bar code expands the number of possible system components represented by system cards. Two digits are always used to mark a system component card, increasing the number of possible system components from six to ten per subsystem. This approach was necessary for the GRD and AOCS subsystems with respectable eight and nine different system components.

4. Serious Elements and Training Methods

The main focus of the game "Operation Luna" is to teach and train an audience of players core principles, processes, procedures and the technical jargon of spacecraft operations. While "Operation Luna" uses a generic fictional mission, no training of satellite or system specific anomalies could be incorporated. With this higher grade of abstraction, the focus changes from component and platform specific knowledge to general operational problems, team cooperation and technical jargon as well as general anomalies. Some anomaly types are generic enough, that they have the possibility to occur across multiple different S/C platforms. Anomalies in the AOCS or THM sector are prevalent for such an approach. Keeping the S/C as a satellite orbiting a larger body in a relative unchanging orbit allows to transfer other anomalies and request types from the predecessor game to this one, such as station

keeping maneuvers and a constant orientation of the solar panels via a fixed turn rate. Furthermore, the concepts of an eclipse seasons and some of the GRD systems at GSOC are still applicable as well. The software tools and their distinctive anomalies and quirks were also kept, like the Mission Control System (MCS) SCOS, developed by ESA, , which is used in many different missions at GSOC.
The use of TCs is represented by action cards and the use of FOPs and Ground Operations Procedures (GOPs) by advanced action cards. The cooperation aspect is introduced through certain anomaly cards. These range from an outage of the Voice over Console System (VOCS) that prohibits talking for all subsystem players except FLD, over reduced bandwidth, forcing the players to decide which subsystem has to be fixed first, to complex anomalies that involve multiple subsystems, like a safemode entry.
While the action cards of the subsystem players are mostly for commanding and fixing problems of their respective system components, the FLD player has a special role. The action cards of the FLD player are mostly of a supportive nature, enabling other players in solving their tasks more efficiently. This includes cards to resend TCs that were lost due to a radio interference anomaly card or cards to find the root cause of an anomaly faster by checking the backside directly. Like in real life, the FLD has the final decision if the team is unsure what actions are to be performed. With cooperation being one of the main aspects of this board game training approach, the minimum number of players to get the full trainings experience from the game is increased to two players. While the "Operation Luna", like its predecessor, can still be played in a single-player mode, to familiarize once self with the anomaly handling aspect of the game, it is recommended to play the game with anywhere between two and seven players.

5. Discussion

Players show a high motivation to interact with the trainings material, signify that the principles of gamification incorporated into the board game, are working. This leads to a significant increase in the amount of material being understood and remembered [1]. With the amount of people that train to become subsystem engineers being strongly limited, a shift to a wider audience promises a larger pool of subjects for future evaluations of the benefits and effectiveness of the board game approach as an added method of training. It could also help in increasing the number of people interested in choosing a career path in S/C operations, but such claims would need to be verified in further studies.
For a serious game to be successful, it must achieve a delicate balance between educational values and entertainment. In the present proposed approach, both aspects appear to have been fulfilled, however a systematic data acquisition is still needed for this newer version. Translating complex real-world problems into structured and curated, game-based scenarios, the game reduces the cognitive load on the working memory of the player [8]. This simplification likely enhances the players' capacity to absorb and retain information.
Another strength of the board-game-based approach lies in its ability to contextualize abstract or highly technical topics, making it more accessible and relatable to especially learners from outside the S/C operations field. For engineering roles, such as subsystem engineers, this contextualization could be particularly impactful, accelerating their learning curve by embedding key operational concepts and knowledge within an interactive board game framework. A subsequent quantitative study, with a large group of participants, will be necessary to thoroughly test the effectiveness of "Operation Luna". Future works should specifically aim to determine whether the use of such a game can measurably improve the operational knowledge of subsystem engineers and reduce the overall training duration. Such outcomes would most likely have strong implications for the broader application of serious games in teaching S/C operations and other related technical disciplines.

6. Conclusions

After the promising results in the training for payload engineers by adding the serious board game "Flight Team - A serious game" to the regular training, a successor for a wider audience was developed. The board game "Operation Luna" is based on the previously used ideas of anomaly handling and a bar code based TM check mechanic, while advancing its core game play mechanics to a cooperative approach, including all subsystem engineers of a typical satellite mission. Its scenario of a moon based S/C while keeping the base aspects of the former version, aligns it with current initiatives of the space sector in the near future. For reliable results of the impact as a tool for training of operations engineers and engagement of people outside the field of S/C operations, a test campaign with a mid to large sample size is required. It however provides a fun and low risk way of learning about S/C operations while maintaining a low barrier of entry.

7. Outlook

The new generic satellite mission in "Operation Luna" provides an ideal platform to have interchangeable mission parameters based on the need for specific trainings. The game concept itself could be further refined, for example with distinct anomaly decks depending on the phase the mission is currently in. A deck with activities and typical anomalies in the Launch and Early Orbit Phase (LEOP), could be used at the beginning of the game, followed by an anomaly deck for the routine phase of the mission, ending in an End of Life (EoL) anomaly deck which could include activities and requests to passivate the S/C and send it to a graveyard orbit.
The number of around eighty anomalies available right now should be further increased, based on real-life anomaly cases on comparable spacecrafts. The list of possible anomalies for lunar missions should be extended as well based on studies from that sector. In combination with a computer, a smartphone or tablet, a supportive app could help select certain anomalies to be solved each round, making sure anomalies do not contradict each other.

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