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Columbus Ground Systems: What Current Operator Interfaces Can Teach Us About Efficiency, Effectivity and Worker Satisfaction for Future Astronautical Exploration Missions

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Abstract

The Columbus module of the International Space Station (ISS) is one of Europe’s most significant contributions to astronautical space exploration today. Columbus was launched on February 7th, 2008, docked to the ISS a few days later on February 11th and has been a part of the ISS since then. On behalf of the European Space Agency (ESA), Columbus is currently operated from the Columbus Control-Center (Col-CC), which is part of the German Space Operations Center (GSOC), at the German Aerospace Center (DLR e.V.) near Munich, Germany.

All software used at Col-CC for operations supports the flight controllers to perform their tasks on console effectively, efficiently and to their own satisfaction. In doing so, the used software should consider relevant human factors in this context, specifically situational awareness, workload, human error and multitasking. The existing software covers those aspects to some extent, but no formal analysis of the human factors has been conducted with the current version of the ground software before. Therefore, the goal of this work is to identify which parts of the ground software lack in these aspects and how to optimize the ergonomics of the software, while also enabling the flight controllers to maintain a high level of situational awareness, do multi-tasking, and handle the corresponding workload on console.

For that purpose, this paper is logically divided into two parts. The first part highlights how the Columbus module of the ISS is operated nominally and which ground tools are currently used. The second part of this paper highlights an empirical study that was conducted at Col-CC, identifying areas of improvements in terms of effectivity, efficiency and worker satisfaction, when flight controllers are performing nominal scheduled on-board activities. The study was conducted as semi-structured interviews with 13 flight controllers at Col-CC, which were subsequently analysed, using qualitative content analysis.

This study is first and foremost supposed to help improve current operator interfaces in use at Col-CC. Furthermore, since the Lunar Gateway is also going to be operated from GSOC, the findings will provide useful insights for the design of future operator interfaces, as well as for further developments in the context of astronautical space exploration missions. Finally, with the recent emergence of Artificial Intelligence (AI) and Machine Learning (ML), the way operations are performed today, is about to be revolutionized. Intelligent assistant systems, like the Mars Exploration Telemetry-driven Information System (METIS) are bound to not only improve what the operators can do, but also how they do it. This work will give first hints for improvements of operator interfaces, in order to facilitate these new AI/ML capabilities, while also allowing operators to perform at the same or at a better level than before.

Keywords: UX/UI, HMI, MCS, Data Processing, Situational Awareness, Ergonomics

Topic: 14. Human Factors Training and Knowledge Transfer (HFT), 2. Human Factor & Behaviour on Operations

Acronyms and abbreviations

See annex A.

1. Introduction

The Columbus module of the International Space Station (ISS) is one of Europe's most significant contributions to astronautical space exploration today. The launch of the Columbus module took place on February 7th, 2008, as part of the STS-122 mission, with subsequent docking to the ISS occurring on February 11th. Since its integration into the ISS, Columbus has been an integral part of the station's operations. Under the custody of the European Space Agency (ESA), Columbus is currently managed from the Columbus Control Centre (Col-CC), a facility which is part of the German Space Operations Centre (GSOC) located at the German Aerospace Centre (DLR e.V.) near Munich, Germany.

Continuous operation of the Columbus module by Col-CC has been instrumental in the successful execution and support for all subsequent missions and increments since its inception. The most recent notable achievement involving substantial European involvement was the culmination of Andreas Morgensen's Mission "Huginn", encompassing ISS Expeditions 69 and 70. During his mission, he assumed the role of ISS Commander until its conclusion, accumulating a total duration of 199 days on board and conducting over 30 distinct European experiments [1].

In order to support Columbus operations, Col-CC is equipped with a dedicated suite of software tools, that enable flight controllers to monitor and control Columbus, including all subsystems and experiments, at all times. This software facilitates efficient task accomplishment by flight controllers, however, it is imperative that such systems take into consideration relevant human factors in this context, including situational awareness, workload, human error, and multitasking, as well. While the existing software partially addresses these aspects, a comprehensive analysis of human factors has not been performed with respect to the current version of ground software. This study aims to identify areas where ground software falls short in relation to ergonomic optimization, while enabling flight controllers to maintain situational awareness, perform multi-tasking efficiently, and handle workload effectively on console.

The goal of this research is to identify potential improvements regarding the currently used software suite at Col-CC, but also to give indications for how future mission control software might be designed, so that an even higher level of support by ground can be achieved.

For that purpose, an empirical study was conducted at Col-CC, identifying areas of improvement in terms of effectiveness, efficiency, and worker satisfaction, when flight controllers perform nominal scheduled on-board activities. The study was carried out through semi-structured interviews with the flight controllers at Col-CC, which were subsequently analysed, using qualitative content analysis.

This paper presents the results of this survey and is structured in five parts: Chapter 2 highlights how the Columbus module of the ISS is operated nominally and what ground tools are currently used. Chapter 3 analyses the theoretical aspects of human factors within the context of Columbus operations. Chapter 4 introduces the methodology of the conducted survey, describing the structure of the questionnaire and the relevant variables that were subject to the survey. In chapter 5 the questionnaires are evaluated and the findings of our study are presented. Finally, chapter 6 concludes this paper with a discussion on how the identified improvements can be implemented at Col-CC, and how they can contribute to the design of software for ground control in the future with almost permanent coverage. All used acronyms and abbreviations can be found in annex A.

2. Background

2.1 Columbus operations overview

The Columbus module provides a paradigm for international cooperation in space exploration. Operated by Col-CC, it also supports research from other ISS partners, including the National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA), and Roscosmos. Since its installation, the module has facilitated a range of scientific experiments and research activities. Significant advancements have been achieved in various fields, including biology, physics, and technology development, thereby continuing to fulfil a critical role in the ISS mission. The module is equipped with facilities necessary for conducting scientific experiments across diverse disciplines, such as life sciences, materials science, fluid physics, and other fields. To fulfil its role as Europe's primary laboratory in space, Columbus accommodates ten International Standard Payload Racks (ISPRs), and provides essential resources, including data, communications, life support, cooling, and power, which are required for accommodation of crew and enabling research. The operation of the Columbus module is entrusted to a collaborative effort between Col-CC, ESA, and various international partners of the ISS. The primary control center for the module, the Col-CC, oversees the day-to-day operations of the module and monitors the module's systems to ensure proper functionality. The centre enables scientists and on-board crew to conduct experiments without interruption or loss of time. Effective operation of Columbus necessitates close cooperation with other ISS partners, including NASA, Roscosmos, JAXA, and the Canadian Space Agency (CSA), to ensure efficient use of resources and shared expertise. Additional User Support and Operations Centres (USOCs) across Europe provide support for specific experiments and payloads within Columbus, collaborating closely with researchers to plan, execute, and analyse experiments. Meanwhile, astronauts on board the ISS perform hands-on operations of these experiments and conduct maintenance as required. Effective communication between ground control centres and the ISS is paramount for operation of Columbus. Commands and data are transmitted via satellite links, enabling real-time monitoring and control of the sub-systems and experiments.

2.2 Mission control basics

The Flight Control Team (FCT) at Col-CC is responsible for the operation and monitoring of the Columbus module, ensuring its safe functioning. The team comprises several specialized positions, each with distinct roles and responsibilities:

- The Columbus Flight Director (COL-FD) position supervises all operations and makes critical decisions concerning the Columbus module's activities. They ensures the successful completion of scientific campaigns and promote effective communication with other positions in the FCT and international counterparts.
- The EUROCOM position is tasked with facilitating verbal communication between the astronauts who are conducting operations inside the Columbus module and the ground positions.
- The COSMO position oversees all maintenance tasks pertaining to the Columbus module's structure and storage space, thereby maintaining its physical integrity.
- The COMET position coordinates and plans all activities, including scientific experiments and payloads, within Columbus. These efforts are in collaboration with researchers, who work together to optimize experiment utilization.
- The STRATOS position is responsible for monitoring and controlling the module's on-board sub-systems, thereby ensuring that systems operate correctly and any anomalies are addressed promptly. This includes managing the Data Management Subsystem (DMS), the Environmental Control and Life Support Subsystem (ECLSS), the Communications Subsystem (COMMS), as well as the Electrical Power Distribution Subsystem (EPDS) and the Thermal Control Subsystem (TCS).
- The Ground Control (GC) position is responsible for the European ground segment, coordinating with USOCs, other ISS control centers, and supporting overall operations of the Columbus module from ground.

Notwithstanding, only COL-FD, STRATOS, and GC are staffed 24/7 at Col-CC. Among these personnel, only STRATOS possesses the capability of issuing on-board commands to the module and responding effectively to off-nominal situations arising from system operations. As stated above, Columbus comprises five sub-systems, which are monitored and controlled by STRATOS [2]:

- The DMS consists of computers and data networks structured into two layers (vital and nominal DMS). Initially, vital DMS monitors the most critical systems of Columbus, ensures vehicle and equipment safety, and triggers certain Failure Detection, Isolation and Recovery (FDIR) actions upon detecting certain failures in critical hardware. Second, nominal DMS executes operations such as configuration of payloads for data up-/downlinks or software updates, which may have small or large operational impacts depending on the type of change.
- The COMMS comprises all video and audio equipment in Columbus, including a high-rate multiplexer for high-rate data downlinks, the Columbus Ka-band antenna, as well as the Multi-Purpose Computer and Communication (MPCC) system.
- The ECLSS is integrated into the overall ISS life support system. Breathable air, provided by the United States Orbial Segment (USOS) to Columbus, is distributed, cleaned, and circulated internally throughout the module. Temperature and humidity control are also responsibilities of the ECLSS.
- The EPDS comprises two primary units, referred to as Power Distribution Units (PDUs), which receive, convert, and distribute power to the Columbus power consumers.
- The TCS supplies cooling water to all active racks and systems in Columbus, facilitated by one of two primary pumps and individual on/off valves for each rack and system. Temperature settings for TCS are adjusted by operating modulating valves and transferring heat to the USOS via two heat exchangers.

Hence, this survey highlights the need for effective interaction between STRATOS and ground software in order to enhance Columbus operations.

2.3 Operator interfaces

As the basis for nominal operations of the subsystems by STRATOS, a mission timeline is created for each day of operations. The mission timeline, as shown in figure 1, contains a multitude of activities that are executed by the on-board crew, or ground.

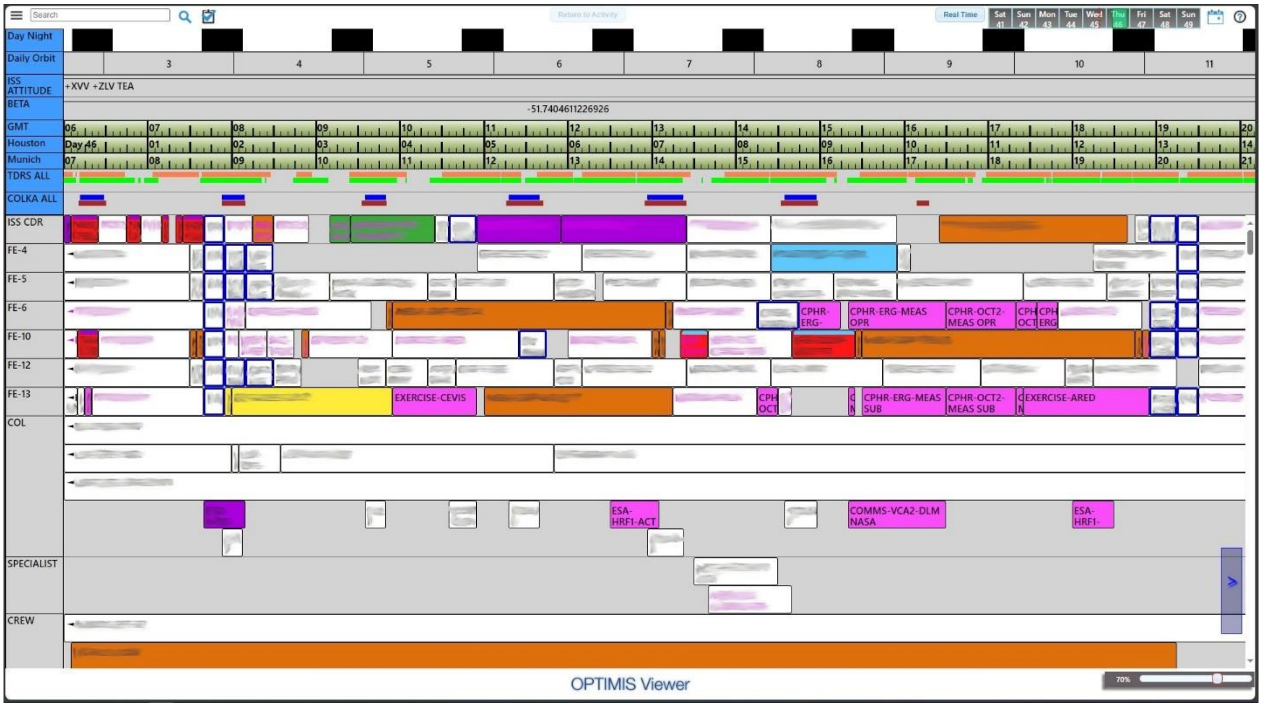

Figure 1: Example mission timeline, executed during Expedition 70, Day of Year (DoY) 46, 2024

As can be seen on the left-hand side, the column labeled “COL”, contains all activities that are being executed by Col-CC. In this example, STRATOS performed several tasks throughout the day, ranging from activating/deactivating payloads in Columbus, configuring and routing video streams, and actively monitoring communication links between the Columbus Ka-band antenna (ColKa) to the European Data Relay Satellites (EDRS). Activities which are colored similarly, have a dependency on one another. In this case, the activation of one of the payloads at 12:30 GMT was a prerequisite for crew to perform their related on-board tasks, which are all colored in pink. The names of all other activities are blurred due to crew and data privacy.

Once a mission timeline is released for execution, STRATOS is able to perform all of their activities, by following step-by-step instructions, which are contained in a specific Operational Data File (ODF), colloquially referred to as procedures. Each procedure contains steps to verify incoming on-board telemetry and, upon successful verification, sending software commands to the Columbus DMS for on-board execution.

Therefore, to enable the completion of activities (i.e. executing procedures), two distinct software tools exist to cover a) telemetry processing and command execution (including the adjustment of monitoring values), and b) telemetry visualization. Both software tools are introduced in the next two paragraphs, starting with telemetry processing and command execution.

For the processing of incoming telementry packets as well as sending commands to the on-board computers, a software called Monitoring and Control System (MCS) is used [3]. Figure 2 depicts what MCS looks like for the controllers on console.

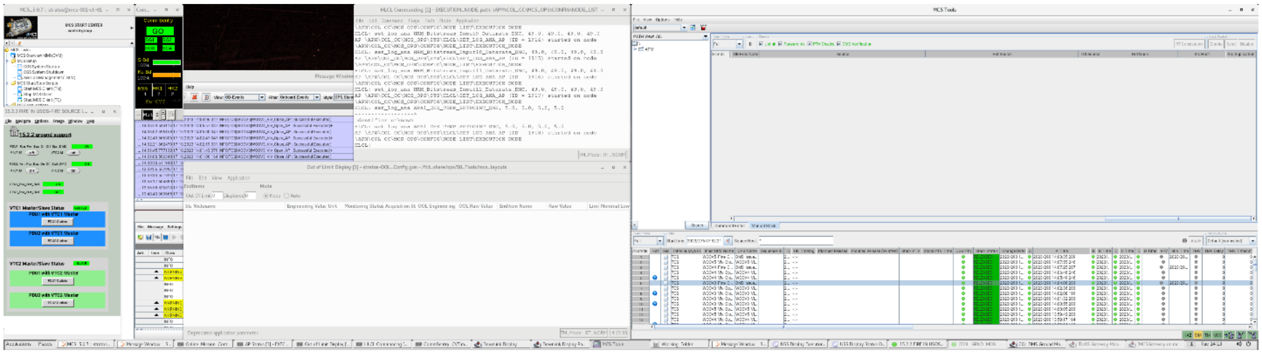

Figure 2: MCS client used for execution of software commands and adjustment of monitoring values by Col-CC

Physically, one MCS client covers two screens, while two MCS clients are available at the STRATOS console (i.e. four screens). The main features of MCS are:

- Processing of incoming telemetry packets, using a given parameter definition set.
- Providing processed parameters to other applications as well as facilities for visualisation and further analysis.
- Adjustment of the monitoring values (i.e. upper and lower bound that a parameter needs to be in for it to be considered “nominal”) for dedicated parameters, including the visualization of all parameters which are out-of-limit at any point in time thorough an Out-Of-Limit (OOL) display. There are two sets of monitoring limits, that can be applied to an individual parameter, a soft limit, displayed in yellow and a hard limit, displayed in red.
- Creation, maintenance and storage of command stacks. Those are MCS specific files, containing the software commands, which are to be sent to the on-board computers for a specific procedure.
- Loading of previously created command stacks, and individual on-demand execution of each command contained therein.

For telemetry visualization a tool called SATMON is used which directly connects to and interfaces with MCS [4]. Figure 3 depicts what SATMON looks like for the controllers on-console.

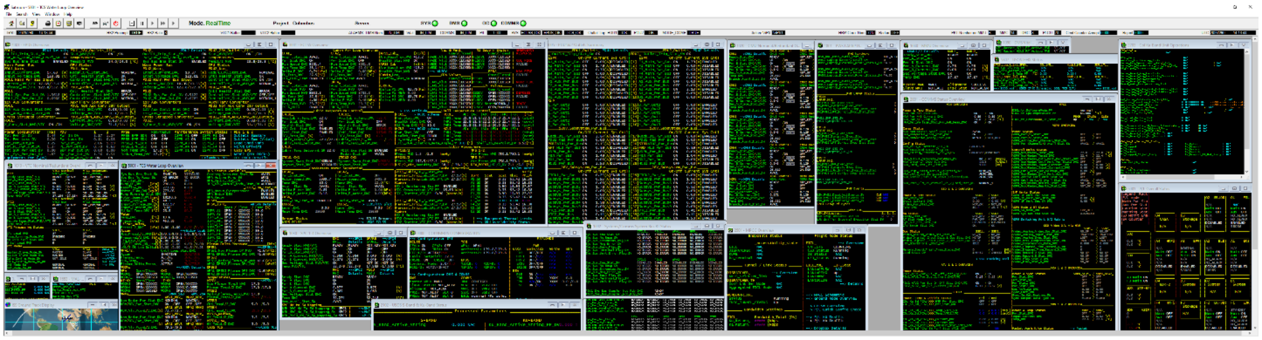

Figure 3: SATMON client used for telemetry visualization by Col-CC

Physically, one SATMON client covers two screens, while two SATMON clients are available at the STRATOS console (i.e. four screens). The main features of SATMON are:

- Display of real time data in the form of individual “end-items”, i.e. parameters collected by the on-board and/or ground systems. In total there are around 26000 parameters that can be displayed this way.
- Plotting of time series data, with adjustable time-scale, i.e. parameters can be plotted over several seconds, minutes, hours, days, etc.
- Activity/procedure specific monitoring windows, containing only those telemetry parameters that have to be validated as part of a single activity and/or procedure, including their current value, their target value and a coloured indicator showing whether the current value matches the target value.

Figure 4 shows what the STRATOS console looks like in the main control room at Col-CC.

Figure 4: Layout of the STRATSO console at Col-CC

As can be seen, in addition to four screens for SATMON and MCS respectively, the STRATOS console also provides two more screens for operations support tools (e.g. to display the timeline, procedures and other operational information), two screens dedicated for the MPCC subsystem on the far right, and a screen for the real-time Voice Communications System (VoCS).

The interaction between STRATOS and their console tools is analysed hereafter, in order to identify potential improvements in effectivity, efficiency, and job satisfaction (i.e. usability). The objective is to identify improvements in terms of the degree of goal achievement (effectivity), the resources used to achieve these goals (efficiency) and the contentment with the system (job satisfaction), from a psychological and human factors standpoint [5].

3. Human factors of Columbus operations

3.1 Situational awareness

The overarching goals of Columbus operations include the successful monitoring and control of systems and the execution of activities. To monitor and control a dynamic, safety-critical environment, operators must achieve and maintain a state of knowledge about current situations to enable timely and accurate judgments and performance. This state of knowledge is referred to as Situation Awareness (SA). The most commonly cited definition of situation awareness is: "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [6]. It should be noted, that time and space are explicit parts of this definition and are highly significant contributors to maintain a high level of SA.
Situation awareness is influenced by individual, task- and system related factors. The failure to achieve or maintain situation awareness can have different causes, depending on the level, where the error occurred. The failure to perceive information, which is level one of situation awareness, can result from data being unavailable, difficult to detect, incorrectly perceived, inadequately monitored by the operator or be caused by memory loss. If information is incorrectly interpreted or integrated, which is level 2 of SA, a lack of or incorrect mental models or an over-reliance on standard values might have been the cause. Failing to project system states to the future, level 3 of situation awareness, may also result from a missing or incorrect mental model or from over-predicting trends. In general, situation awareness errors may also result from a failure to maintain multiple goals or from over-reliance on established habits [7].

3.2 Decision making and action

Decision-making and action involve how operators evaluate options, ultimately decide on a course of action and then translate this into behaviour. Both are influenced by a variety of human factors. In the context of safety-critical, complex, and dynamic domains, workload [8], multitasking [9] and human error [10] are of great importance. These factors are interconnected, as the individual aspects influence one another. For example, a lower workload leads to greater situational awareness, due to the availability of additional resources. The lower the workload and the less operators' multi-task, the more resources are available for achieving and maintaining situation awareness. Having high levels of SA improves decision-making and reduces the probability of error occurrence [11].
In the presented model, depicted in figure 5, the three stages a) situation awareness, b) decision-making and c) performance are seen as separate processes that influence each other through a feedback loop.

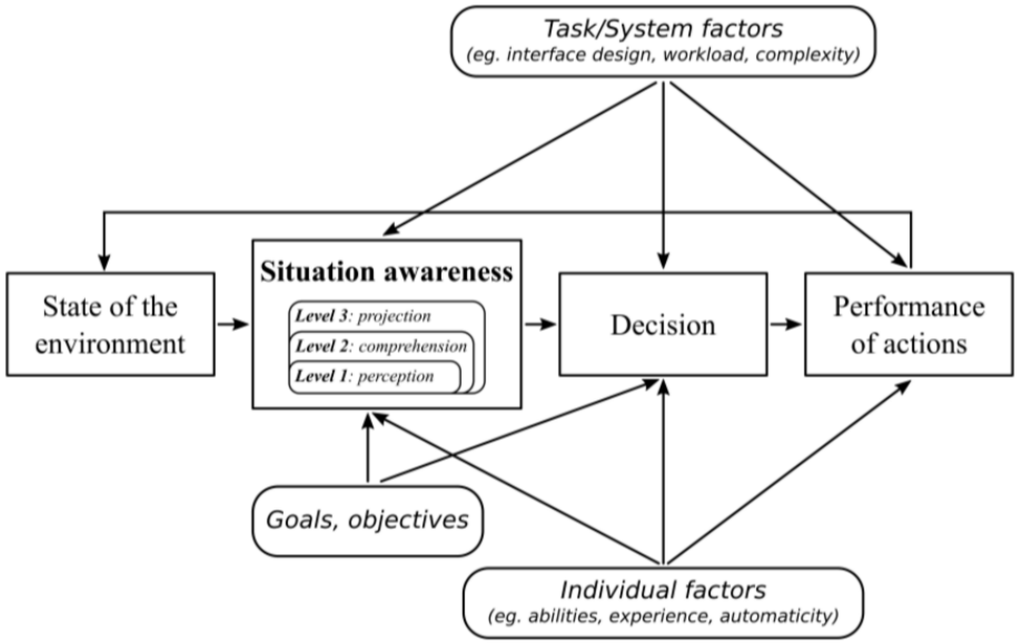

Figure 5: Framework model of situation awareness [8]

Situation awareness influences which decisions are made. The decisions determine the specific actions to be taken and these actions, in turn, influence situation awareness when new information is acquired, perceived, interpreted and projected. STRATOS operators are, as mentioned, responsible for monitoring and controlling the sub-systems of Columbus. One of the objectives is therefore to maintain or adjust the system states according to on-going mission objectives. The system states for example, in particular the discrepancy between actual and target values, determine the decisions that are made and actions that need to be performed. Changes in states are then compared with the expected outcomes and goals and actions are adjusted accordingly. Although the different stages affect each other and deficits in one stage may negatively affect the proceeding stage(s), their link is not necessarily direct. In cases where situation awareness is high or even perfect, the decisions made can still be incorrect [8, 12]. On the other hand, situation awareness might be low, but the decision that is made might still be correct, for instance due to luck [12].
For comparison, an analysis covering four years of aircraft accident investigation reports revealed that 88% of all human error-related incidents involved difficulties in achieving or maintaining situation awareness. Most of these problems were related to errors in the perception of information (level 1: 72%), followed by errors in the interpretation and understanding of information (level 2: 22%), and lastly, errors in predicting future states (level 3: 6%) [7].

3.3 Individual and internal factors

The characteristics and limitations of human information processing should be considered when designing user-centered systems [13]. Internal and individual factors can influence the interactions of operators with their console tools. Personal qualities for instance contribute to the success of operations. For mission control, seven basic principles are listed and defined to achieve professional excellence: discipline, competence, confidence, responsibility, toughness, teamwork, and vigilance. 'Competence', for example, implies the importance of preparation and commitment within the context of a safety-critical, dynamic environment. Other factors, such as fatigue, e.g. during night shifts, may also influence performance. In addition, the amount of practical experience gained on console can promote situation awareness, decision-making, and action execution when pre-existing expectations and established mental models provide a reference framework for dealing with situations. In this regard, pre-existing mental models and expectations need to be accurate since inaccuracies affect performance negatively and may result in wrong objectives.

3.4 Further contributing factors

The nominal states of the sub-system are set, monitored and modified via MCS through dedicated ground monitoring displays. System states are considered nominal when they correspond to the defined expected setpoint or remain within the defined expected limit range. For discrete variables (e.g., 'on' or 'off' status), expected states are defined; for analogue variables (e.g., temperature), soft and hard limits as well as delta limits are specified. Soft and hard out of limits refer to the deviation difference from the expected limit ranges, while soft out of limits indicate minor deviations and hard out of limits indicate severe deviations. Delta limits define the tolerated rate of change. All values that deviate from these defined setpoints or limit ranges trigger out-of-limit alerts, but not all deviations represent abnormal conditions. Changes expected in relation to the execution of timeline activities (e.g., opening a valve) also trigger alerts, as the ground monitoring is not linked to the timeline and not automatically adjusted to what is commanded. Previously defined limits must be adjusted by operators, and these adjustments then represent the new setpoints or limit ranges and, thus, the new nominal state. Apart from limit violations attributable to timeline activities, limit violations that are known (e.g. loss of signal due to an anticipated handover from one relay satellite to another) or not malfunction-related (e.g. optical sensors of smoke detectors are dirty) also do not indicate problems with any system per se. Therefore, the adjustments of all limit violations mentioned so far are part of nominal operations. Unexpected deviations will be classified as so-called faults, that represent "abnormal conditions that can cause an element (3.41) or an item (3.84) to fail" and may include safety-critical conditions [14]. They can be distinguished in flight anomalies, that indicate a failure or malfunction on board, and ground anomalies that indicate an issue on the ground segment. Faults can indicate simple limit value violations or, in more severe instances, cautions, warnings and emergencies.
Accidents are typically a result of a combination of several contributing factors rather than one single cause. In [15] the author metaphorically describes each contributing or potentially contributing factor in an accident, as a slice of cheese. Each slice contains holes, which vary in size and location and represent flaws and safety deficiencies. An accident occurs when the holes in these slices line up in a way that a protective barrier is no longer present. When analysing human error, two approaches can be differentiated: Focusing on the individual's fault (persons approach) or accounting for human error and implementing respective changes into the system to minimize human errors (systems approach) [15]. If the focus is solely on finding individual fault without considering factors that might have contributed to or enhanced erroneous behaviour, the fault might be repeated, as making errors is part of being human [10]. Thus, considering human capabilities and limitations when designing and evaluating systems, instead of focusing predominately on functionalities and presuming rational, optimal use, which is difficult in acutely stressful situations, can reduce error occurrence by building or enhancing a protective barrier [10, 16-17].

4. Methodology

An interview study was conducted aiming to identify usability shortcomings of interfaces and applications of the STRATOS console. Relevant human factors are considered: What hinders operators from achieving and maintaining situation awareness, making correct and timely decisions, and performing efficiently and effectively? What type of errors occur and how fault tolerant are the systems? Furthermore, the characteristics and effects of multitasking and task-switching on the overall process are investigated. To answers these research questions, semi-structured interviews are conducted with the STRATOS operators. Interviews are analyzed using qualitative content analysis, according to [18], defining 11 steps to be followed. Categories were initially derived deductively based on results from participant observation and theoretical and empirical findings. Details and nuances as well as relevant concepts not yet defined were then added inductively.

4.1 Material

Participant consent is obtained through a confidentiality agreement, and demographic data is collected using a questionnaire. The questionnaire includes information on age, gender, and academic background. Regarding the job as a flight controller, questions about previous work experiences in the space industry, comparably demanding past jobs, and information on training (duration, certification date) and specialization were of interest. Language skills were not surveyed, as fluency in English is a prerequisite and is tested before training.

Interviews were conducted using a semi-structured interview guideline. In preparation of this interview study, the workplace and the tasks of the STRATOS position were analysed by work-shadowing combined with interviews of STRATOS operators. This workplace analysis focussed in particular on the nominal tasks and the necessary interactions between users and technical systems.

The interview guideline contains all topics identified as relevant by a literature review (ref. chapter 3) and were tailored to specific context by prestudy work shadowing. The following human factors topics were identified as particularly relevant for evaluating the interaction between STRATOS and their console tools:

- Situation awareness:
  - Information management
  - Alerts
  - Projection to future states
  - Visualization
  - System feedback
- Decisions and performance
  - Workflow and complexity
  - Errors
  - Manual work and adjustments
- Multitasking and task switching
  - Interruption management
  - Playback and communication
  - Cognitive load and task management
  - Office work
- System limitations
  - Performance capabilities
  - Data transmission and processing feedback
- Workload off-console and habituation.

4.2 Participants

At the time of the study, the STRATOS team consisted of 16 people, 14 of whom were certified and two of whom were in training. Due to the ongoing training and lack of on-the-job training on console, the two trainees were not interviewed. Of the 14 certified operators, 12 were interviewed. Two other operators were not available during the period of interview conduction. Additionally, one former STRATOS operator, who was in training to become a flight director, was also interviewed since the time on the STRATOS console was recently. Thus, 13 operators aged between 26-35 years (M = 30.08, SD = 2.75) were interviewed (11 were male). The number of specializations is about even; seven specialize in DMS/COMMS and six in ECLSS, EPDS, and TCS. The most experienced operator, referring to years of experience, has been working as a STRATOS operator for seven years. The newest operator got certified a few weeks before the interview. Nine of the 13 interviewed people had prior work experience in the space industry before becoming a STRATOS operator. Eleven operators had not worked in a comparably demanding job in the past, and thus, only two operators indicated having previous experience in a similarly demanding job.

4.3 Procedure

Interview appointments were coordinated via email or on-site. Subsequently within a period of six weeks, interviews were conducted individually on-site, either in the office of operators or a conference room. Before the interview, operators were informed verbally about the objective of this study, subsequently signed the confidentiality agreement, and completed the demographic questionnaire. Afterward, the interviews were conducted in English. Interview conversations were recorded from start till end using the voice memos app on a business iPhone. Only during the first two interviews, two interviewers were present. Interview 3 till 13 were subsequently conducted with only one interviewer. Two interviews were divided into two parts due to a lack of time or a break. Interview five was continued on another day, and interview 11 included a one-hour break between the two parts. Interviews lasted overall between 1 hour (shortest: 00:57:03) and 2 hours (longest: 01:58:59). Overall, the semi-structured guideline served as a reference and was not always followed from top to bottom. The order of questions depended on the conversation - sometimes, later topics were advanced, questions were omitted if already addressed by the operator, or new follow-up questions were added.

5. Results

5.1 Overall results

The study investigated various human factors of the systems used by STRATOS operators, highlighting strengths, weaknesses, and suggestions for improvement.
Overall, the number of statements for each category are shon in figure 5. As can be seen, situational awareness received the most amount of statements, with n = 373 statements. This was closely followed by statements regarding decisions and performance, with n = 303 statements. Multitasking and task switching was only identified with n = 119 statements, while system limitations, workload off console, and habituation received n = 31, n = 19, and n = 17 statements, respectively. Due to the distribution of statements, in the following paragraphs, the results are summarized for situational awareness, decisions and performance, multitasking and tasks switching individually, while the results for system limitations, workload off console and habituation are grouped into one paragraph.

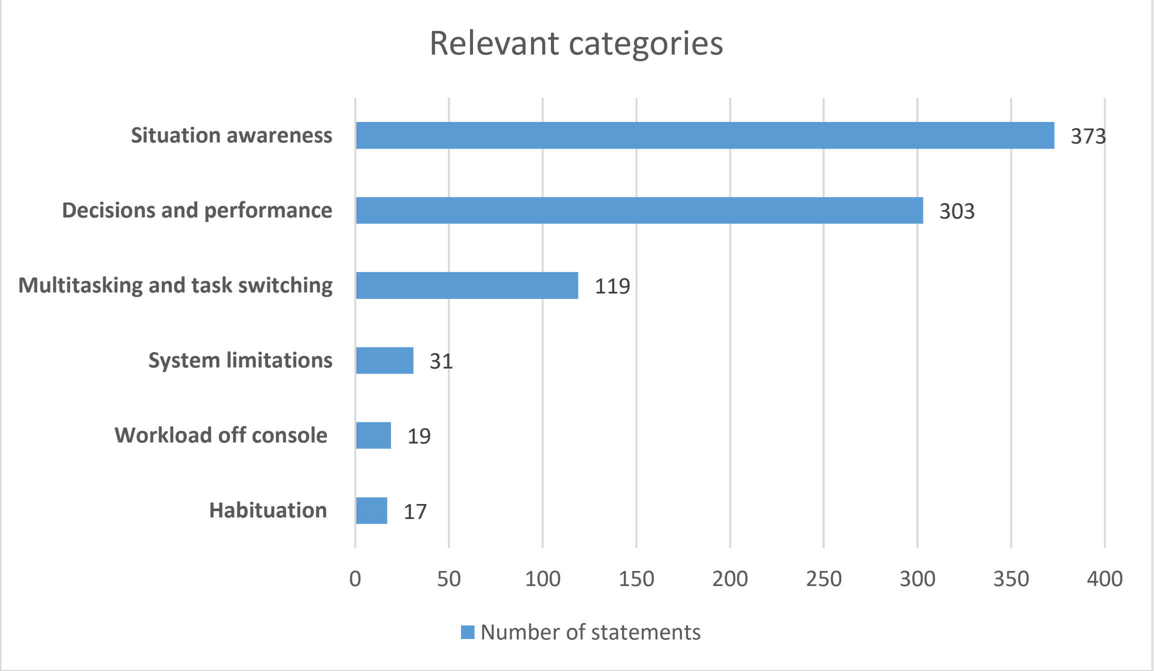

Figure 6: Statements of the semi-structured interviews sorted by category.

5.2 Analysis of statements regarding situational awareness

The operators who provided feedback on monitoring systems, highlighted several key points of interest. The most significant parts of the feedback are summarized hereafter.
In general, the physical distribution of information and the use of different clients impacted monitoring effectiveness, with some out-of-limit conditions being missed. Operators preferred using the closest client to ops support tools and suggested that clients further away are used less frequently. Therefore, while separating information could be beneficial for redundancy and problem classification, there was a strong desire for better integration and reduced physical distance between monitors.
Operators found the information on MCS and SATMON complete but noted that not all displayed information was equally useful. The volume of information in SATMON was both a strength and a challenge, with suggestions for better filtering and availability. The information architecture in SATMON was praised for providing good overviews and facilitating focus, with a preference for a bottom-up approach for monitoring and a top-down approach for troubleshooting.
Visual consistency and layout standardization were appreciated, but improvements were suggested for visibility and adaptability. The concept of receiving visual and audible alerts was positively rated, although weaknesses were noted,

such as the need for manual scrolling when many out-of-limits were displayed. Operators also suggested improvements for audible alerts, including differentiation between soft and hard out-of-limits.
Expected out-of-limits influenced perception and interpretation, with potential improvements suggested, such as grouping or filtering functions. Toggling of out-of-limits reduced situation awareness, and operators suggested adjustments to limit values or disambiguation between severity levels.
Predictions of system states and telemetry changes were noted as beneficial, but concerns were raised about reliability and context-awareness. Operators appreciated the plotting capabilities in SATMON, but rarely used the topological overviews in MCS. Improvements were suggested for visual guidance and understandability.
The system provided feedback after commanding, but successful command execution was not always apparent. Operators noted that wrong commands could lead to unexpected out-of-limits and potential additional errors if monitoring was not updated correctly. The study highlighted the need for better integration, visibility, and adaptability in monitoring systems to improve overall effectiveness and situational awareness.

5.3 Analysis of statements regarding decisions and performance

How the scope and nature of activities influence the interfaces and systems required for execution of said activities are examined in this paragraph.
Operators noted that the organization and number of information sources significantly impact workflow, especially for complex activities involving multiple systems and procedures. Integration and interconnectivity between data were highly desired to streamline operations. While some operators appreciated the distribution of information for separate command stack preparation, others found switching between different clients challenging. Multiple displays helped track activities and procedures, but condensing information onto a single display or providing reminders could improve efficiency.
File transfers were highlighted as activities requiring multiple sources and steps, with operators suggesting reminders for acknowledgment status and better organization of command stack files and folders. Outdated folder versions posed a risk of loading incorrect command stacks.
The SATMON procedure pages and search function were praised for facilitating access to procedures, although missing or incorrect links were noted. Operators preferred the search function over topological overviews and suggested having critical displays readily available. A digital device, like a tablet, for quick procedure access and note-taking was also desired.
Some operators found procedure execution instructions complex and confusing, with suggestions for better visual highlighting of conditional statements. Standardization and consistency in SATMON pages and procedures were lacking, with both strengths and weaknesses identified in customization options.
Command errors were attributed to task overload, distractions, time pressure, and inattention, with most errors being minor and rare. Common errors included commanding during signal loss and skipping steps. Preventive mechanisms were discussed, with suggestions for better error indication and prevention, particularly for timing errors and command sequence checks.
Manually adjusting command stacks for irregular activities was considered time-consuming and error-prone. Operators suggested automating routine activities and improving visual indications of associated procedure steps. Aligning system states due to expected changes was also noted as time-consuming, with improvements suggested for the command line interface. Overall, the study highlighted the need for better integration, standardization, and error prevention mechanisms to enhance operational efficiency and reduce errors.

5.4 Analysis of statements regarding multitasking and task switching

The impact of interruptions and distractions on operators that were examined as part of this study, highlighted several key issues. Interruptions occur frequently, with the majority of operators finding it challenging to return to interrupted tasks, depending on various factors such as task complexity and individual experience. System support, such as an AI assistant tracking tasks and providing notifications, was suggested to manage interruptions more effectively. However, some operators expressed concerns about the complexity of implementing such support.
Distractions from voice loop conversations were common, especially during busy communication periods or when operators were fatigued. While some operators were not bothered by these distractions due to habituation and information filtering, others found them challenging. The playback function for missed conversations was noted as limited in usefulness, with suggestions for replaying individual loops and improving input sensitivity. Visual or written communication was proposed as a means to reduce distractions and enhance communication effectiveness.

Task management was found to depend on urgency and prioritization, with timeline-related activities and faults taking precedence during nominal and off-nominal operations, respectively. Operators often completed similar tasks together for efficiency, and individual factors influenced task selection for less urgent tasks. Some operators found managing the number of tasks on the console challenging and stressful.

Offline tasks were sometimes performed on the console due to limited off-console days, leading to frustration among some operators who preferred a stricter separation between online and offline work. Overall, the study highlighted the need for improved systems to manage interruptions and distractions, as well as better task management strategies to reduce stress and enhance efficiency.

5.5 Analysis of statements regarding system limitations, workload and habituation

Several challenges and suggestions related to system performance and workload management for operators were identified. Limited system performance was noted, particularly when processing large volumes of data, such as plotting telemetry in SATMON. Operators desired higher performance and identified weaknesses in data transmission between MCS and SATMON, including a lack of redundancy. Integrating MCS and SATMON more closely was suggested to ensure reliable telemetry display in case of system failures.

SATMON's lack of feedback regarding stale process parameters was also addressed, with suggestions for a timer to indicate data freshness. Off-console tasks, such as creating and updating interfaces and applications, contributed to workload, with limited resources available for improvements. The STRATOS team's role in developing procedures and command stacks was noted, highlighting the need for additional support.

Habituation to current interfaces and tools was discussed, with experienced operators emphasizing the advantages of familiarity in a dynamic environment. However, this habituation might obscure weaknesses in the system. Evaluating system performance was challenging due to a lack of comparisons and alternatives, making it difficult to identify strengths and weaknesses comprehensively. Overall, the study underscores the need for improved system performance, better integration, and additional resources to support operators effectively.

6. Discussion and Conclusion

The study reveals several critical insights into the operational dynamics and challenges faced by operators in managing complex systems such as the Columbus module of the ISS.

Operators report that the physical distribution of information across different clients negatively impacts monitoring. Therefore, integration of information is highly desired to enhance situational awareness and reduce the cognitive burden associated with switching between systems. While on one hand, the available information is comprehensive, operators suggest that filtering mechanisms could improve accessibility and relevance. On the other hand, information hierarchy is less imprtant, with both top-down and bottom-up approaches having their advocates.

Consistency in visual presentation is important for operators, who prefer standardized layouts that facilitate easy access and orientation. The current layouts are often criticized for being overly rigid, with operators expressing a need for more adaptable and less cluttered displays. The design and color schemes also require improvements to enhance usability and reduce visual strain.

Visual and auditory alerts are generally well-received, but their effectiveness is diminished by the frequent occurrence of false alerts and the challenge of managing numerous out-of-limits alerts simultaneously. Operators suggest that distinguishing between expected and unexpected out-of-limits conditions could significantly improve the alert system.

Furthermoer, the study identifies limitations in the system's ability to provide feedback after command execution, particularly in identifying incorrect commands. On top, performance issues, especially with large data volumes, highlight the need for more robust computational power. Integrating MCS and SATMON could enhance redundancy and reliability in telemetry data transmission.

The organization of information across multiple sources complicates workflow, particularly during complex activities. Operators advocate for greater integration between data and systems to streamline operations. While SATMON procedure pages are appreciated, there is a recognized need for improved standardization and clarity in procedure presentation.

Commission errors, such as commanding during signal loss, are more prevalent than omission errors. Operators suggest implementing more robust error prevention mechanisms, including command verification against procedures and automated reminders.

Frequent interruptions pose a significant challenge, with operators struggling to manage multiple tasks simultaneously. System support for tracking tasks and providing reminders could alleviate some of this burden. The cognitive load

associated with multitasking is identified as a major source of stress, particularly when balancing console tasks with office work.
Predictive tools are seen as beneficial, but concerns about their reliability and context-awareness are noted. Enhanced visualization and visual guidance to telemetry could improve situational awareness. Overall, the study underscores the need for more integrated, adaptable, and supportive systems to enhance operational efficiency and reduce cognitive load.

This study is first and foremost supposed to help improve current operator interfaces in use at Col-CC. Furthermore, since the Lunar Gateway is also going to be operated from GSOC, the findings provide useful insights for the design of future operator interfaces, as well as for further developments in the context of astronautical space exploration missions. Finally, with the recent emergence of Artificial Intelligence (AI) and Machine Learning (ML), the way operations are performed today, is about to be revolutionized. Intelligent assistant systems, like the Mars Exploration Telemetry-driven Information System (METIS) are bound to not only improve what the operators can do, but also how they do it [19]. This work gives first hints for improvements of operator interfaces, in order to facilitate these new AI/ML capabilities, while also allowing operators to perform at the same or at a better level than before.

Currently a redevelopement of MCS, called MCS-R, is ongoing at Col-CC. MCS-R uses the European Ground Segment Common Core (EGS-CC) as a framework and is fully accessible through a web browser. This approach makes the application more user friendly by making the user interface highly configurable and still keeping a ESA wide standard for monitoring and control systems. Looking at future missions such as Lunar Gateway a commonly used standard framework for monitoring and control systems can be highly beneficial not only for the development of the adaption layer to work with specific mission requirements but also for the introduction of a new system to the operator.

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ANNEX A – Acronyms and Abbreviations

AI – Artificial Intelligence
Col-CC – Columbus Control-Center
COL-FD – Columbus Flight Director
ColKa – Columbus Ka-band Antenna
COMMS – Communications Subsystem
CSA – Canadian Space Agency
DLR e.V. – German Aerospace Center (ger.: Deutsches Zentrum für Luft- und Raumfahrt)
DMS – Data Management Subsystem
ECLSS – Environment Control and Life Support Subsystem
EDRS – European Data Relay Satellite
EGS-CC – European Ground Segment Common Core
EPDS – Electrical Power Distribution Subsystem
ESA – European Space Agency
FCT – Flight Control Teal
FDIR – Failure Detection Isolation and Recovery
GC – Ground Control
GSOC – German Space Operations Center
ISPR – International Standard Payload Rack
ISS – International Space Station
JAXA – Japan Aerospace Exploration Agency
ML – Machine Learning
MCS – Monitoring and Control System
METIS – Mars Exploration Telemetry-driven Information System
MPCC – Multi-Purpose Computer and Communication
ODF – Operations Data File
OOL – Out-Of-Limit
PDU – Power Distribution Unit
SA – Situational Awareness
TCS – Thermal Control Subsystem
USOC – User Support Operations Center
USOS – United States Orbital Segment
VoCS – Voice Communication System