Expert Tool
to Support Crew Autonomous Operations
in Complex Human Spacecraft

ETECA Final Presentation
Noordwijk, 15th September 2009
ESA contract no. 21585/08/NL/HE
Presentation Overview

• The ETECA team and approach
• Activities performed
• Findings
  – Research on topics and tools
  – Iterative development process definition + human factors engineering
  – Scenario definition + astronaut interviews
  – Operational concept definition
  – Requirements baseline
  – Proof-of-concept development and evaluation
• Conclusion
Project Team

Consortium of 4 European companies:

Astrium Space Transportation, Bremen, Germany

Science & Technology, Delft, The Netherlands

Space Applications Services, Zeventem, Belgium

TNO Defence, Security and Safety, Soesterberg, The Netherlands
Project Team: Astrium

- Christian Knorr
  - Columbus Crew Software, Mission Support Software, Human Computer Interfaces

- Frank Plassmeier
  - Software Architecture, Crew Support Systems, Procedure Systems

- Dieter Arndt
  - Operations Engineering, Columbus Operations, Data Management Subsystem, DMS Flight Controller
Project Team: S&T

• Leo Breebaart
  – Software Architecture, System Health Management, Decision Support Systems, GUI Design

• Paul van Gelder
  – Systems Engineering, System Health Management, Satellite Operations and Engineering
Project Team: SAS

- Frederic Reiter
  - Spacecraft avionics, system engineering, real-time software, flight simulation

- Lynn De Proft
  - Flight training, Cockpit operations, Human Factor, Usability

- Jeremi Gancet
  - Robotics, Human robot interactions, Software engineering, AI / task planning and scheduling
Project Team: TNO

- **Mark Neerincx**
  - Human Factors, cognitive engineering, human-machine collaboration, operations in high-demand environments

- **Jasper Lindenberg**
  - Cognitive engineering, adaptive autonomy, human factors

- **Nanja Smets**
  - Artificial Intelligence, mobile user interfaces, game-based evaluation
Study Logic (1)

KO

Research in decision support topics, tech. and tools, WP200

Usability requirements support WP430

Columbus like FDIR scenario WP420

Management & Reporting WP100

Development Process Definition WP300

Requirements Baseline (Initial Version) WP410

Progress Reports & Minutes of Meeting

Project Website

TN2 (Draft): Process definition for iter...

TN1: Survey on relevant research topics...

TN3 (Draft): Requirements baseline and spec...

Specification WP510

MTR

Step 2

Deliverables

Astrium

Science & Technology

Space Applications Services

TNO
Distribution of Work

- **Astrium:**
  - Prime Contractor
  - Columbus scenarios and mission experience
  - Specification
  - Development of PoC

- **S&T**
  - Decision support technologies and tools research
  - Development of diagnostics component for PoC demonstrator

- **SAS**
  - Requirements analysis
  - PoC demonstrator evaluation

- **TNO**
  - Human factors analysis and usability requirements
  - Development process definition
End-users and Specialists Involvement

• Identified groups:
  – **Astronauts** to be users of the system
  – **Columbus operations engineers** and **flight controllers** for operational expertise
  – **Astronaut training staff** for crew tasks and mission simulation experience
Research on Topics and Tools: Approach

• **Scope**
  – Investigate latest developments and trends (state of the art) in decision support research and tools
  – Provide input to requirements engineering process

• **Methodology (bottom-up)**
  – Collection phase:
    • Large starting set of relevant and recent articles / references
  – Reading and evaluation phase:
    • Annotated bibliography
  – Interpretation phase:
    • ETECA relevance, conclusions and recommendations
Research on Topics and Tools: Results

• Latest research topics:
  Data fusion, Health determination, Procedure automation, Situational awareness, Adaptive tools, Development processes.

• Latest research trends:
  Increasing levels of abstraction; More holistic approaches; More autonomous tools; More multi-disciplinary approach towards decision support.

• Latest tools:
  Mostly diagnostics and maintenance.

Recommendations for ETECA:
  Design to certify; Start from the bottom up; More than one subsystem; Modular architecture.
Iterative Development
Process Definition

• Goal:
  – A coherent situated cognitive engineering (sCE) development process, addressing operations, human factors and technology systematically, as foundation of the RB and DST specification.

• Outcome:
  – A refined process description of the sCE methodology as “best practice” of cost effective development of decision support tools for onboard crew autonomous operations of complex space vehicles.
Situated Cognitive Engineering

Derive

- Operational Demands
- Human Factors Knowledge
- Envisioned Technology

Specify

- Scenarios
- Claims
- Core Functions

Requirements Baseline

Test

- Review
- HitL-test
- Sim-Assess

Refine

- Comments
- Refine
- UX
- Sim Results
Situated …

Theories and models that…

• help to establish sound support systems by accounting for how context and actions are coupled and mutually dependent;
• apply to the specific domain or environmental description that is part of it;
• include accepted features of cognition such as limited processing capacity, are validated in the context of a specific domain and possibly group of task performers, and provide predictions of the task performance within this domain.

Development processes in which…

• design specs are refined & functions are incrementally prototyped from a coherent concept & S/W framework
• tests are addressing the user characteristics, overall setting and rich operational contexts
ETECA process

Operational Demands → DST Requirements

Human Factors Knowledge → DST Requirements

Technological Design Space → DST Requirements

DST Requirements → PoC Requirements

PoC Requirements → Generate PoC Prototype

PoC Requirements → Test PoC Prototype

Cost-effective development of DST for onboard crew operations
Human Factors Analysis

MECA:
- Cognitive Task Load
- Situation Awareness (SA)
- Sense Making
- Decision Making
- Dynamic Human Capacities
- Trust and Emotion
- Collaboration
- Crew Resource Management

ETECA:
- Usability Framework
  - Task level
  - Communication level
- Integrated Task Support
  - Rule provision
  - Information handling
  - Problem exploring
  - Rule checking
- Adaptive Support and SA
  - Eight “demons”

Social ePartners
ETECA and MECA

- ETECA represents a class of model-based Decision Support Tools (DST) for supervising systems' health state, providing diagnostics to the crew when off-nominal states appear to initiate appropriate troubleshooting actions.

- MECA’s ePartners harmonize the planning and coordination of crew responses to the (social, cognitive and affective crew states) and the overall work context.

- In a next project, the DST-ePartner-Astronaut collaboration should be worked out and tested (from architecture to joint operation).
Scenario Definition

• Assumption:

*The future crew vehicles and/or equipment will be highly automated systems even beyond the capabilities of Columbus.*

• Definition of selection criteria: Scenarios shall
  – Cover different types of anomalies
  – Illustrate dependencies between subsystems or equipment
  – Identify limitations of current on-board set of tools
  – Comprise situations which are not covered by ODF procedures
  – Require system knowledge and mission experience to be analysed and solved
  – Support the discussion with astronauts and crew
Requirements Specification

- RB should be based on & explicitly refer to the *design rationale*:
  - The *core functions* from the operational demands and HF aspects;
  - For each core function, one or more testable *claims* on its operational effects (positive and negative);
  - Decomposition of *core functions* into requirements
  - *Scenarios & use cases*;

- Initial considerations / inputs
  - ESA initial inputs;
  - User inputs
  - State of the art considerations
  - Columbus-like FDIR scenarios considerations
  - Other initial considerations (standards)
Operational Concept Definition

Operation concept: 2 main operational modes

1. Support to troubleshooting
   - Supporting S/C subsystems safing, preventing further degradation
   - Once stabilized, supporting recovery to the nominal state

2. Support to day-to-day operations
   - Supporting tedious / repetitive tasks implementation
   - Supporting re-training (tutor)
   - Improving procedures and other reference documents availability and presentation
• 7 Core functions have been identified with related testable claims;
• 9 Use Cases have been described;
• Risks have been identified w.r.t. space systems complexity, human factor considerations, robustness and dependability;
• Traceability of Use Cases to requirements, initial considerations, core functions and testable claims has been ensured;
• Derived requirements have been defined:
  – General Requirements (GR)
  – Functional Requirements (FR)
  – Operations and Usability Requirements (OUR)
  – Maintenance and Maintainability Requirements (MMR)
ETECA Core Functions

1. Make the decision maker aware of the need to make a decision
2. Identify relevant procedure(s) in the current context and present them to the decision maker
3. Course-of-Action (CoA) generation and value estimation, “what-if” simulation modes, results and justification display
4. Provide guidance to implement the selected course of action
5. Support the implementation of the steps in the course of action
6. Provide guidance to verify the implementation
7. On-request background / reference documentation consultation
PoC Approach

• Concentrate on selected functions
  – Increase Situation Awareness (SA)
    • “Make the decision maker aware of the need to make a decision” (Core Function 1)
    • “Identify relevant procedure(s) in the current context and present them to the decision maker” (Core Function 2)
  – Provide integrated, consistent and task oriented user interface
    • Cognitive task support as specified by usability requirements
  – Integrate available data and automatically create links
    • “On-request background / reference documentation consultation” (Core Function 7)
PoC Components

- Use realistic data from Columbus simulation (SITE)
- Derive scenarios from real operations (ESC Bremen)
- Re-use Lapap Mk II
- Integrate Uptime diagnostics module
- Link data, provide diagnostics user interface and integrate functions

ETECA PoC
PoC Architecture

Diagnostic Process
- Diagnostics Server
- Diagnostic Model

Lapap Mk II Process
- Diagnostics Component
  - Messages
  - Procedures
  - Displays
  - Ref Doc

Simulator Process
- Simulator (State Machine)
  - Sim Data
Diagnostics Component in a Nutshell

• Modelling the ISS Columbus Active Thermal Control System (TCS)
  – Model-Based Diagnosis (*abductive* reasoning)
  – S&T Uptime Solver and Modelling Language
• Integrating the diagnostic TCS model and the Uptime solver into Lapap Mk2
  – Loosely-coupled service-oriented architecture
  – Uptime Web Services (UWS) for ETECA
• Designing and implementing a diagnostic Graphical User Interface for Lapap Mk2
  – Integrate with telemetry system (diagnostic input) and synoptic displays (diagnostic output)
  – Support system message tagging
Diagnostics Component in a Nutshell

ETECA Console

Current diagnostic status: loss of redundancy in TCS

**Diagnostic Event Overview**
- **ROOT CAUSE OF FAILURE**: WPA1 EU Data Processor - Failed
- **DIAGNOSIS CONFIDENCE VALUE**: High
- **AFFECTED SYSTEM COMPONENTS**: WPA1
- **SYSTEM-LEVEL IMPACT**: Loss of TCS redundancy

**Columbus System Overview**
- **COLUMBUS SYSTEM STATUS**: Non-Nominal
- **COLUMBUS OPERATIVE MODE**: Nominal
- **AFFECTED SYSTEMS**: TCS
- **NR. OF FAULTY COMPONENTS**: 3
- **NR. OF REDUNDANCY-LOSS COMPONENTS**: 1

**TCS System Overview**
- **TCS CRITICALITY TO COLUMBUS**: High
- **REDUNDANCY OF CRITICAL COMPONENTS**: CHC: 1(1); WPA: 0(1); HX: 1(1)
- **TCS SYSTEM FAULT TOLERANCE**: 0-fault tolerant
- **TCS SYSTEM CRITICAL COMPONENTS**: WPA: Electronics Unit, Pump, Fl.
- **POSSIBLY RELEVANT PROCEDURES**: 2.101 TCS LOOP WPA1 TO WPA2, 2.102 TCS LOOP WPA2 TO WPA1, 2.103 ACTIVE WPA, 2.104 PASSIVE WPA, 2.109 PASSIVE WPA, 2.110 LOSS OF WPA
- **POSSIBLY RELEVANT DOCUMENTS**: TCS USER MANUAL, 4.2.1 Water Pump Assembly, 4.3.3 WPA Accumulator, 5.2.3 Specialist Level Tasks
- **URGENCY OF RESPONSE ACTION**: Low (24 hours)
- **NEXT WORST FAILURE IMPACT**: Low (cooling water circulation)

**DMS System Overview**
- **DMS CRITICALITY TO COLUMBUS**: <Unknown>
- **REDUNDANCY OF CRITICAL COMPONENTS**: Nominal
- **DMS SYSTEM FAULT TOLERANCE**: Nominal

**EPDS System Overview**
- **EPDS CRITICALITY TO COLUMBUS**: <Unknown>

**Time | Classification | Subsystem | Equipment | Text**
--- | --- | --- | --- | ---
11Aug09 13:39:03 | INFO | SW | DMC_USS | Closed display /home/leo/svn/astrium-o4/ieap/ETECA/share/displays/SYNOPTICS/TCS/TCS_FUN.uss

**Water Pump Assembly 1**
- **WPA1 Electronics**: Off
- **Flowmeter**
- **Pump Controller**
- **Water Pressure Sensor**
- **Motor Speed Sensor**
- **Water Temp Sensor**
- **Data Processor SW**: [FAULTY]
PoC Evaluation Purpose

The purpose of the evaluation was to:

– Analyze the usability and viability of the ETECA system as a decision support tool for autonomous crew operations.
– Identify usability shortcomings in the system design that could hinder the astronauts.
– Identify problems related to the specific skills and expectations of the astronauts.
– Analyse key characteristics that influence user performance.
PoC Evaluation Approach

2 types of evaluation have been conducted

- Expert evaluation: inspections of the user interface design addressing usability issues:
  - 3 usability experts performed a cognitive walkthrough.

- User testing: a qualitative assessment of the system’s effectiveness (fit for purpose), efficiency (resources required to use), learnability (ease to learn) and clarity of interaction:
  - 4 evaluation sessions (3 on site and 1 remote evaluations) involving 2 Flight Controllers, 1 Astronaut Instructor and 1 Astronaut.
PoC Evaluation Scenario

**WPA Switchover from WPA1 to WPA2 by FDIR**

- The test run consisted of two consecutive tasks:
  - A nominal situation during which 5 activities were performed.
  - A Columbus sub-system failure occurrence and management during which 9 activities were performed.

- The final objective of the scenario was to regain redundancy.
Expert Evaluation Results

Points for improvement

– Multiple and complex failure handling;
– Implementation environment dependency;
– Diagnostics confidence value;
– Assistance for procedure selection;
– Problem prioritization and follow-up;
– Interface manipulation.

Strong points

– Efficient system tree function;
– Effective overview of the redundancy and failure of the subsystem presented to the user;
– Message filtering capability;
– Highlighting of specific measurements.
User Testing Results

Core functions and corresponding claims were addressed by the evaluation:

- Easily usable and efficient support to the understanding of the situation. It provides a valuable synthesis of the event.
- Minor modifications regarding the representation, the content and the organisation of the information shall be considered;
- Efficient notification of a diagnostics event but no anticipation of situation is supported by the tool;
- The identification of relevant procedures and documentation is of added value, however the type of procedures and way of presentation was not fully as expected;
- Limited ability to guide the user in the solving process.
User Testing Results

General findings

• Knowledge of Lapap Mk II has driven the approach used by the evaluators;
• Strong connection and preference for a procedure-based approach;
• Easy to use but an appropriate training shall be considered;
• The concept should be implemented in a more complex demonstration scenario;

➢ All evaluators positively experience the system as support to autonomous crew operations but all of them expected more features and support from the system;
➢ The evaluation confirmed current requirements baseline.
ETECA Findings

⇒ The ETECA concept has been strongly supported by the proof-of-concept demonstrator and its evaluation
⇒ The general usability has been approved
⇒ Close coupling with Lapap Mk II
  …provided many specified functions already
  …introduced certain complexity (of all Lapap Mk II functionality)
  …made evaluation of only the ETECA concept difficult
⇒ The defined process has been successfully applied
⇒ Several topics of the concept need to be further researched
Conclusions

- The opportunities of an effective decision support tool have been demonstrated
- By increasing the autonomous problem solving capabilities ops preparation effort could be reduced
- By increasing flight crew’s autonomy ground ops effort could be reduced
Conclusions & Next Steps

• More functions should be implemented to improve the demonstration of the concept
• More complex scenarios need to be demonstrated to better evaluate the concept
• Evaluate the concept with a broader audience to confirm study results
• Evaluate the concept in a different implementation environment
• Individual technologies need to be studied to judge effort and feasibility of their application
• Applicability and benefit for other domains (e.g. ground operations) should be assessed
• Applicability of defined process should be verified in operational development
Cost-Benefits

Development savings:
• Development time and cost for only relevant functionality, less late changes
• Reduced redesign needs for improving usable in next versions

Revenue increases:
• Increased competitive edge
• More satisfied customers
• Higher ratings for usability in the trade press

Usage savings:
• Reduced task time and increased productivity
• Reduced user errors
• Reduced training time for users
• Reduced staff turnover as a result of higher satisfaction and motivation

Maintenance, support and training:
• Reduced costs of producing training materials
• Reduced time providing training
• Reduced time spent by staff assisting users in troubleshooting
• Reduced help line support
Common starting point

- At start of system development, a coherent design and test approach should be established for consistency and cost-effectiveness.
- For general work practices, a high-level RB could be established for core functions like procedure guides and alarm-handling tools, as input for:
  - core infrastructure
  - software frameworks for general functions
- Developers should always show the operational outcomes of their applications (in the design rationale and the evaluations)

Initiating and maintaining best practices

- A platform or network of stakeholders that are involved in the concerning development and evaluation activities.
- A practical guide providing the guidelines to apply the DST for equipment and design rationale patterns.
- Training development teams to apply the proposed design and test methodology.
Scenario Selection

- Scenarios derived from actual Columbus failure situations:
  1. Equipment failure due to software error
  2. Subsystem error due to single event upset in commercial equipment
  3. Payload unavailability due to interface problems between station segments
  4. Preventive action due to equipment deviation from expected behaviour
Astronaut Interviews

• Goals
  – Gather end-user expectations and requirements
  – Learn about current problem solving techniques on-board
  – Identify weaknesses of current on-board toolset and user interfaces

• Preparation
  – Detailed questionnaire prepared consisting of two parts
    • General questions plus questions guided by an interviewee chosen example scenario
    • Detailed questions along with prepared Columbus scenarios
  – Scenarios derived from real Columbus incidents
  – Problem solution elaborated with Columbus flight controller and engineering support staff
  – Questionnaire reviewed by astronaut instructor staff

• Execution
  – 2 ‘live’ telephone interviews performed in December 2008
  – 1 offline interview in January 2009
  – 1 offline interview late March 2009, not processed, yet
ETECA-UWS

Web Server + Wrapper Code

Core Uptime Toolkit

Diagnostic Request
"POST /diagnosis/mvcdas/ISS_Columbus_TCS HTTP/1.1"

Diagnostic Response
"Content-type: text/plain"