Design of the Attitude and Orbit Control System for ESA’s Solar Orbiter

Colin Maule and Andrew Pollard
Tessella Ltd.
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Overview

• Introduction to Tessella
• Our part in the Solar Orbiter programme
• Control Engineering with MathWorks
• Integrating MathWorks into large projects
Altran
GLOBAL LEADER IN ENGINEERING AND INFORMATION SERVICES

29k employees

300 of the Global 500 are clients

1.9 bn euros revenues

Industries: from automotive to utilities

23 countries
Tessella, Altran's World Class Center for Analytics
We use data science to accelerate evidence-based decision making

OPERATIONS
UK, US, NL, FR, ES, DE, SE, PT

EXPERIENCE
30+ years of experience delivering 1000s of data analytics projects

DNA
Data is in our DNA. 250 of the brightest scientific minds, 50% hold PhDs

KNOWLEDGE
Unique combination of domain knowledge, data engineering expertise, maths & statistics excellence
Our work allows businesses to improve profitability, reduce costs, streamline operations, avoid errors and out-innovate the competition.

Predicting the best coatings for ships. Reducing fuel costs by up to 15%

Data analytics powers H3 Biosciences drug research. Reducing time to go from lab to clinic by 75%
Generating maps of disease risk in weeks not years. So medical intervention is better targeted.

Streamlining the creation of new oil wells. Saving BP $100s of million.

Helping Unilever’s customers identify wholesome alternatives to existing preferences.
Tessella’s part on Solar Orbiter
Fundamental AOCS requirements

• Get it where it needs to be
• Point it in the right direction
• Keep it safe
Earth 1 AU: Dia=1

Venus 0.7 AU: Dia=1

Mercury 0.4 AU: Dia=0.33

Solar Orbiter 0.28 AU

The Sun: Dia=109

Credit: Airbus Defence and Space
Scope

Airbus Defence and Space

Tessella
- Mode design
- Functional design
- Control algorithm design
- Analysis, tuning and simulation
- Algorithm specification
- Test case design
- Performance verification

Terma
- Flight software
Tessella’s Part in the AOCS Subsystem

Solar Orbiter AOCS

Year

FTEs


Launch
Oct 2018

Preliminary Design
Detailed Design
Qualification
Control Engineering with Matlab & Simulink

Andrew Pollard
Mathematical Modeller & Algorithm Developer
Tessella Ltd.
Key Engineering Challenges

• Very extreme environment close to Sun

• Sun shield must remain pointed towards Sun, otherwise the heat will destroy the spacecraft

• Need to achieve precise trajectory for gravity assist manoeuvres
The Solution

AOCS: Attitude and Orbit Control Subsystem

- Autonomously control angle of rotation around 3 axes to keep spacecraft correctly oriented and execute ground-commanded manoeuvres
- Perform orbit correction manoeuvres with thrusters
- A critical subsystem!
Spacecraft AOCS Hardware

Sensors

• Fine Sun Sensor
• Star Tracker
• Inertial Measurement Unit

Actuators

• Reaction Control System (thrusters)
• Reaction Wheels
The Attitude Control Loop

"Where we want to be" ➔ "Where we are"

"Determine what we want to do to the spacecraft" ➔ "Turn demanded outputs into actuator commands"

Sensor Processing ➔ Estimated Angle/Rate

Sensor Processing ➔ Demand Torque

Sensor Processing ➔ Actuator Commanding

Sensor Processing ➔ Sensors

Disturbances (environment, mechanisms, gyroscopic torques) ➔ Spacecraft

Applied Torque ➔ Spacecraft

Angle/Rate ➔ Spacecraft

Tessella

altran | Part of the Altran Group
**Design Challenges**

- Very stringent autonomous pointing requirements for making scientific observations: *Equivalent to pointing at this screen for 10 seconds... from Greenland!*
  - MATLAB & Control Systems Toolbox

- Flexible modes of appendages must not be excited
  - Control Systems Toolbox & Signal Processing Toolbox

- Very limited fuel
  - Optimization Toolbox

- Complex system to model
  - Simulink
Autonomy

• “Safe modes” of AOCS need to be fully autonomous to recover quickly from hardware failure

• Any ground intervention occurs slowly – can take ~ 10 minutes for signal to reach spacecraft

• Up to 70 days no comms at all during solar conjunction

• Required orbit corrections calculated by ground operations team, but manoeuvre is autonomous
Controller Design and Tuning

- Control Systems Toolbox used to compute envelope of frequency responses in presence of uncertainty and variability.
  - Ensures spacecraft is stable with enough margin
  - Robustness
- Signal Processing Toolbox for candidate flexure filters. Genetic algorithm to investigate parameter improvements
Controller Design and Tuning

- In-house tools developed in MATLAB for repeated tasks, such as:
  - Constraint & sensitivity analysis
  - Automated controller tuning
  - Reporting of analysis results
- Allows rapid response to changes in inputs
Controller Design and Tuning

- Optimization toolbox for thruster modulation proving 6-D control
  
  ➢ Given force and torque demands, determine which thrusters to fire and for how long
  
  ➢ Minimise fuel consumption
Controller Design and Tuning

- Simulink for modelling full control loop, including hardware models
  - Rapid prototyping and design trade-offs
  - Verification of performance and robustness of control algorithms via Monte Carlo campaigns
  - Simulation of specific scenarios
Key Benefits of MathWorks-based Solutions

- Control Systems toolbox for controller design
- Optimization toolbox for thruster modulation
- Simulink for modelling & simulation of full system

**Benefits**

- The industry benchmark. Nothing else comes close for control engineering
- Attitude control will use only 40 kg propellant in 10 years
- No other tool gives us the multidomain simulation capability and block diagram environment in a way that is scalable to represent complex systems. That is why we use Simulink.
Integrating MathWorks into Large Projects
Further Challenges

• Schedule
  ➢ Changing the launch date is major!

• Knowledge transfer in a changing project team

• Large-scale system design problem
  ➢ SW alone has 100s of tuneable parameters
  ➢ Cannot be held in the head of 1 person!
Running the Project

• Very large collection of MATLAB code for long-term internal use by a large team

• Rigorous software engineering practices & tools appropriate for maintaining this code:
  - Bitbucket for distributed Git version control to promote code review, linked to CI server
  - JIRA Issue Tracking System linked to version control
  - TeamCity Continuous Integration for automated tests, and long-running analyses / simulations
Benefits of Continuous Integration

We used continuous integration to:

• Automatically run unit tests & integration tests daily to check impact of code changes

• Help with configuration management of delivered files

• Run simulation campaigns on a server at the press of a button

• Run lengthy analyses and enable configuration management of the results

➤ Improved response time & verification
Object-Oriented Programming in MATLAB

• Improve traceability of a parameter by storing metadata in an object, e.g.
  ➢ where the value is documented
  ➢ in which database version was it last changed
  ➢ which program calculated it, etc.

• Automatic unit conversions reduce the occurrence of mistakes & hardcoded numbers

• Other uses of OOP included standardising how tuning & analysis functions are used
  ➢ Easy to learn how to update documents

```matlab
>> params.Design.SASM.Objective.LOS.sigma_ang_ctrl_farSun
ans =
    ParameterValue
    
    name: Design.SASM.Objective.LOS.sigma_ang_ctrl_farSun
    design ref: calculateSASMPointingObjectiveLOS
    reference: SASM Tuning and Stability Analysis (SOL.S.ASTR.TN.00373 2 draft)
    source: Objectives / DesignDB_SASM V4_01.xml
    version: 4.1
    author: TESSELLA
    status: Derived
    datatype: double

    value [rad]:
    0.0116

    value [deg]:
    0.6655
```
Lessons Learnt

• Results of complex analyses require high level of traceability
  ➢ E.g. “Which parameters were used to produce these results from 2 years ago?”
  ➢ Traceability requires configuration management
  ➢ Continuous integration supports this

• Review of code, models & analysis has high value even if not deliverable
  ➢ Everyone’s work is reviewed, and everyone reviews work

• Document your modelling assumptions
  ➢ Turn into tests where possible
The Project Today

• Tessella’s key deliveries are complete

• Detailed testing of AOCS algorithms being carried out by Airbus DS; we continue providing support

• Next stop... THE SUN!
Summary

• Solar Orbiter is an exciting ESA mission at the forefront of science, and a very complex engineering challenge

• Tessella made good use of MATLAB & Simulink to develop the algorithms for one of Solar Orbiter’s key autonomous control systems

• Supporting tools and good software engineering practices were also used to get the best out of MATLAB on a large project, and these practices can be used in other domains
Further information

• MATLAB File Exchange
  www.mathworks.com/matlabcentral/fileexchange/

• Solar Orbiter
  sci.esa.int/solar-orbiter/

• Tessella
  Come and see our stand at the expo!
  https://tessella.com/

• MathWorks Training Services
  www.mathworks.com/services/training.html
Questions