OBSIdian

On-Board System Identification for Uncertainty Modelling & Characterization

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Executive Summary

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1 INTRODUCTION

The present document is the Summary Report of the On-Board System Identification for Uncertainty Modelling & Characterization (OBSIdian) project, which has been executed by the National Technical University of Athens (NTUA), the Centre Suisse d'Électronique et de Microtechnique (CSEM), and Thales Alenia Space France (TASF).

The **main goal** of the activity was the end-to-end development (where necessary) and application of numerically efficient system identification techniques of space systems, to obtain dynamic mathematical models for space systems for simulation and control purposes.

The **generic scenario** considered in OBSIdian was that of a robotic manipulator equipped Chaser satellite (space manipulator system – SMS) approaching and capturing a Target satellite, before proceeding to a manipulator induced mating of the two S/C, in the scope of an On-Orbit Servicing (OOS) mission. According to the requirements from OBSIdian, the System Identification (SYSID) can be performed during the following stages: (a) Prior to Forced Motion, the Chaser performs internal SYSID tasks to identify the necessary values of its system parameters, and (b) After the capturing of the Target by the manipulator gripper, and during the motions required for the mating of the two S/C, the Target SYSID was performed.

The **considered uncertain parameters** for identification in OBSIdian (both for the SMS and the Target) were (a) the *Fuel Sloshing model parameters* i.e., the equivalent sloshing mass, stiffness and damping parameters of a mass-spring-damped sloshing model, (b) the *flexible appendages* (e.g., solar panels) *modal parameters* i.e., natural frequencies, damping ratios and modal shapes, and (c) the *system inertial parameters*, both for the two S/C bases and for the manipulator links, i.e., mass, moment of inertia and Centre of Mass (CM) location.

Models for dynamic systems can be derived either analytically or experimentally. Analytical modelling leads to the so-called white-box models, which require parameter values that can be obtained experimentally. Experimental modelling leads to the so-called black-box models, which describe systems inputs/ outputs behaviour. Use of a combination of the two approaches was employed to exploit the advantages of each approach, leading to the so-called grey boxes.

After determining the type of the model (and thus the type of the SYSID) to be used and the required SYSID accuracy, the **SYSID for lumped parameters** (e.g., inertial and sloshing model mass-spring-damper parameters), in the case of regressor-based SYSID, consists of determining/ developing the appropriate SYSID *methods* (i.e., system equations, to be formulated in regressor form) to be used by the chosen SYSID *algorithm*, such as Total Least Squares (TLS), or Instrumental Variables (IV); this was in general unavailable in the literature at the beginning of OBSIdian. Moreover, measures needed to be determined for dealing with unmodelled disturbances and signal noise, such as appropriate filtering. These were followed by the validation of the identified model, typically accomplished by comparison of the experimental setup response with the predicted by this model. Based on a preliminary trade-off performed early during the project, regarding the parametric methods, the Unscented Kalman Filter (UKF), Prediction Error Method (PEM), IV, and TLS were the most promising algorithms.

Modal Analysis algorithms are suitable for the identification of the modal parameters of continuous models (e.g., flexible appendages). Traditional Modal Analysis (MA) makes use of input (excitation) and output (response) measurements to estimate modal parameters (i.e., modal frequencies, damping ratios, mode shapes and modal participation factors). A main MA classification was between identification algorithms utilizing time domain data and those that use frequency domain data. A preliminary trade-off performed for the MA algorithms, results in Frequency-Spatial Domain Decomposition (FSDD), Rational Fraction Polynomial (RFP), Least-Square Complex Exponential (LSCE), and Covariance- and Data-driven Stochastic Subspace Identification (SSI-COV and SSI-DATA respectively), being the most appropriate ones.

Both parametric and modal SYSID can be implemented with *input signals* being either *operational* or *artificial test* signals, resulting in Operational or Experimental SYSID. Operational SYSID is usually implemented online, as the operational task evolves, while Experimental

SYSID can be either online or offline, where the measured data are first stored and are later transferred to the computer utilized for data evaluation and are processed there.

2 Benchmark Problems and Study Cases

Chosen SYSID algorithms were tested in selected scenarios in the form of Benchmark Problems (BPs, see Table 1) and a trade-off analysis determined which algorithms are the most suitable. Moreover, these BPs were implemented in the consortium experimental facilities, providing further insight on the proposed SYSID schemes. Finally, selected Study Cases (SCs, see Table 2) scenarios, were used to provide data (both in planar implementations in the consortium facilities and in full-scale 3D simulations) for the proposed SYSID schemes. In all experiments (simulated and experimental), the generic idea was the system excitation under certain conditions, letting the system to react on this excitation, and accrue the data for post-processing, except for BP3B and SC2 that implemented an online, recursive format.

Table 1. Benchmark Problems (BPs) tested during the OBSIdian project.

Benchmark Problem 1 (BP1A)	Benchmark Problem 1 (BP1B)	Benchmark Problem 2 (BP2)	Benchmark Problem 3A (BP3A)	Benchmark Problem 3B (BP3B)
Identification of inertial parameters (no sloshing, no flexibilities)		**Identification of sloshing model parameters** (known satellite, no flexibilities)	**Identification of appendages modal parameters** (known satellite, no sloshing)	
Experimental Identification Excitation is user's choice		**Experimental Identification** Excitation is user's choice	**Experimental Identification** Excitation is user's choice	**Operational Identification** Excitation by the task
Non-recursive SYSID (Parametric Identification)		**Non-recursive SYSID** (Parametric Identification)	**Non-recursive SYSID**	**Recursive SYSID**
Models 2D *free-floating* space robot		**Models** ▪ 2D satellite and 2D sloshing models	**Models** ▪ 2D flexible appendage on hub	
(only arm joints active)	(full actuation)			

Table 2. Study Cases (SCs) tested during the OBSIdian project.

Study Case 1 (SC1)	Study Case 2 (SC2)
Full System Identification (inertial, sloshing, and modal parameters of flexible appendages considered simultaneously)	
Experimental Identification Excitation is user's choice	**Operational Identification** Excitation by the task
Non-recursive SYSID (Parametric SYSID for lumped models + EMA for continuous models)	**Recursive SYSID** (Parametric Identification Method for lumped models + OMA for continuous models)

A difficulty of this project had to do with the fact that during on orbit operations in which a robotic manipulator is included, one deals with a fundamentally nonlinear system undergoing large motions. Therefore, in this study the consortium opted to focus on the full nonlinear dynamics of the system and try to identify the real physical parameters of the system or combinations thereof, sufficient to reconstruct the system dynamics. Using this representation, one can then either linearize and obtain transfer functions, singular value plots, and design linear robust controllers for distinct configurations, or use the full nonlinear equations to design directly nonlinear robust controllers, as desired, allowing both the most accurate model and associated parameters possible, and the maximum flexibility in terms of subsequent control design.

3 Verification and Validation Plan

To verify and validate SYSID, a representative system and corresponding experiments under representative conditions had to be implemented. Two main challenges were identified during the definition of V&V. The first was to identify the degree of the simulation and emulation complexity. The second was to warrant the representativeness of such simulations and emulations. To validate the SYSID methods developed in OBSIdian, models were created to simulate the behaviour of various system configurations (BPs and SCs). Validation experiments were performed for selected S/C configurations, which took place at the Space Robotics Emulator (SRE) of NTUA-CSL and the Quanser setup. Such experiments are of low cost, very flexible, and are characterised by quite good representativeness of the tasks addressed.

4 ARCHITECTURE OVERVIEW OF BP AND SC EXPERIMENTAL SETUPS

The experimental setup used for *BP1* experiments consisted of the autonomous robot Cepheus floating over a low surface roughness blue-black hard rock table, using air bearings with CO_2, allowing emulation of zero gravity in two dimensions. Cepheus is equipped with a CO_2 tank for the air-bearings and for its thrusters, which operate in On-Off or PWM/PWPF modes, a Reaction Wheel and a 2 DoF manipulator, as well as Li-Po batteries for electrical autonomy. The NTUA SRE employs an 8-camera PhaseSpace motion capture system, providing S/C pose feedback. Cepheus sensors include also an IMU and motor encoders. The BP2 experimental setup was like the one used for BP1, but there was no manipulator and on top of the Cepheus, a sloshing fuel (i.e., water in this case) tank was installed, see Figure 4-1.

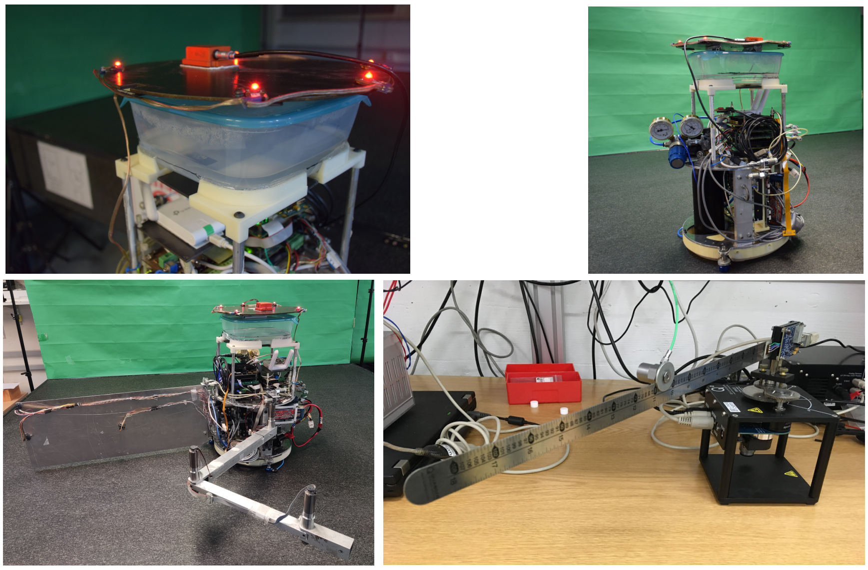

Figure 4-1. Sloshing "fuel" tank on top of the Cepheus robot for BP2 experiments (top-left), and Cepheus during BP2 experiments (top-right). Full Cepheus robotic system as used in SC1 (bottom-left) and the Quanser flexible link setup with accelerometer mounted on the flexible link (bottom-right).

5 PROCEDURE FOLLOWED DURING OBSIDIAN

The analytical and Simscape models have been developed for all BPs, based on known engineering formulations. These BPs were used to test the various Parametric and Modal SYSID algorithms in simplified planar models of the sull-scale systems. Based on these tests, the final *trade-off analysis* of the system identification methods and algorithms was performed, to be used later in the more realistic Study Cases. For each BP, a weighted performance was calculated for each SYSID scheme, based on the performance metrics of the RMS value of the estimated parameters relative errors, and on the computational time. The best algorithms for each BP case were found to be TLS for lumped parameters SYSID and SSI-COV for Modal Analysis. Following this activity, hardware tests took place at both the SRE and Quanser (i.e., scaled-down emulators), while scaled-down planar models of the experimental facilities were also developed and simulations of the hardware test were performed, to assess the developed SYSID schemes performance, and for modelling and identified model validation.

A similar approach took place for the SCs. In particular, the full-scale, 2D models of both SC1 and SC2 were also developed, while Simscape models for these cases were also constructed.

To identify all parameters of the system considered in SC1, a two-stage Method was developed, consisting of two consecutive experiments, Experiment 1, and Experiment 2. These include the modal parameters of the flexible appendage on S/C, the parameters of the sloshing fuel model, and the inertial parameters of the system. In SC1, it was assumed that all parameters are unknown initially. The operational task of SC2 was performed by the Chaser S/C manipulator that has grasped the Target S/C, and was divided in two parts: first, a general motion (i.e., both translation and rotation) that aligns the captured Target berthing fixture to the Chaser berthing fixture, and then a pure translational motion that brings the two berthing fixtures together.

The performed full-scale, planar SC1 simulations yielded promising results, though certain SNR issues were observed. Full-scale planar SC2 simulations indicated that, with the current state of sensors and actuation capabilities, and with the realistic limitations imposed (even for space approved sensors), is not expected to yield acceptable or useful results. Thus, scaled-down simulations and experiments, as well as full-scale 3D simulations, were not further pursued.

Both SC1 experiments were performed at the SRE facility (*scaled-down* system), and though measures were taken to improve the obtained measurements quality and mitigate the signal noise levels, while Modal Analysis provided identification results with acceptable relative errors, the Parametric SYSID processes resulted in identification relative errors way beyond the acceptable limit. This was verified also in the simulated experiments, in which, when using realistic system, sensor, and actuator model parameters (from the actual SRE facility), the obtained identification results were again off limits, in a manner very similar to that of the SYSID when using the experimental data. Simulated experiments with adequate (large) SNR yielded very good results, verifying that the issue lays with the measurements SNR adequacy. When the actual system scale was reduced to that of the SRE, while sensor resolution does not scale down accordingly and laboratory sensor quality is inferior to that of an actual space system, then measurement SNR and obtained results deteriorate to the point that they cannot be useful. Note that the recursive implementations of the SYSID algorithms (i.e., RTLS and RSSI-COV), displayed similar results to their non-recursive counterparts.

However, the *full-scale* 3D system needed for the *SC1* identification simulations was developed and yielded very good SYSID results with data from realistic simulations (not subjected to the sensing and actuation restrictions of the SRE facility), demonstrating that the proposed methods and algorithms are valid and can result in valuable parametric identification in an actual full-scale system. Moreover, the modelling validation for the SC1 system (where all uncertainties are included), verified the simulated models, further strengthening the claim of a meaningful identification on an actual, full-scale system.

6 CRITICAL ANALYSIS AND SYNTHESIS OF THE RESULTS

During on orbit operations in which a robotic manipulator is included, one deals with a fundamentally nonlinear system capable of large displacements and configuration changes, even for the nominal motions required for typical OOS scenarios. System dynamic equations linearization around an equilibrium point results in models invalid in any other configuration, as the system configuration-dependent nature is abolished during linearization, and a controller based on these linearized models would face the same problem. Therefore, in this study the consortium opted to focus on the full nonlinear dynamics of the system and try to identify the real physical parameters of the system or combinations thereof, sufficient to reconstruct the system dynamics. In particular, the analytical equations of motion of a 3D space manipulator, including sloshing dynamics and a flexible appendage (as in SC1), are very complex and large in size, depending on manipulator type/ DoFs and level of realism considered. However, these models are integrated for the simulations of the 3D system only and not for the SYSID per se. The derived analytical equations of motion used in Simulink were also verified by comparison to a Simscape model of the same system.

Another aspect of the simulated tests worth mentioning is the sampling rate used. For the *Parametric SYSID* (i.e., sloshing and inertia parameters identification with TLS-RTLS), the sampling rate in OBSIdian (both simulated and SRE tests) was set to 2.5 - 66 Hz, depending on the case. However, a high sampling rate is not a requirement for the methods to work. On the contrary, lower data sampling, in par with the system dynamics, results in improved regressor condition number and better SYSID. However, the SYSID requirement for enough data with low sampling rate, leads to prolonged experiments, a fact demonstrated clearly in the 3D SC1 (simulated) case, where experiments were running for two to four times that of the SRE simulated experiments, helping get the very good results obtained with the 3D SC1 data.

Regarding the *Modal Analysis* (SSI-COV and RSSI-COV), and to be able to identify and distinguish from any identified spurious modes the largest natural frequency considered to have a significant effect on the motion of the system, the sampling rate is required be at least 2 to 3.5 times this frequency, for the cases run. Therefore, even in Modal Analysis, sampling rate can be lowered significantly, even to acceptable levels for space approved sensors, depending on the highest natural frequency with significant effect on system motion.

7 CONCLUSIONS

Important conclusions regarding the experimental and simulated data results, include:

(a) All experiments attested to the difficulties observed during the simulated experiments, such as the difficulty of identifying damping and the requirement for adequate excitation and high SNR levels, satisfying simultaneously system functional or mission limitations.

(b) The performed SYSID with the experimental data had similar results (either in success or in failure) to the SYSID with the corresponding simulated data, with some experimental data SYSID yielding worse results to the corresponding simulated data SYSID, due to well documented additional issues of the experimental data SYSID case.

(c) The developed system models are verified to a great extent, while the proposed SYSID methods are found to be promising, delivering results within or close to acceptable error limits, provided adequate SNR is available from either the simulated or experimental tests.

(d) The recursive algorithms implementation yielded similar results to those of the simple TLS and SSI-COV, with relative errors little larger, in all the tested cases. However, those results were obtained at most halfway through the corresponding experiment.

It was also observed that the SYSID results obtained from the data collected from both the simulations and experiments, were affected by four main factors:

(a) Accuracy of model parameters provided by CAD/ FEM/ CFD models with respect to the actual (true) system parameters, both in terms of comparing SYSID results to inaccurate “true” values, and of inputting inaccurate “true” values to the SYSID algorithms.

(b) Signal to Noise Ratio (SNR).

(c) Sampling Rate.

(d) SRE facility disturbances due to air bearing friction and aerodynamic resistance.

A preliminary sensitivity analysis was run, for some characteristic cases. It was demonstrated that SNR is an important factor for a successful SYSID task, for all studied cases. The levels of required SNR in specific identification tasks were also observed. It was found that the various subsystems mass ratio for the studied cases, though affecting the identification process, has a rather limited effect, even for significant mass ratio variations. A more thorough sensitivity analysis campaign is suggested as an important next step.

Finally, a case study on how the results of the project can be used for the development of more efficient robust controllers has been presented. As a case study, the statistics of the uncertainty were obtained for the inertial parameters’ identification on BP1A. The use of those statistics in the design of a robust controller, even for a nonlinear system such as the studied free-floating SMS, was also briefly outlined. The requirements for on-line robust controller adaptation with the uncertainty statistics derived from a repetitive SYSID process, were also discussed, in terms of statistics derivation time and buffer size requirements, and of additional system constraints.

8 EXPLOITATION OF PROJECT'S CONCLUSIONS

Several experimental systems to test SYSID algorithms in space were identified. The use, of the SPHERES, which can be used as a platform to test SYSID algorithms and methodologies is suggested, before applying them to larger systems. Alternatively, the design of similar systems was also be proposed, based mainly on the Astrobee concept, allowing more complex experiments to be executed. The goal of such experiments would be to validate SYSID algorithms and find in a case-by-case basis which types of algorithms are optimal in each case, while at the same time find the most appropriate excitation sequences to achieve the best results, in the actual orbital environment, without the additional issues of the terrestrial experimental facilities. A Full Mated experiment was recommended, with two satellites, i.e., a Chaser satellite, equipped with all the necessary subsystems and a 7DoF manipulator, and a Target satellite, which will be active and with capability to modify some of its characteristics using simple mechanisms, allowing the Control Room to initiate different scenarios. The systems for these experiments can employ the Newspace trend for small satellites.

Finally, important highlights from the OBSIdian project were summarized and developed as guidelines and as reference and suggestion during the discussions for the draft development of the ECSS documents for SYSID concepts development and standardization.