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Towards controlled free flight experiments in a supersonic wind tunnel facility

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Abstract

In aircraft design, wind tunnel testing is an important part of the aerodynamic identification process. It serves to extend knowledge gained from simulations (e.g. CFD) and reduces uncertainties before real flight tests. Being able to perform dynamic manoeuvres in a wind tunnel creates a better understanding of the system dynamics and enables a first validation of control algorithms. However, for hypersonic vehicles, such experiments are challenging due to the short test durations and limited space for testing. Recent experiments at the University of Southern Queensland demonstrated the ability to perform actuated experiments that control motion in pitch and roll for a sting-mounted model.
Building on this work, this current paper describes the development of system upgrades and new tools to achieve pitch and heave manoeuvres, and free flight testing subsequently. As part of this work, a new embedded hardware architecture was developed. This has resulted in a more compact system using new actuators, improved control bandwidth, on-board power for control and actuators, and improved flight computers. Embedded software was also updated to include more complex state estimation to allow improved determination of aerodynamic angles for post-treatment. A digital twin framework was developed to tune and validate controllers before the experimental runs, and to enhance the ability to post-process experimental data.
The new system is evaluated in bench tests. These highlight critical capabilities - the new embedded system is completely autonomous from ground support, estimators accurately track aerodynamic angles, and altitude estimation is acceptable. Similarly, the digital twin framework displays good performance when analysing previous campaigns, validating linear controllers and when comparing transient simulations to experimental data.

Keywords: *Hypersonic wind tunnel, free flight, control, system identification, digital twin*

1. Introduction

Wind tunnel testing is an essential part of the aircraft development process. Test data enable aerospace engineers to validate and update aerodynamic model (aero coefficients) obtained from simulations, such as from computational fluid dynamics (CFD). In this context, the ability to perform experiments using actuated and controlled models can extend the validation of aerodynamic models to also include dynamic manoeuvres. This enables a first assessment of the controllability of an aircraft. However, performing such tests in supersonic and hypersonic test facilities is challenging because of the short test durations and the small core flow regions.

Recent experiments conducted in the University of Southern Queensland's hypersonic wind tunnel (TUSQ) have demonstrated the feasibility of performing closed-loop control experiments within tests lasting 300 ms in hypersonic flow conditions [8]. The model was mounted on a sting with two degrees of freedom (pitch and roll). The onboard controller achieved good control for both pitch and roll. This was a stepping stone for actuated tests in short duration facilities. It validated several hardware choices,

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such as the actuator technology and onboard controllers, and demonstrated the feasibility of such experiments.

To perform more complex manoeuvres that include translational degrees of freedom and free flight, further upgrades of hardware and embedded code are required. This paper describes the ongoing development activities at University of Southern Queensland (UniSQ) to prepare for these experiments.

The paper is structured as follows. Section 2 describes the current state of technology for actuated testing in hypersonic facilities. Section 3 presents the development of a new generic embedded systems that can be integrated in future experiments and presents the proposed *pitch & heave* experiment. Section 4 discusses the develop digital twin simulation and post-treatment tool, which is used to analyse data from past experiments. Concluding remarks are provided in section 5.

2. Current status of controlled experiments at UniSQ

2.1. TUSQ hypersonic wind tunnel

Controlled experiments are carried out in UniSQ's hypersonic wind tunnel – TUSQ, shown in Fig. 1. TUSQ operates as an isentropic compression Ludwieg tube and is able to generate free-stream conditions between Mach 3 and Mach 7 [1, 3, 5]. The TUSQ facility provides an extensive suite of diagnostics tools. For actuated model testing we primarily use high speed imaging (shadowgraphy) to capture model motion, and Schlieren visualise flow structures.

Fig 1. TUSQ hyersonic wind tunnel at the University of Southern Queensland.

2.2. Previous research

Several campaigns on controlled models have been completed in TUSQ. van Hoffen et al. [10] performed control on a one degree-of-freedom wing, which was mounted on a rod perpendicular to the airflow. Pitch angle control was achieved using a motorized flap and PID controller. The sensor measuring the pitch angle was mounted mounted externally at the junction between the rod and the wind tunnel frame, allowing for direct measurement of wing angle. This first experiment highlighted the need for powerful and high speed control surface actuators.

In a second campaign, van Hoffen *et al.* [7, 8] utilised a custom designed voice coil actuators control two-degree-of-freedom motion. The model included two canard control surfaces and was mounted on a sting that allowed pitch and roll rotations. The custom designed voice coil actuator overcomes limitations of commercially available actuator technology. This actuator incorporates a magnetic angle sensor to enable a fast angle control loop (around $15\,$ms). In addition, the model also includes an IMU and onboard controller to control roll and pitch angle through two independent PID loops.

These experiments demonstrated the ability to perform controlled experiments in short duration hypersonic test facilities [8]. Pitch and roll angles tracked set-point changes well. Inversion of the system dynamics allowed aerodynamic and mechanical moments applied to the model to be identified.

2.3. Enhancements towards free flight experiments

The previous work performed in TUSQ paves the way towards more complex manoeuvres. The following requirements can be identified for free flight tests:

- *Compact and bespoke Voice Coil Actuators:* The uniform core flow in hypersonic facilities is limited and defines the usable manoeuvre space. A smaller model means more usable space and longer tests. To shrink the model, a smaller set of actuators, with torque sufficient to rotate the controls surfaces under air flow is required.
- *On-board power:* Removing the need for a power cable simplifies ground-support requirements. The on-board power supply must be compact and lightweight and provide sufficient energy for a single test.
- *More capable and robust control algorithms:* In previous campaigns, only pitch and roll angles were required for control and to analyze tests. For six degree-of-freedom motion control more robust and complex estimators, and additional control loops are required (e.g. altitude on longitudinal axis). Moreover, increased manoeuvre complexity may display unmodelled external disturbances, which means that the controller must be designed to be robust to uncertainty.
- *Efficient simulation and post-treatment tools:* To facilitate efficient planning of experiments, pre-test evaluation and tuning of control loops, and post-treatment of experiments, there is a need for tools that allow systematic testing.

A development approach that incrementally increases complexity and validates new systems at each stage has proven effective in the development of actuated models. For this reason a pitch-and-heave manoeuvre has been identified for the next test campaign.

3. Free flight system architecture

3.1. Overview

An overview of the embedded hardware is presented in Fig. 2. The aim of this system is to be generic, so that it can be used with a wide range of flight models. The systems can be split into four sub-systems: (a) Flight Computer, Sensors, and Communications; (b) Power Management and Energy Storage; (c) Actuators; and (d) FPGAs to group all subsystems linked to actuator control (motor driver, position sensor, position control loop) and improve computing capacities of main flight computer.

This will be combined with new model and ground support and a new embedded software.

3.2. Flight computer

A printed circuit board (PCB) has been designed to integrate all the electronic components required for the control and communication with the model. This reduces the required space compared to off-the-shelf components. Integration of the hardware components is presented in Fig. 2.

The PCB is built around an RP2350 micro-controller, which serves as the primary “flight computer”, which is responsible for the control algorithms, estimators and communication protocols. This works in conjunction with the FPGA module used for actuator inner-loop control, described in section 3.5. Model acceleration and angular rates are provided by dual ICM-45686 ultra high-performance 6-axis MEMS motion sensors. Communication is provided by a Microchip RN4678 Bluetooth module. Furthermore, the PCB also has an amplifier and analog-to-digital converter capable of supporting one pressure transducer. The RP2350 MCU has enough internal memory to store the measured parameters during the run and can be unloaded through Bluetooth at the end of the run. To reduce the size of the model, no non volatile data storage is available.

3.3. Power management

The system has dual power sources. A 3.3 V battery is used to power the flight computer and to provide a stable voltage source for sensors.

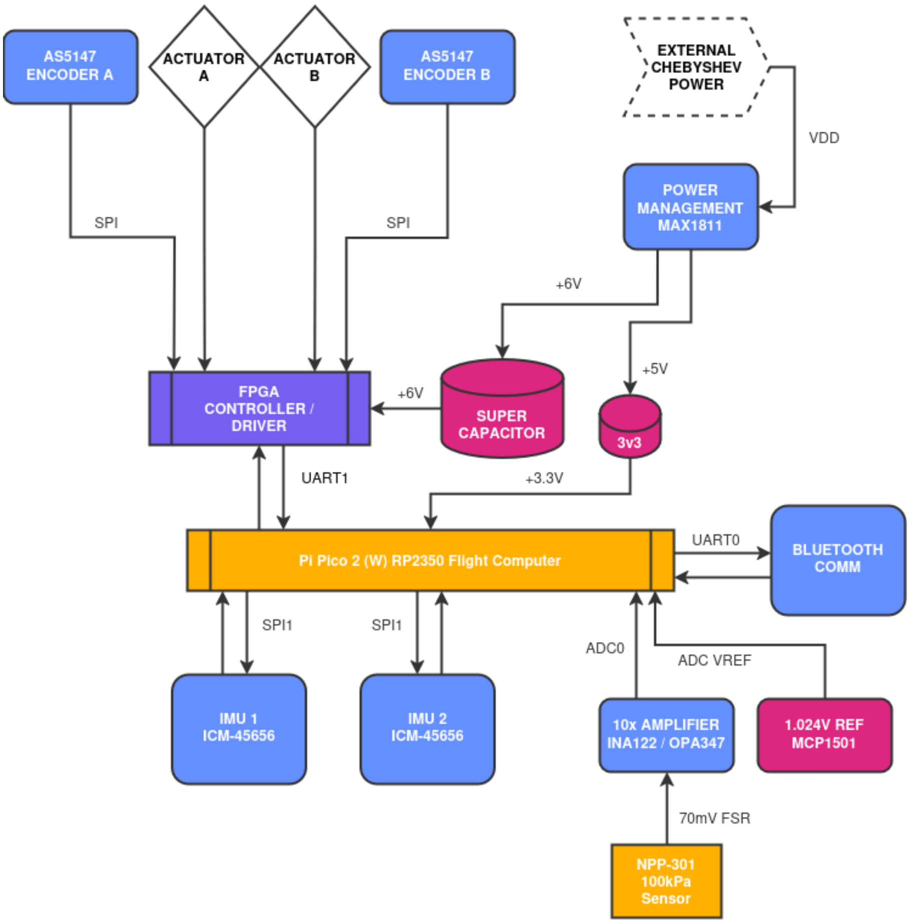


Fig 2. Embedded hardware architecture

A supercapacitor with a capacitance of approximately 5 Farads was selected as the primary power source for the FPGA motor drivers. Capacitance was selected based on power consumption of voice coil actuators from previous experimental campaigns. This technology enables quick recharge between each test (around 20 s) and has been designed to provide enough power to the actuator throughout the whole test, sustaining a bus voltage of between 5 and 6 V. The supercapcitor was selected over a traditional battery as it enables maximum instantaneous current discharge which is preferable for driving the actuators within the limited test time, and it has a better power to weight ratio for the required voltage, current and discharge time for these experiments.

3.4. Actuators

Inner-loop control of the actuators is performed using a dedicated control module, discussed in section 3.5

The actuators are designed using the same technology and requirements as used by van Hoffen *et al.* [9]. To reduce the space required and to allow better packaging in the model a linear voice coil actuator arrangement is selected (see Fig. 3).

To convert the linear motion of the coil into a rotation, a 3D-printed flexible link is used (see Fig. 4). The design intent behind this flexible link is to create a near linear relationship between linear and angular motion, without introducing hysteresis or backlash. The control algorithm uses a rotary position encoder on the output shaft to provide feedback to the controller and account for any introduced non-linearities. This allows for the design of a robust controller.

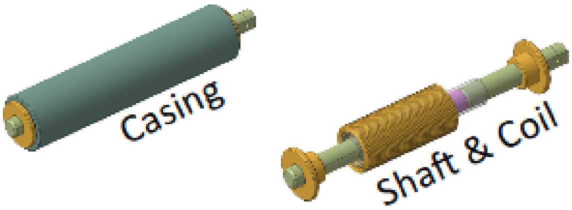


Fig 3. CAD view of linear voice coil actuator

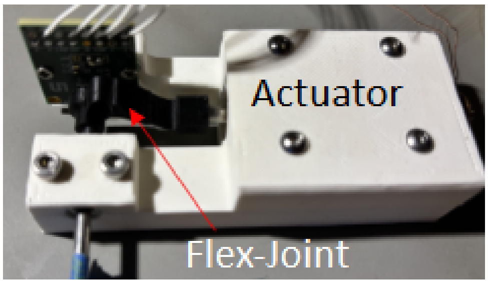


Fig 4. Actuator on test rig

3.5. FPGA actuator inner loop controller

Both actuators are driven by a custom-built controller PCB, designed by HyperFlight Systems Pty Ltd (see Fig. 5). This PCB incorporates a Field-Programmable Gate Array (FPGA) as its central controller, power management circuitry, coil power drivers and communications interfaces. The FPGA runs each actuator's control loop, with two AS5147 magnetic encoder angular sensors used for feedback. Control loop gains are adaptable if required.

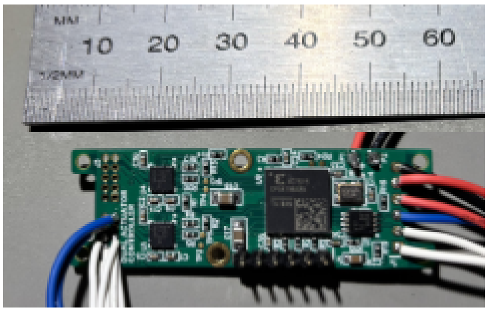


Fig 5. FPGA for each actuator.

The control loop has been designed using a simple representation of an electro-mechanical actuator [11]. The resistance was measured, and the inductance of the coil was estimated using chirp voltage inputs and using linear system identification presented by Tischler [6]. The mechanical equations have been identified using chirp inputs between 5 and 30 Hz.

The controller has been designed with the following constraints:

- 95 %-time response to a step input of 15 ms or lower
- 6 dB gain margin
- 8 ms delay margin
- 80 ms time response to perturbation rejection

Based on the linear model estimated previously, a PID-like controller has been designed based on pole-placement method. The derivative term is filtered with a first-order $2\,\text{ms}$ low-pass filter to reduce noise of derivative signal. The direct precommand term has been extracted to tune the time-response to a step input.

Representative results from controller test are shown in Fig. 6. These confirm excellent time response properties and good stability margins. These data also show the supercapacitor voltage, confirming a small voltage drop over a $1\,\text{s}$ test period.

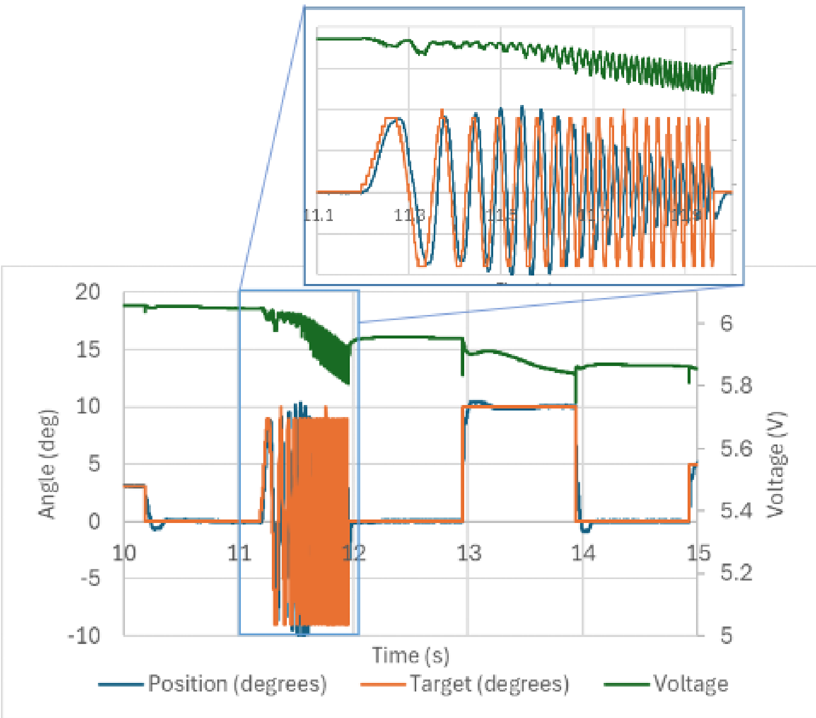


Fig 6. Evaluation of actuator time responses to frequency sweeps and step changes in set point.

3.6. Model and ground support

A new model and ground support architecture is developed, to support the proposed pitch and heave and free flight manoeuvres, and to validate the hardware and software,

The ground support system has the following requirements:

- Support the model in a fixed and an adaptable pose (attitude) before an experimental run. Release immediately prior to flow arrival to minimize transient movements.
- Provide energy to the onboard power management system before the run to ensure full charge at the beginning of a run.
- Quick retraction out of core flow at the beginning of a run to minimize model or flow disturbances.

Based on previous experiments performed in TUSQ, a Chebyshev release mechanism was selected as the ground support platform for the model, as shown in Fig. 7. The Chebyshev mechanism is spring-loaded and retracts in a downwards direction just before flow arrives, leaving the model in freefall for a few milli-seconds before flow arrival.

Before free flight manoeuvres, pitch and heave manoeuvres will be performed in the tunnel. The Chebyshev release mechanism will be used along with two support wires, as shown in Fig. 7. Small diameter wires are selected to create minimal flow disturbance. The release mechanism will also hold the model to create wire tension before the experimental run to minimize transient behaviour.

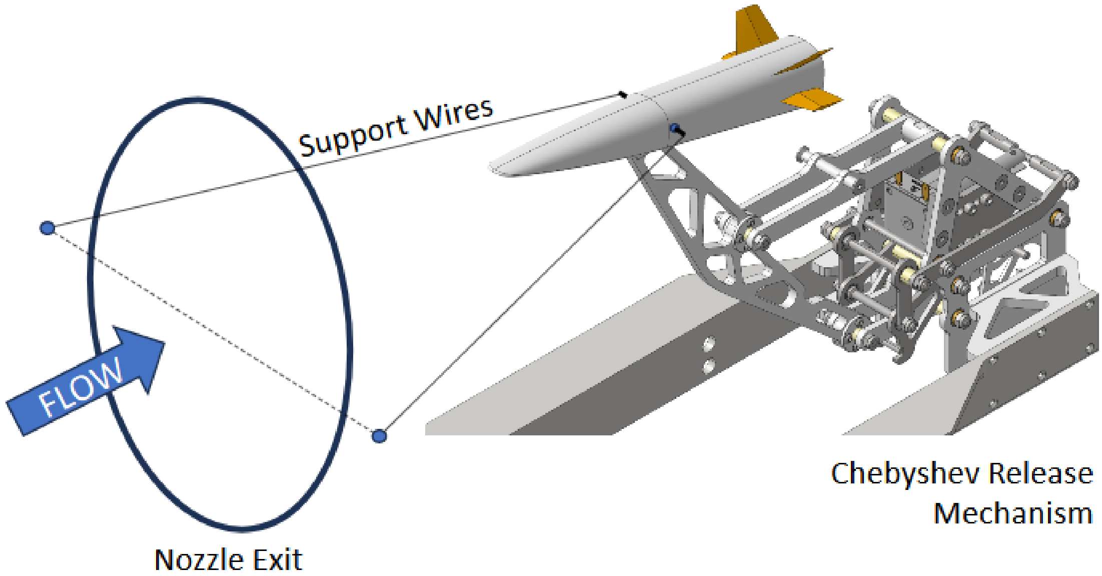


Fig 7. Ground architecture chosen for pitch and heave manoeuvres. Support wires will be removed for free flight tests.

The exact aerodynamic shape of the vehicle model is still in development. Contrary to the model used by van Hoffen *at al.* [7], we are using elevon control fins and the model has been designed with a wave-rider inspired lower surface.

3.7. Embedded software

The embedded software is written in C/C++ using the Raspberry Pi Foundation RP2350 software development kit. Several libraries are custom-made, including those for actuator control, sensor data fusion, Bluetooth communication and controller implementation.

For control, the IMU sensor data are transformed into the model body referential. The sensor data fusion is performed by using the average value of both IMUs, and the values are then fed to the state estimator.

The estimator uses the body accelerations N_x, N_y, N_z, the roll rate $P1$, pitch rate $Q1$, and yaw rate $R1$ in body axes to estimate the following parameters:

- Roll angle ϕ, pitch angle θ, yaw angle ψ
- Angle of attack α, angle of sideslip β
- Altitude h

The estimators are based on the inertial equations of a six degree of freedom moving object and axes transformation defined in [4]. Attitude angles are estimated by integrating Eq. 1:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & sin\phi tan\theta & cos\phi tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & \frac{sin\phi}{cos\theta} & \frac{cos\phi}{cos\theta} \end{bmatrix} \begin{bmatrix} P_1 \\ Q_1 \\ R_1 \end{bmatrix} \tag{1}$$

Acceleration in body axes from each IMUs are transported to the centre of gravity of the model and are merged using an average. They are then integrated and transposed into ground axes using rotation matrix to yield the model speed at centre of gravity in ground axis U_0, V_0, W_0. Altitude h is obtained by integration of vertical speed W_0 and aerodynamic angles are obtained from geometric definition detailed in Eq. 2 and Eq. 3.

$$\alpha = \text{arctan}\left(\frac{W_0}{V_0}\right) \tag{2}$$

$$\beta = \text{arctan}\left(\frac{V_0}{\sqrt{U_0^2 + W_0^2}}\right) \tag{3}$$

Validation of the control equations has been performed by injecting various forces and moments on all axes in a 6DoF model. These inputs were defined to verify the behaviour of the estimator with a range of various inputs on all axes. They have low amplitude to keep small values of the estimated states over the validation period. IMU dynamics were modelled with random noise applied to rotation rates. Fig. 8 shows the estimators' outputs with the following inputs:

- Force on x axis: 0.01 mN sine wave at 1 rad/s
- Force on y axis: 0.01 N pulse at $t = 0s$ for 0.5 s
- Force on z axis: -0.2 N pulse at $t = 3s$ for 0.2 s
- Moment on x axis: 0.01 mN m pulse at $t = 6s$ for 0.5 s
- Moment on y axis: 0.01 mN m pulse at $t = 4s$ for 0.3 s
- Moment on z axis: 0.002 mN m sine wave at 0.1 rad/s

These results highlight the good behaviour of the angles estimators. However, the altitude estimation is biased, mainly because of the noise levels on the acquired data.

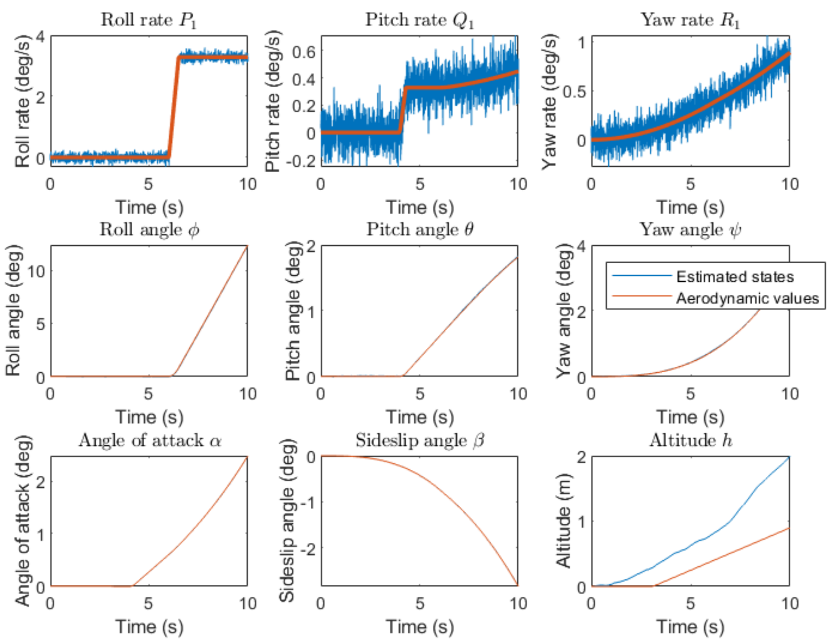


Fig 8. Comparison of estimated states (blue) and aerodynamic parameter (true values, orange) values.

As a first iteration, this computational method is deemed acceptable:

- Due to strong coupling between aerodynamic angles and forces/moments acting on the model, these are most important to estimate accurately. Excellent performance is achieved.
- Bias on altitude is due to double integration on noisy data. Some tests with a filtered measurement to reduce the noise level have been performed to improve the altitude estimation. However, the gain on altitude precision was marginal and it lead to delay on the other parameters, which was not deemed acceptable for such short test durations.
- The aim of proposed flight experiments is to display controlled movement, based on noisy sensor data. This means a control law designed to adjust/control altitude, h, or climb rate, $\dot{h}$, vertical motion motion will still occur.
- No additional sensor to measure altitude is required, either on the model or in the ground architecture. This results in a simpler hardware and software implementation.
- Considering planned test have a duration of around 300 ms, the cumulative error in altitude remains small.
- The current estimator architecture is simple to implement and doesn't require prior knowledge of the system, as would be required in model based estimators (e.g. Kalman filter).

So far, this approach has been validated by simulation only. Wind tunnel tests are still required. If required, the estimated altitude or climb rate could be filtered to improve accuracy.

The control algorithms are coded in Simulink using the digital twin described in section 4.1. This allows for automatic generation of C++ code using Matlab.

4. Simulation and post-treatment

In order to perform time-domain simulations, controller design and validation, and post-treatment, a new in-house tool has been developed, based on Mathwork Matlab and Simulink. This tool brings a generalizable approach to the design and post-treatment of actuated and controlled experiments. It can be used for different experimental setups (one degree of freedom sting or six degree of freedom free flight). The overall workflow of the tool is described in Fig. 9.

4.1. Digital twin

As the experiments become more complex, the need for a more representative digital twin, to simulate the system and develop controllers arises. With increased accuracy, it is easier to anticipate the expected behaviour during the tunnel runs, and to evaluate how the controller would respond in case of unexpected aerodynamic behaviour of the model.

The digital twin has been developed in Mathworks Simulink. This software presents several advantages:

- Embedded discrete-time simulation algorithms, with time cycle adapted for each component of the closed-loop system to match the experimental parameters.
- Modularity for each subsystem. This allows easy switching of components to compare various tunings or physical models.
- Automated C++ code generation for the embedded code. This minimizes the gaps/differences between code validated on the digital twin and embedded code.
- Access to extensive suite of control system analysis tools. For example, the linear analysis tools evaluates pole placement and stability margins of the control algorithms.

The digital twin is constructed as a modular system. That is, main functions of the closed-loop models are segregated in several subsystems. The four main subsystems and their functions are:

- *Controller:* Data fusion when needed, estimators, control loops (inner and mid), and optionally actuator inner loops the recreate previous test campaigns. This block is can be converted to C++ code and uploaded to the flight computer described in section 3.2.

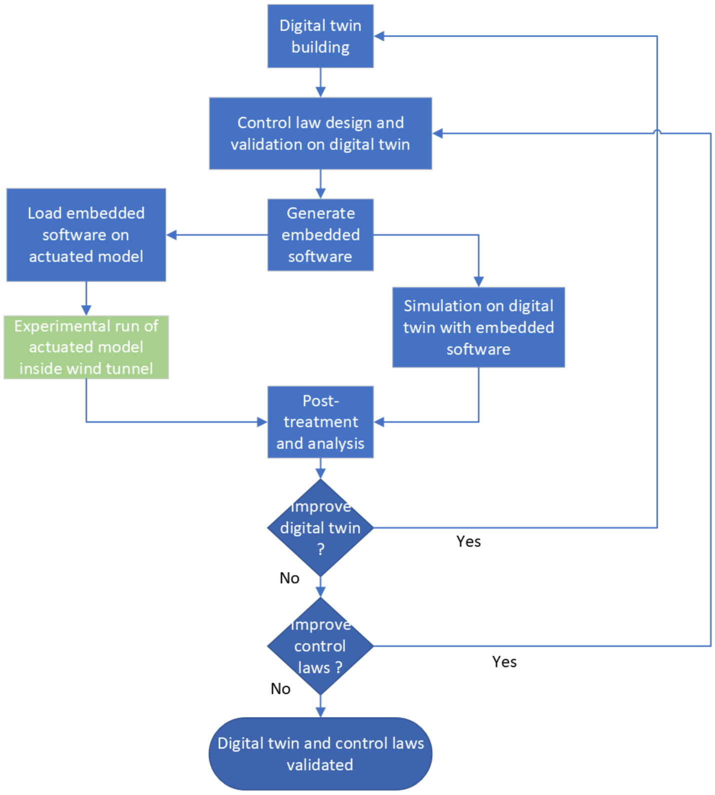


Fig 9. Overall workflow for experimental run, from outer shape design to complete aerodynamic identification.

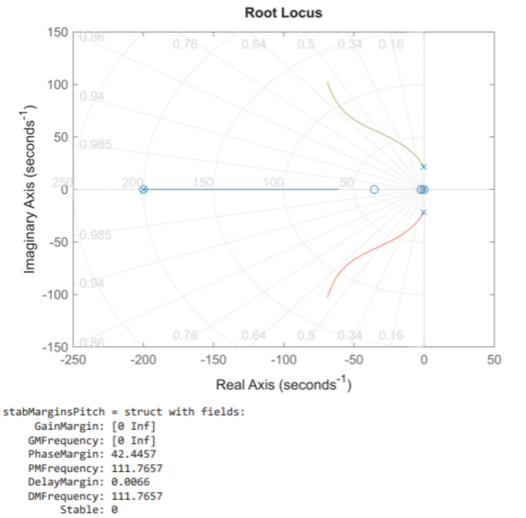
- *Actuator:* Electric and mechanical dynamics of the actuator, and representation of actuator inner control loop implemented on FGPAs (see section 3.5). Implementation is for linear voice coil actuators.
- *System Dynamics (e.g. 6DoF):* Governing equations of motion that determine how the model responds to forces and moments. The motion degrees of freedom can be restrained in order to adapt to specific experimental setups. Aerodynamics and inertia forces and moment are represented in this block. Aerodynamic forces/moments are included in the form of surrogate models.
- *Sensor:* IMU, with dynamics, bias and noise.

Validation of the digital twin was performed using data sets from previous experimental campaigns. It is set to be used for future controlled experiments in TUSQ.

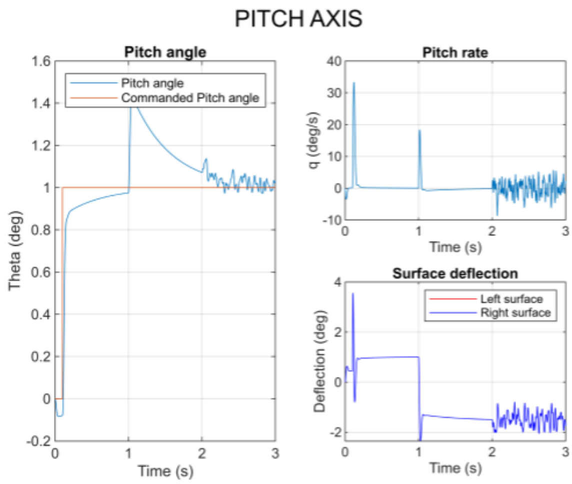
4.2. Controller design and validation

The digital twin simulation capability is an efficient tool for the design of controllers. The complete system model can be linearized to compute controller gains using various linear techniques. The controllers can then be validated in the Laplace domain to compute stability margins and pole placement analysis, and in the non-linear domain with the complete digital twin to evaluate time response and perturbation rejection. Fig. 10 shows the results obtained from using the digital twin to evaluate the controller for pitch only experiments, used by van Hoffen *et al.* [7].

These results provide insight on the stability of the system, how the system performs in unitary tests, and how it is able to reject noise. The digital twin enables us to evaluate the robustness of the controller to uncertainty which may arise from partial aerodynamic knowledge of the model. Time simulation on the digital twin for controller validation features errors on the forces and moments applied to the model



(a) Linear analysis of controller showing root locus and stability margins. In this example, the Matlab closed-loop check fails due to numerical approximations (integral pole approximated to non-zero value)



(b) Non-linear evaluation of controller closed loop response to step change at $t = 0.1$ s and disturbance at $t = 1$ ms.

Fig 10. Linear and non-linear analysis of pitch controller using digital twin.

to validate the controller on the non-linear model.

As the manoeuvres in the wind tunnel are intended to highlight aerodynamic effects not captured by CFD, a new set of requirements for future control algorithms has been defined. These new requirements ensure that the controller is able to respond within the limited test time with enough perturbation rejection performance. These criteria can be validated with the digital twin framework:

- Gain margin of at least 6 dB, delay margin of 5 ms for the complete controller (inner and outer loops)
- Slower modes placed with a damping of at least 0.5 to enhance perturbation rejection
- Inner control loop 95 % time response of 60 ms.
- Outer control loop 95 % time response of 250 ms.

4.3. Post-treatment

The post-treatment of experimental runs is performed in two steps. First, the focus is on the forces and moments acting on the model, and second, the complete closed-loop digital twin is validated. Both approaches have been validated using results from previous test campaigns.

4.3.1. Forces and moments extraction

The main uncertainty in the digital twin model arises from forces and moments acting on the model and variations in model states or aerodynamic angles. These forces and moments can be aerodynamic, but also include friction in supported models. The force/moment extraction approach is explained for a six degree of freedom system, but can be extended to other experimental setups with fewer degrees of freedom.

After each run, a focus is made to identify the model motion inside the wind tunnel. The rotational and longitudinal accelerations at centre of gravity are computed based on experimental data, for example from IMU data, externally mounted shaft encoders, or through analysis of high speed videos [2].

The equations of motion are then inverted to deduce the total forces and moments acting on the model.

These measured forces and moments are then compared to the forces and moments computed by the digital twin in "open loop" mode, that is using experimentally measured states (control surface deflection and attitude) as the input. Forces and moments in the digital twin are calculated with mechanical forces (gravity) and aerodynamic forces, first modelled using CFD data and simple gain contributions for various terms (e.g. a single gain for roll moment due to left control surface), and then enhanced throughout the test campaign to match the experimental data. This approach allows a direct comparison of measured total forces and moments to the ones predicted by the simulation model for the state at each point in time.

For a second comparison, we compute the "closed-loop" response. Here the digital twin simulation model uses the experimentally measured control surface deflections (actuator state) as the input to the simulations. The system response is then calculated using implemented system dynamics. Example results, corresponding to roll-only experiment reported in van Hoffen *et al.* [7] are shown in Fig. 11.

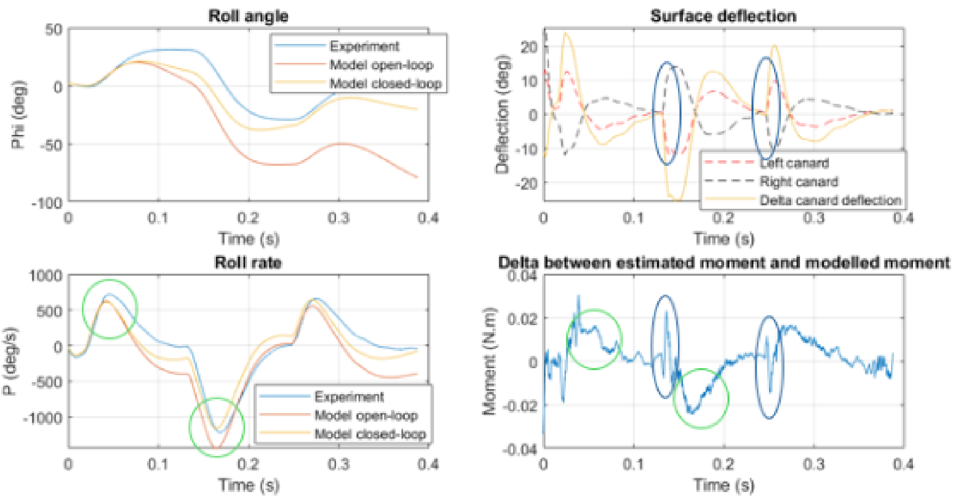


Fig 11. Digital twin evaluation: Forces and moments comparison for roll-only experiments.

The delta curve in Fig. 11 shows the total moment discrepancies between the digital twin and the estimation. The discrepancies marked by green circles seems to be correlated with the roll rate of the model. This indicates that the selected approach for modelling of rate dependent (damping) term needs to be corrected. This was achieved by reducing the gain applied on roll rate in the roll moment equation of the digital twin. The discrepancies marked by blue circles are correlated with fast control surface motion. Based on physical equations, this means that the momentum conservation due to moving actuators inside the body cannot be neglected. To enhance the digital twin, a new moment term was added to take into account this effect in the digital twin time simulation.

For this case, the digital twin enabled fast troubleshooting and validation of the proposed improvements.

4.3.2. Closed-loop validation of the digital twin design

Once the motion and force/moment prediction subsystem has been tuned, the complete digital twin can be evaluated with respect to experimental data. Fig. 12 compares the response predicted by the digital twin operating in closed-loop control mode to actual experimental data. The matching is very good, both in terms of motion and control surface deflection, which validates the overall approach.

Results shown in Fig. 12, in conjunction with unitary that have tested sub-components and increased degree of freedom have verified the approach. Further validation is planned using pitch and heave and free flight experiments and in accordance to the process presented in Fig. 9. Access to a digital twin that can truthfully recreate closed-loop control of hypersonic models is an enabler for *in silico* development of advanced controllers and control strategies.

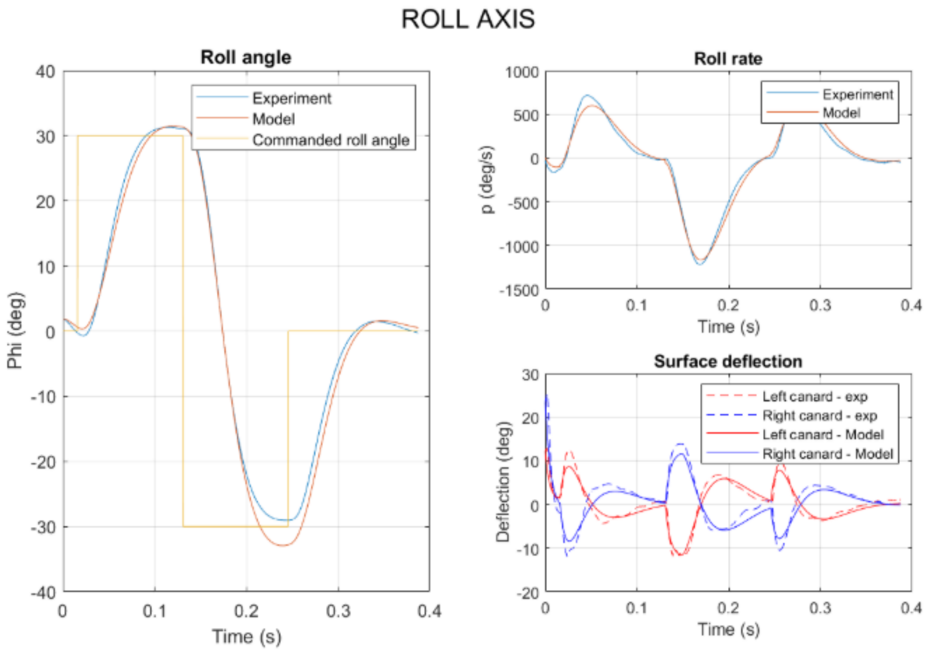


Fig 12. Digital twin evaluation: Comparison of closed-loop control response for roll-only experiment.

5. Conclusion

This work presents the evolution of embedded hardware, software, ground support system, and digital twin simulation tools to support controlled flight experiments in the TUSQ hypersonic wind tunnel. Hypersonic test facilities, pose specific challenges for controlled flight experiments. These include short test durations (100s of milliseconds or less) and small regions of uniform core flow.

The design changes of the new hardware are presented. These include, more compact flight computers, smaller linear voice coil actuators, autonomous power, FPGAs for actuator inner-loop control, and an updated model release mechanism. Together, these are enablers for planned pitch and heave, and free flight experiments. The reduction in size allows for manoeuvrability within the time and space constraints of hypersonic ground test facilities. The new model is currently undergoing bench-testing.

In parallel a new digital twin simulation framework has been developed. Using simulated aerodynamic data, this has allowed us to efficiently enhance our understanding of model dynamics, and estimator and controller behaviour. This has resulted in more efficient control law development and evaluation. Good performance is achieved for estimation/control of aerodynamic angles, but improvements to altitude estimation may be required. The tool is validated using data from past experimental campaigns. Analysis of past experiments show-cases the value of this digital twin framework.

Tunnel tests for controlled pitch and heave, and then free flight are planned. These will validate the capability of the newly developed controllers and generate data to further validate the digital twin controller simulation and analysis tools.

References

[1] David R Buttsworth. Ludwieg tunnel facility with free piston compression heating for supersonic and hypersonic testing. In *Proceedings of the 9th Australian Space Science Conference*, pages 153–162. National Space Society of Australia Ltd., 2010.

[2] Andrew Lock, Flynn Hack, Ingo Jahn, Gerard Armstrong, Byrenn Birch, and David Buttsworth. Aerodynamic measurements of hypersonic free-flight via optical tracking and bayesian state estimation.

AIAA Journal, 63(5):1655–1670, 2025.

[3] Jeremy Moran, David R. Buttsworth, and Lachlan Noller. Mach 6 and mach 7 conditions in tusq at reynolds numbers up to 30 million. In *AIAA AVIATION FORUM AND ASCEND 2024*. American Institute of Aeronautics and Astronautics, July 2024.

[4] Brian L Stevens, Frank L Lewis, and Eric N Johnson. *Aircraft control and simulation: dynamics, controls design, and autonomous systems*. John Wiley & Sons, 2015.

[5] Phillip Swann, Jeremy Moran, and David Buttsworth. Commissioning of a supersonic test facility at unisq. In *21st Australian International Aerospace Congress (AIAC21)*, pages 137–137. Engineers Australia; Royal Aeronautical Society, March 2025.

[6] Mark B Tischler and Robert K Remple. *Aircraft and rotorcraft system identification*. American Institute of Aeronautics and Astronautics Reston, VA, 2012.

[7] Morgan van Hoffen, David Buttsworth, and Ingo Jahn. Aerodynamic controllability testing in a short-duration hypersonic facility. In *AVT-SET-SCI-396 RSY on Technological Challenges due to Hypersonic Flight and the related Weapons Threat*, 2024.

[8] Morgan van Hoffen, David Buttsworth, and Ingo Jahn. Dynamic wind tunnel testing of an actuated canard-controlled hypersonic model. In *AIAA SCITECH 2024 Forum*, 2024.

[9] Morgan van Hoffen, David Buttsworth, and Ingo Jahn. High-speed voice coil actuators for hypersonic wind tunnel experiments. *IEEE Aerospace and Electronic Systems Magazine(Under Review)*, 2025.

[10] Morgan van Hoffen, Liam McQuellin, Andrew Lock, David Buttsworth, and Ingo Jahn. Aerodynamic identification of an actuated hypersonic wind tunnel model. *AIAA Journal of Aircraft (Accepted with Revision)*, 2025.

[11] Luca Zaccarian. Dc motors: dynamic model and control techniques. *Lecture Notes*, 01 2005.

