PRELIMINARY RESULTS FROM PROPELLANT MASS GAUGING IN MICROGRAVITY WITH ELECTRICAL CAPACITANCE TOMOGRAPHY

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The Propellant Mass Gauging Problem

- Most propellant gauges are designed to work in gravity or accelerated environments
- Most propellant tank mass gauging systems currently in-use have at least one major drawback. Examples:
  - Require propellant to be settled in aft end of tank and/or quiescent
  - Propellant must be in contact with walls
  - Require 100’s of pre-computed simulations that are compared to measurements to find a best fit propellant distribution
  - Require the propellant to be constant density
  - Require mechanical actuators
  - Most have low (>3%) mass gauging accuracy
- Need a technology that addresses these issues
Impacts of Mass Gauging Improvements

• Applicable to all launch vehicle and spacecraft providers, as well as their customers
• Improvements to accuracy and precision:
  – More accurate propellant utilization tracking
  – Lower propellant mass dispersions
  – Lower required residuals/margins for filling-topping as well as final residuals
  – More informed decisions on whether or not to perform a deorbit burn = potential to reduce orbital debris
• Enable mass gauging during all phases of flight would:
  – Better tracking of propellant usage, distribution, and dynamics during launch
  – Remove need to perform maneuvers in space to settle propellant: improves efficiency, reduces propellant consumption, and allows for tracking cryogenic boil off
• Impacts: improved mass gauging accuracy, lower risk, slight performance improvement, reduced orbital debris
Electrical Capacitance Tomography

• The Technology
  – ECT works by measuring the capacitance between multiple pairs of thin, conducting plates.
  – Since capacitance is related to permittivity, which in turn is related to density one can measure the distribution of liquid inside of a tank using ECT.
  – Measurements can be done in real-time
  – Finally, integration of the density distribution yields the mass inside the tank.

• ECT is not new. Originally developed for the oil and gas industry to measure multi-phase mass flow rate in pipes.
• ECT has recently been applied to tanks to measure liquid volume and mass.
• ECT has not been tested in microgravity – until now.

Example ECT System
Experiment Purpose and Objective

- Primary Objective: Demonstration of accurate liquid mass gauging in a subscale propellant tank using an ECT system during a zero-g parabolic aircraft flight.
- Secondary Objective: obtain the 3D liquid distribution vs. time and use this in a CFD validation study
- Tertiary goal: encourage US-based funding for ECT development work

- Funded by an LSP Study in 2021
- NASA Flight Opportunities Program funded the flights on Zero-G’s “G-force 1” aircraft
  - Flew in May 2022
- Technology *Demonstrator*: LSP did not design nor develop the ECT hardware. LSP rented it from a company that already had a plug ‘n play setup.
a.i. Solutions’ Role in Project

• ELVIS Contract
  – Support NASA Launch Services Program (LSP)
  – LSP Special Studies (six to eight studies at any given time)
  – Propellant Mass Gauging in Microgravity with Electrical Capacitance Tomography (ECT) Study

• ECT Study
  – a.i. received RFP/SOW from NASA
  – Contracted UK company that developed ECT test setup
    » Lease of ECT hardware
    » Provide training and support ground testing
    » Support as required during test flights
  – Zero G flight procured by NASA LSP through NASA Flight Opportunities Program
Experiment Design Overview

- 2.8L aluminum, spherical test tank partially filled with a non-hazardous propellant simulant liquid (3M FC-72)
- Tank has 8 thin, internal electrodes on the interior
- ECT system installed in test tank, with data acquisition (100 Hz) box outside the test tank
- LSP addition to meet secondary objective: Small single board computer collects data from a 6-DoF IMU
- Everything mounted to a 10mm thick aluminum plate, which is bolted to the aircraft deck.
- Total volume: 1.2m x 0.6m x 0.5m
- Total mass: approximately 50kg
- Total power requirement: 110VAC, 170W (nominal).
Parabolic Flight

- Aircraft flies in parabolas, at the top of which the passengers experience freefall

- Zero-G (~0G)
- Hyper-G (1.8)
- Zero-G (~0G)

This is where most people get sick

Image taken approximately level with aircraft window (aircraft is highly pitched up)
Flight Experience and Lessons Learned

- Flights were nominal with no equipment failures
  - 4 flights at 4 fill levels: 5%, 20%, 50%, 80%
  - Collected 25GB of ECT and IMU data
  - Observed swings of +/- 1-4% fill during 0g.
- Have procedures for contingencies and practice them
- Cover everything with foam, zip tie and tape everything down
- Zero-G time and entry/exit is not consistent between flights and parabolas
- Bring backup humans, at one time half of our crew was sick
- Automated experiments let you enjoy microgravity
- Put a GPS tracker on your experiment if you ship it
The Fun of Microgravity
The Fun of Microgravity
• Once we measure capacitance, need to turn the result to a permittivity field
• A number of simulations are used to determine the sensitivity (s) of the electrodes to different permittivity fields (ε) yielding different capacitances (C)
• Once this is complete, a simple method of determining the permittivity distribution is via Linear Back Projection (LBP)
• Using the matrix S and the normalized experimental capacitance λ, an approximation of the permittivity g (and thus the density) is obtained.
Example Results – 0g

- Capacitance data was filtered with a 10Hz cut-off high order cheby2 low pass filter prior to reconstruction and volume calculation.
  - No additional filtering applied.
- Measured volume fraction swings from 47%-59%.
  - Slightly more than observed in-flight with the experiment’s software
- Peaks occur during 0g, flat portions are during hyper-g (about 1.8g's).
- Slosh decay visible during initial portions of hyper-g.
- Settled capacitance corrections may be able to correct the offset present while under acceleration.

LW reconstruction of a time point during a 0g parabola from the 50% (notional) volume fraction flight. Aircraft deck is in direction of image down.
Error Sources and Improvements

- The electric field is not uniform, particularly near the electrode edges: high gradients.
- Linear assumption is poor in regions of non-uniform electric field.
  - Liquid moving between regions of high and low sensitivity causes the oscillations seen in the 0g portions of the plots.
- Electrodes have gaps between them
  - High, non-uniform E-fields in gaps
  - Gaps result in deadbands in settled liquid volume measurement
  - Electrode placement was not precise, resulting in variable gap sizes.
  - Some extraneous tank features in the split-plane gap
- Temperature
  - Permittivity and density are temperature dependent
  - Low vapor pressure liquid -> mass transfer from temperature changes
  - Sensor and electronics temperature dependence (small, on the order of 0.2% for the temperature range seen)
  - All of these temperature effects have been corrected.
- Mechanical improvements will likely reduce error. Examples:
  - More exact electrode placement
  - Smaller gaps between electrodes
  - Thinner electrode plates and/or preventing liquid from wicking/flowing between the electrodes.
  - More electrodes, though there is a limit because SNR decreases with decreasing electrode size.
- Some processing improvements could reduce error. Examples:
  - Moving average or other low-pass filtering techniques for volume and/or mass calculation will smooth spikes.
  - Nonlinear calibration or capacitance corrections based on ground tests at many fill levels. Useful for settled liquid only.
• **Primary objective achieved:** ECT sensor systems are useful as a propellant mass gauging technology in both an accelerated and microgravity environment

• Expect significantly better performance if previously mentioned improvements are implemented.

• Future work, all in progress:
  - Post-process all of the data
  - Uncertainty analysis and error correction
  - Implement more accurate reconstruction algorithms
  - Write journal papers

• Not currently planning another flight of this hardware.
  - Hoping to inspire other NASA researchers and industry to further develop and use this technology.
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