DEVELOPMENT OF AN AERODYNAMICALLY STABLE TETHERED PAYLOAD FOR IMAGING AND ATMOSPHERIC MEASUREMENT BENEATH THE CLOUD LAYER OF VENUS

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Presenter Biography: Milo Eirew is a prospective Electrical Engineering Student at Stanford University. Milo builds electronic devices, including payloads for high-altitude balloons in the Stanford Student Space Initiative. He co-leads the team at Stanford working on building scale prototypes of Venus probes for testing.

Introduction: Our work follows up on [1], which proposed a towbody payload tethered to a high-altitude balloon, dipping down beneath the cloud layer to take atmospheric readings and capture images of the Venusian surface. The conditions of the Venusian atmosphere do not support sensitive instrumentation for long periods of time, so the towbody must be frequently raised and lowered. The towbody trails behind the balloon and up to 10 kilometers below it, meaning the towbody experiences a wind shear of up to 10 m/s. Our aim is to create a towbody prototype that utilizes this wind shear to remain statically and dynamically stable. Changing winds will also affect the dynamics of the tether itself, resulting in a variable tether attachment angle; our towbody must stay stable despite this. The towbody must also react to turbulent winds. In order for the camera to take clear images of the planet's surface, the towbody's pitch and roll rates must not exceed approximately 0.01 radians/s, and the yaw rate must not exceed 0.4 radians/s. The camera must also stay nadir-facing (downward-pointing), so the towbody cannot stray more than 10º in the pitch and roll axes, and 20º in the yaw axis.

Approach: Under the mentorship of Dr Benjamin Hockman and Dr Ashish Goel of JPL, our group built several prototypes to test the stability of a tethered payload in Venus-like wind conditions. Our design methodology was informed by physical constraints on the system. The towbody's stability in the pitch and yaw axes comes from its tail shape: when the towbody is perturbed in those two axes, the increased force from the wind on the tail pushes the towbody into position. For this to work as a system, the towbody's center of pressure must lie aft to the center of mass. The greater the distance between the CP and the CG, the greater the restorative moment from wind shear. The center of gravity must also lie beneath the tether attachment point to remain stable: the moment exerted by the force of gravity acts restoratively in the pitch and roll axes. These constraints informed the general shape of the design, first suggested by McGarey et. al. The basic shape of our towbody is a spheroid body section, followed by a tail section with a horizontal and vertical stabilizer, approximately 50 centimeters behind the center of mass. The distance between the center of gravity and the tether attachment point is also a major consideration in this design: If the separation is too large, then whenever the tether is non-vertical, it will exert a significant destabilizing moment on the towbody. If the separation is too small, then there is not a sufficient restorative moment from the force of gravity when perturbed in the roll axis.

We started with the most basic body shape — a sphere. In simulated wind, the tail section would oscillate in a 'figure-8' pattern: it was not dynamically stable. We determined that this was due to boundary layer detachment off the rear surface of the sphere, producing turbulent wake. We added a 3D printed conical section on the back of the sphere to mitigate boundary layer detachment, and a 3D printed nose cone on the front to decrease drag (a consideration, but secondary to stability). This aerodynamic profile improved our design's stability, which we confirmed through testing.

To assist us in our analysis of our prototype's performance, we mounted forward facing and downwards-facing (nadir-facing) cameras within the towbody. We equipped the towbody with electronics: an accelerometer, gyroscope, barometer, and thermometer, allowing us to collect data during the flight.

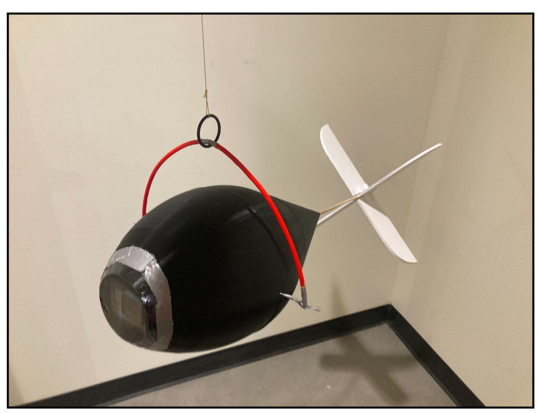

Figure 1: Prototype Towbody

Testing: To test our improved prototypes, we devised a method to reflect the wind shear and turbulence a towbody would experience in the Venusian atmosphere. We attached the towbody to a drone with a ~15 m long tether to avoid downwash effects from the drone's propellers (see figure 2).

Figure 2: Drone Testing of Prototype Towbody

Our selected method of testing allowed for varied tests — we could control the speed of the drone, as well as the orientation with respect to the wind. The cameras on board allowed us to visualize how stable image capture would be and to visually grasp the stability of our towbody. The IMU and sensors on board, allowed us to quantitatively interpret the towbody's stability compared to our requirements.

Findings: From the drone test we were able to collect footage of the flights as well as IMU data. When the drone changes directions or altitude, significant rotation rate spikes are present in the data. When the drone flew without changing direction, speed, or altitude, we noticed 'stable intervals' in the flight where pitch, roll, and yaw rates were lowest. We took the pitch, roll, and yaw rates from one of these intervals, and extrapolated the pitch, roll, and yaw angles over that interval. Figures 3 and 4 show the data over this period.

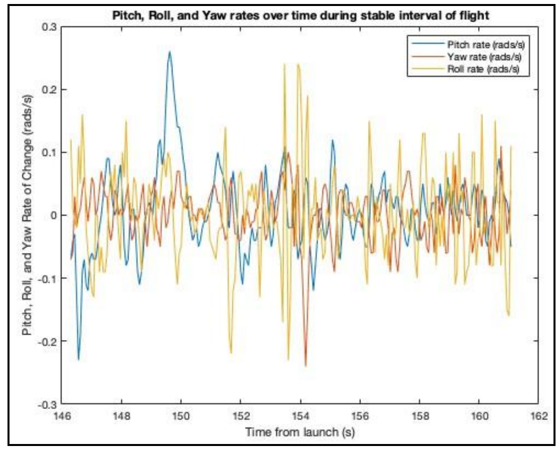

Figure 3: Pitch, Yaw, and Roll rates of change over stable interval of flight

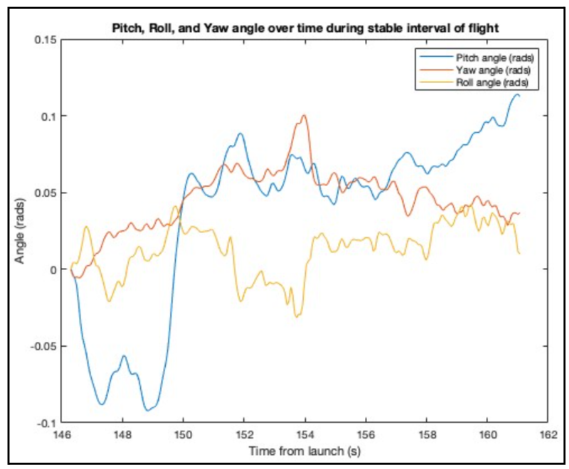

Figure 4: Extrapolated Pitch, Yaw, and Roll angles over stable interval of flight

We observed a few short stable intervals over our flight, separated by drone turns and movements — future testing will involve longer continuous stretches of flight. During stable intervals of flight, our design met the requirements for the yaw rate, as well as pitch, roll, and yaw angle. Further testing will be done to analyze the behavior of the towbody in more turbulent conditions. With continued rounds of iteration and analysis, we will refine our design to decrease dynamic instability.

References:

[1] McGarey, P., ea. (2021) *IPPW*