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The Development of a Real-Time Optical Angle-of-Attack Measurement Capability at the NASA Ames Unitary Plan Wind Tunnel

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The following details the implementation of a real-time optical angle-of-attack capability under development at the NASA Ames Unitary Plan Wind Tunnel (UPWT). Recent advancements in the integration of high bandwidth imaging systems at the Ames UPWT has laid the groundwork for the deployment of a calibrated, imaging based measurement capability. Some of the measurement goals of this data system include: an estimation of the orientation of a wind tunnel model to six degrees of freedom, measurements made at framerates high enough to time resolve model dynamics, triangulate corresponding points of interest from multiple camera views in three-dimensional space, acquire imagery with no impact to the productivity of the test matrix, provide results in real-time, and finally compute an estimation of the errors associated with the measurement. The following will outline the imaging hardware and data systems architecture, describe the data flow and image processing routines currently implemented, and explore example data and results from previous wind tunnel test entries.

I. Introduction

The accurate determination of the angle-of-attack of a wind tunnel test article is of primary importance at NASA wind tunnel ground test facilities. The wind tunnel model angle-of-attack is used along with the force and moment data at a fixed test condition to determine the performance of the vehicle. A previous study[1] has shown that in order to predict the drag performance of a commercial transport aircraft in a cruise condition to within one-half count, the accuracy of any angle-of-attack measurement should be within ±0.01 degrees. At the NASA Ames Unitary Plan Wind Tunnel (UPWT) gravity based accelerometer angle measurement system are installed within the wind tunnel model or located on the model support apparatus. These sensors possess the required measurement resolution and when properly configured are able to determine the model angle-of-attack to within the required accuracy. However there are drawbacks to an accelerometer based angle measurement, namely the accelerometer output is susceptible to model dynamics, is primarily sensitive to motion in the gravity plane and must be mounted within the model or nearby on the model support. Due to the asymmetry of the sliding bock nozzle at the NASA Ames UPWT 9-by-7 foot test section the angle-of attack plane is typically orthogonal to the gravity plane, precluding the use of gravity based accelerometer measurements for angle-of-attack driving the need for a non-gravity based measurements. Imaging based measurement solutions promise a unique capability to provide information regarding a test article's position with respect to time. A calibrated[2] stereo pair of cameras can accurately determine[3] the 3-dimensional position of a corresponding set of points on a wind tunnel model. Combining the 3-D position of these points on the wind tunnel test article with a rigid body estimation leads to the ability to determine the orientation of the test article to six degrees-of-freedom. Recent advancements in compute power and machine vision architecture have enabled integrated real-time imaging data systems[4,5] at the Ames UPWT. This effort seeks to reproduce a similar level of integration with the final data product being a real-time output of wind tunnel model attitude to the facility data system. An added benefit to the proposed measurement technique is that at each time step the model orientation is computed to six degrees of freedom, therefore model angle-of attack, sideslip, roll, and translation in 3-dimensional space will be reported.

A preliminary assessment of the proposed optical angle-of-attack system was performed in a laboratory setting. A stereo camera pair (Imperx CLF-C2880) was setup (Figure 1) to simulate typical baselines that would be representative of a camera system installed at the Ames UPWT. The cameras were synched with high-powered pulsed light emitting diode clusters (IDT Constellation 120E15). A calibrated, 3-axis, gravity based Angle Measurement System (AMS) was used as an angle reference (±0.005 degrees typical accuracy) mounted to a rotary stage. The positioning hardware, or verification apparatus (shown in Figure 2) allowed for fine control of pitch and yaw of 6 targets that were drawn onto the apparatus with a marker. The pitch and roll data were recorded from the AMS which was used as to assess the accuracy of the camera system. Custom software was written in C++ and LabVIEW to perform image acquisition, target tracking and real-time processing of the camera data. The six corresponding targets detailed in Figure 3 were tracked and triangulated at 90 frames-per-second with the orientation

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of the apparatus computed to six degrees of freedom at each time step. The error between the pitch measured by the AMS and the value computed by the optical angle-of-attack system is detailed in Figure 4. Maximum error and root mean square (RMS) values are typically ±0.003 degrees 0.002 degrees respectively. These errors are well within ±0.01 degrees. Therefore the proposed system has demonstrated the ability to meet and exceed the required accuracy.

The aforementioned optical angle-of-attack system was then deployed at the NASA Ames UPWT 11-by-11 foot test section. The system was setup to image and provide real-time results on the orientation of the NASA Ames Check Standard Model (CSM) during a test entry. Six targets (Figure 5) were drawn with an alcohol ink pen on the Ames CSM and the camera system was calibrated. Using an in-situ verification method the computed optical angle-of-attack and roll values were confirmed to agree with an AMS installed on the model to within ±0.005 degrees (Figure 6 and Figure 7). This confirmed that the accuracies of the system characterized in the lab were applicable to the imaging system when installed in the wind tunnel test section. In fact the RMS of the error depicted in Figure 6 is 0.0006 degrees, a value smaller than the RMS error resulting from the verification study in the lab. This was likely due to the larger baseline between targets drawn on the wind tunnel model resulting in an increased sensitivity of the measurement. During the Ames CSM test entry another useful capability of this system was explored: photogrammetry to characterize model dynamics. The framerate of the optical angle-of-attack imaging system was set to 120 Hz in order to resolve model motion. A tap test was performed while recording imagery and time histories of model position and attitude were computed. Figure 8 and Figure 9 detail the computed optical angle-of-attack time history and spectra resulting from the tap test. The natural frequency of the sting-model system is clearly demonstrated by the peak at 10 Hz in the spectra results.

An integrated real-time optical angle-of-attack data system has demonstrated unique capabilities in a preliminary deployment at the NASA Ames UPWT. The proposed system possesses the required accuracies for resolving angle-of-attack in both a controlled setting and during a wind tunnel test entry. In addition to providing a supplemental angle-of-attack measurement this system has demonstrated unique capabilities inherent to a photogrammetry system. By computing the orientation of a wind tunnel model to six-degrees of freedom at high framerates the dynamics of the model motion can be characterized in a manner similar to traditional accelerometer based measurements. Development of the system will continue with future deployments on different types of wind tunnel models (full-span, semi-span, launch vehicles) this will allow for continued testing to improve the robustness of the system. Additionally, new camera interface technologies will be pursued resulting in a more capable measurement system.

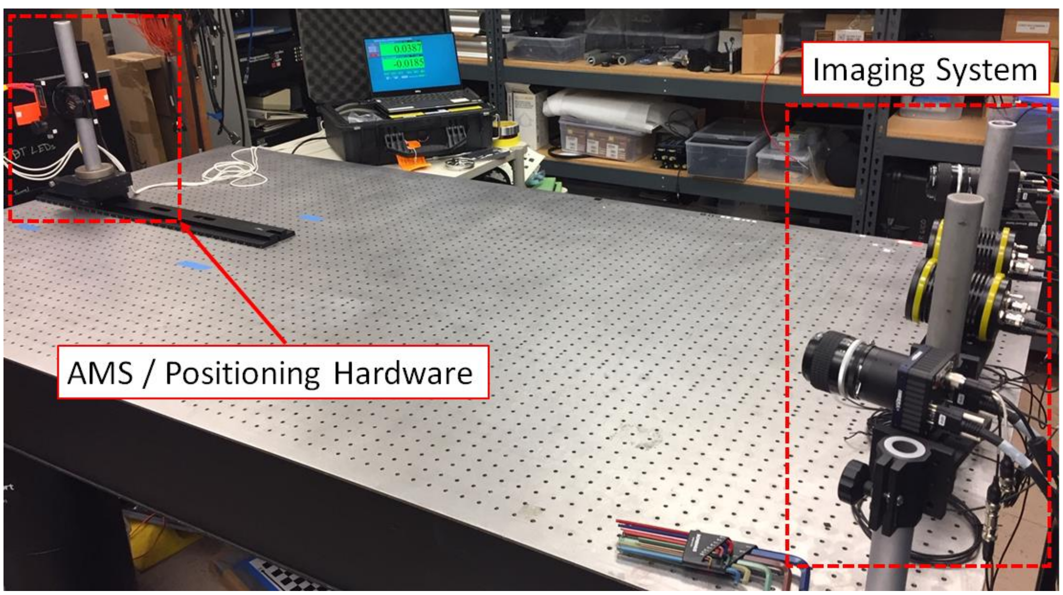

Figure 1: Optical angle-of-attack verification apparatus

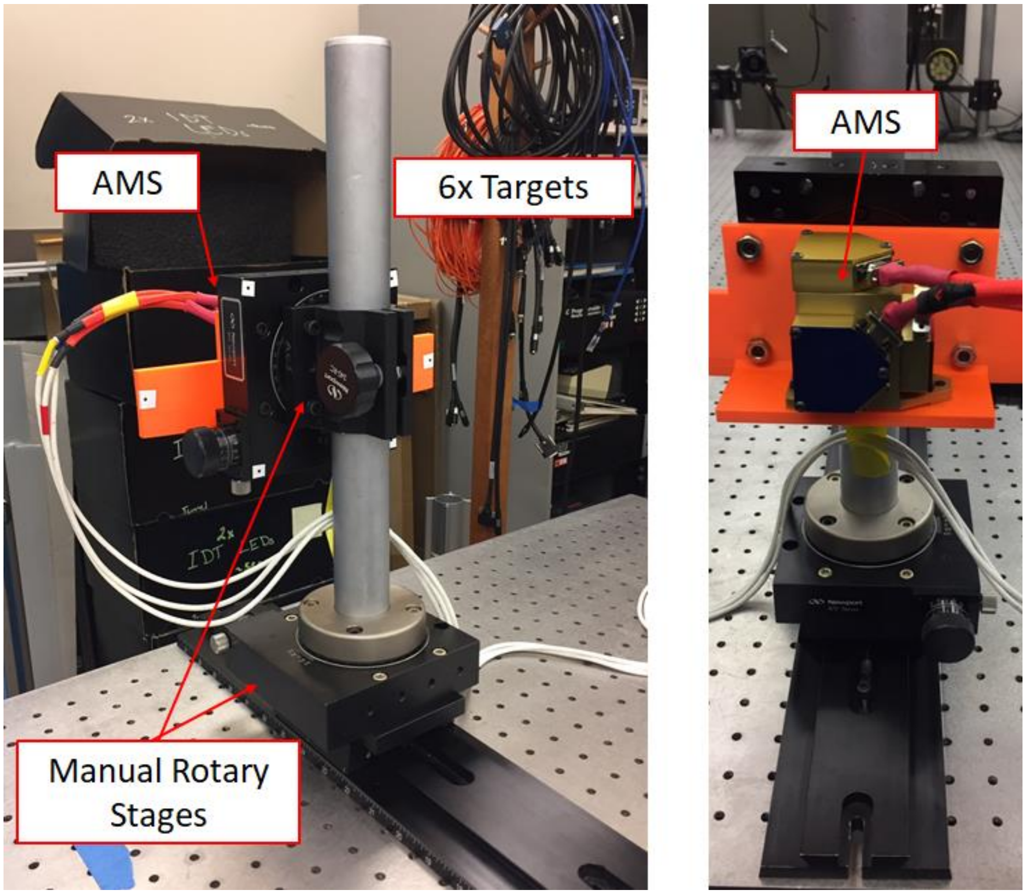

Figure 2: Verification apparatus with positioning stages, Angle Measurement System (AMS) and targets

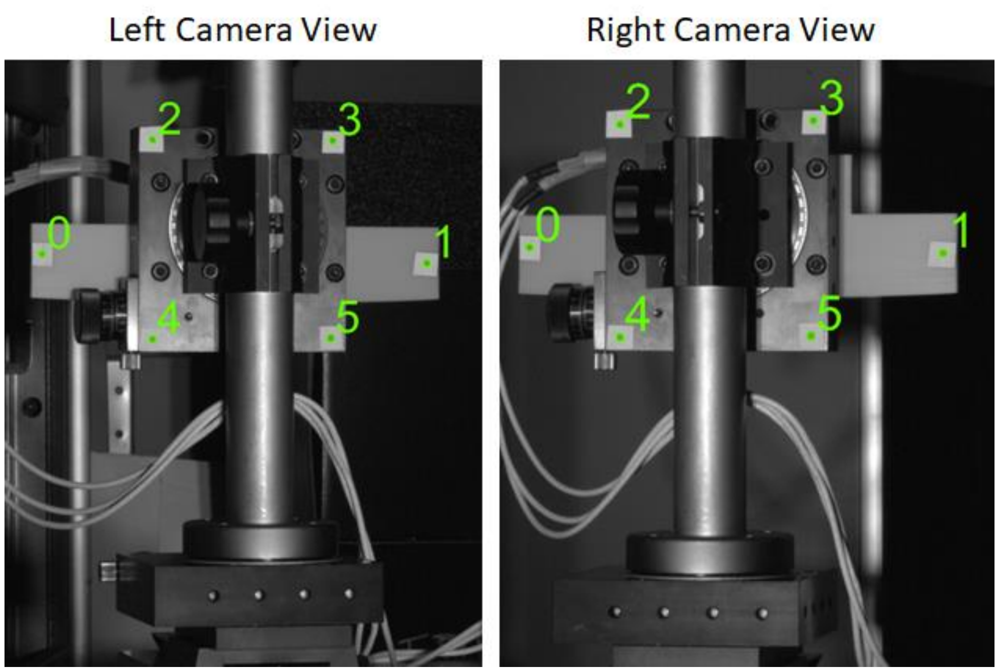

Figure 3: Six corresponding targets tracked and triangulated in real-time

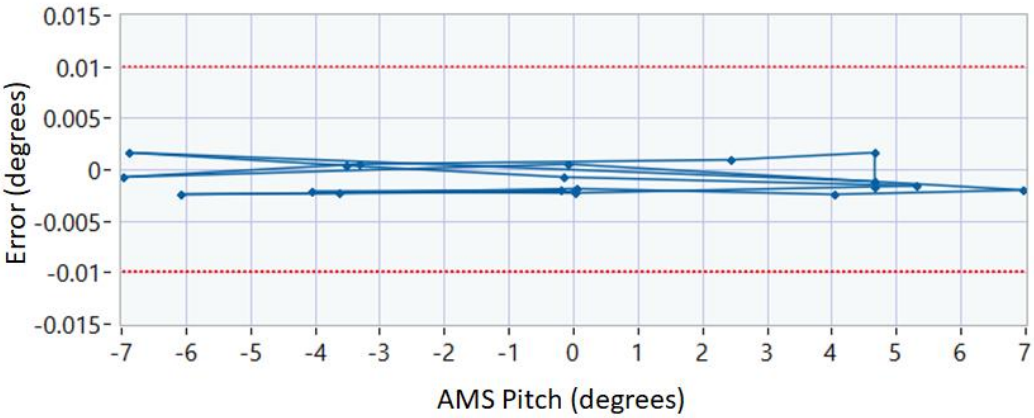

Figure 4: Error (degrees) between computed optical angle-of-attack and AMS pitch

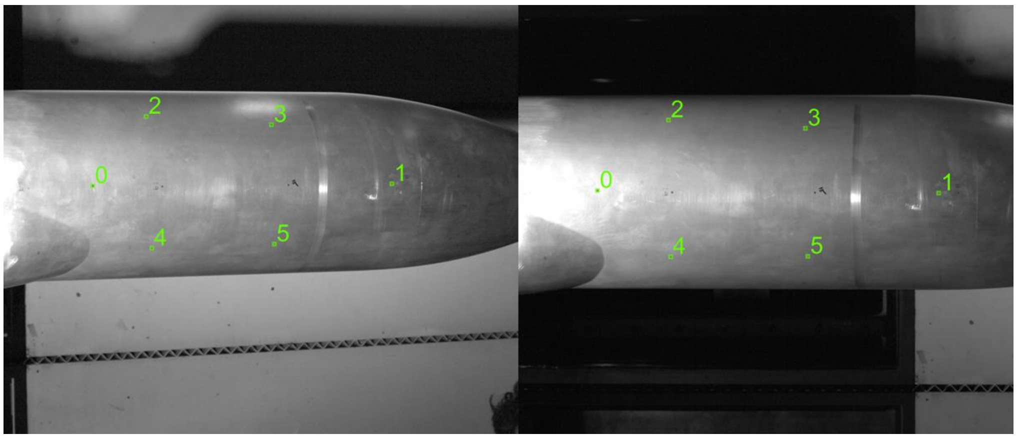

Figure 5: Optical angle-of-attack measurements on the NASA Ames Check Standard Model (CSM) with six targets: NASA Ames UPWT 11-by-11 foot test section

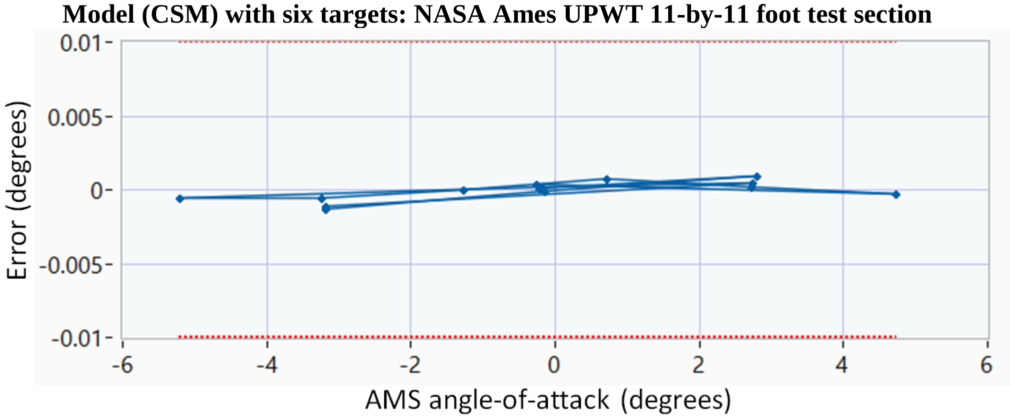

Figure 6: Error between computed optical angle-of-attack and AMS pitch installed on NASA Ames Check Standard Model (CSM)

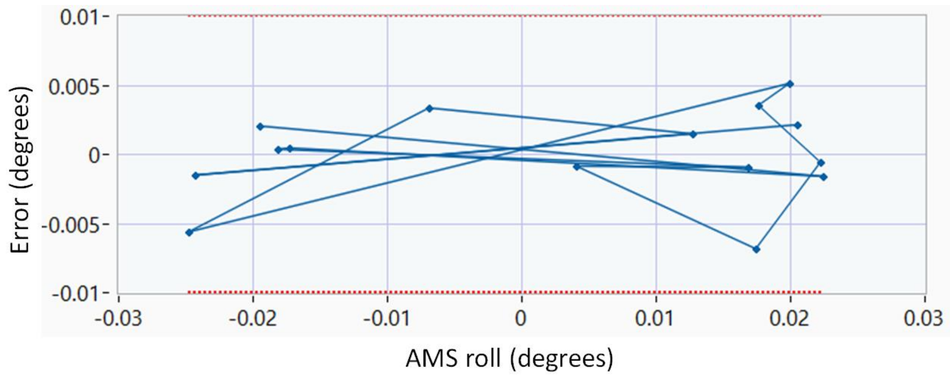

Figure 7: Error between computed optical roll and AMS roll installed on NASA Ames Check Standard Model (CSM)

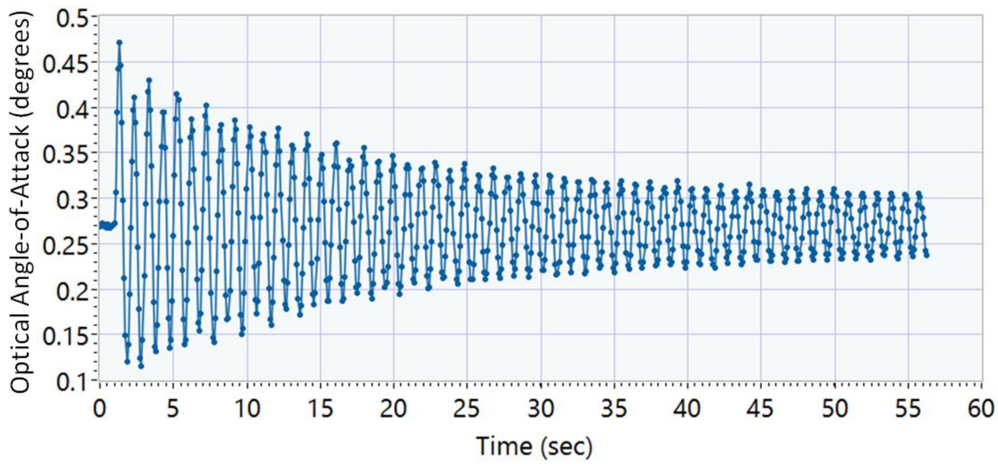

Figure 8: Ames CSM tap test at UPWT 11-by-11 foot test section: Optical angle-of-attack time history

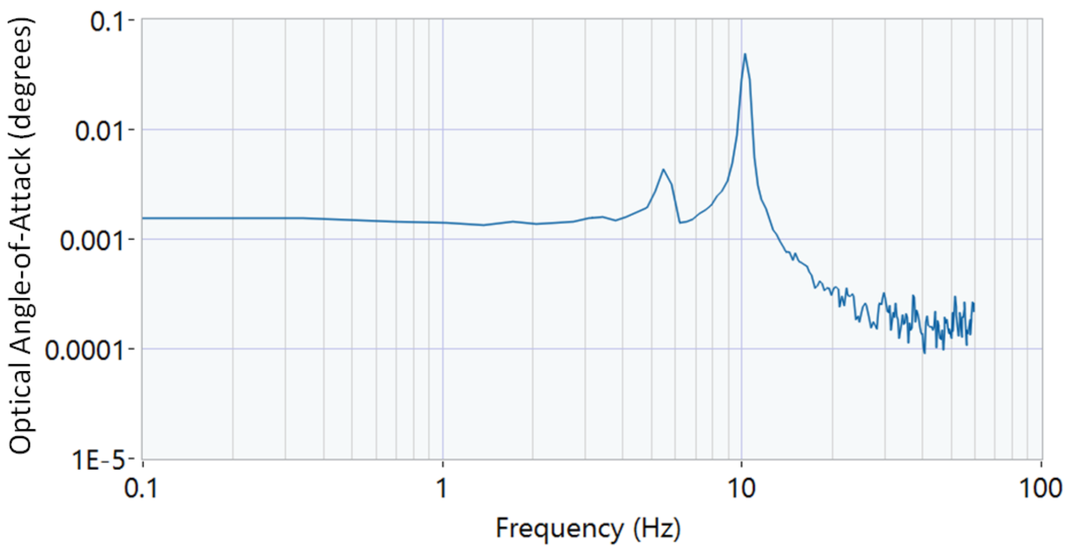

Figure 9: Ames CSM tap test at UPWT 11-by-11 foot test section: Optical angle-of-attack spectra

References

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[5] Garbeff, T.J, Heineck, J.T., et al, "*Institutional Schlieren: A Production-Level Wind Tunnel Test Measurement"* 53rd AIAA Aerospace Sciences Meeting, AIAA SciTech.