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A Travelogue of VAR System

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Abstract: - **This paper describes the design, development and testing of an AR system that was developed for aerospace and ground vehicles to meet stringent accuracy and robustness requirements. The system uses an optical see-through HMD, and thus requires extremely low latency, high tracking accuracy and precision alignment and calibration of all subsystems in order to avoid mis-registration and "swim". The paper focuses on the optical/inertial hybrid tracking system and describes novel solutions to the challenges with the optics, algorithms, synchronization, and alignment with the vehicle and HMD systems. Tracker accuracy is presented with simulation results to predict the registration accuracy. A car test is used to create a through-the-eyepiece video demonstrating well-registered augmentations of the road and nearby structures while driving. Finally, a detailed covariance analysis of AR registration error is derived.**

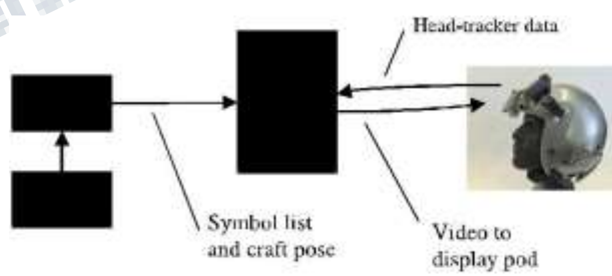
***Index Terms*—Inertial, augmented reality, calibration, registration, hybrid tracking, see through HMD, image processing, sensor fusion**

I. INTRODUCTION

For the past several years it seemed that the early focus on HMD-based AR had largely given way to tablet and phone AR, as the devices became widely available to con-sumers and advertisers saw the novelty of simple video AR as a way to reach them. However, with the advent of Google Glass and many other new see-through HMDs, there is a resurgence of interest in the original wearable AR paradigm, which in some sense can be considered the holy grail of AR because it leaves the user's hands free and can pro-vide an always-on information display that is ready to pro-vide augmentations quickly when they are needed. With this renewed interest in HMDs comes a return to the thorny challenges that consumed researchers in the ear-lier years, mainly optical technologies to produce small comfortable HMDs with sufficient FOV, and head-tracking that can produce convincing spatio-temporal registration of augmentations to their corresponding physical objects in unprepared real-world environments.

II. DESIGN AND ALGORITHMS

The system was designed for use in military and civilian aircraft, and to improve the rate of adoption it was designed to be compatible with as many types of existing aircraft-installed equipment as possible. To make it compatible with different types of mission computer (MC) that may already be present in aircraft, the Scorpion display system implements only the generic head-tracking, rendering and display functions that are common to all vehicular AR systems, and none of the mission-specific functions such as targeting, cueing, enhanced vision or synthetic vision. The MC defines and downloads to the Scorpion image generator an arbitrary set of "symbols", which may include any 2D or 3D shapes involving line segments of any color or thickness and/or bitmaps. Each symbol may be specified by the MC to be ground-stabilized or head-stabilized or vehicle-stabilized. Once the symbols are downloaded, the Scorpion image generator renders them repeatedly at a 100 Hz HMD refresh rate, using new HOB IT head-tracker data and new vehicle INS data for each frame.



Overall system architecture

In general for avionics "harmonization" is the process of aligning the axes of various aircraft systems with one another, such as the inertial navigation system, the heads-up-display (HUD), the HMD tracking system reference, sensor pods or targeting pods, and weapons. We developed a variety of tools and methods to align the fiducially constellation with the aircraft axes, or more specifically with the plat-form INS axes since the INS is the reference frame from which symbol generators are

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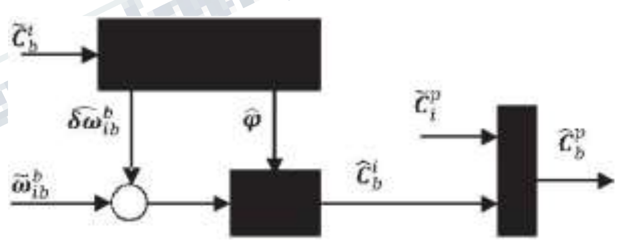
driven. When the aircraft contains a HUD, we assume the HUD is already aligned with the p-frame of the INS and we use a specially developed tool containing a collimated optical scope with a Hob IT sensor aligned on top. By pointing the scope at the watermark in the HUD it can be aligned with the platform x-axis, and at the same time the Hob IT looks up at the fiducially and determines the pose of the scope relative to unframed, from which we solve the rotation of the nframe w.r.t. the p-frame.

TABLE 1
Five Coordinate Systems

i-frame	The i-frame is an inertial reference frame, which for our purposes is a local level North-East-Down (NED) frame on the ground below the aircraft that rotates sufficiently slowly to be considered an inertial frame.
p-frame	The aircraft "platform INS" frame. The "platform INS" is the inertial navigation system that supplies pose data to the mission computer and in turn to the Scorpion display system.
n-frame	The reference frame of the tracking system. For a magnetic tracker the n frame has its origin in and axes nominally aligned with the source coil assembly. For Hob IT, the n-frame has its origin at one of the fiducially and its axes are roughly aligned to the aircraft axes during ground harmonization procedures.
b-frame	The body frame of the tracker sensor. In the case of Hob IT, the b-frame is defined by the Nav Chip inside the sensor assembly, which is mounted upside-down, backwards and tilted relative to the helmet.
d-frame	Display frame defined by the lightguide optical element (LOE) or "paddle" on the Scorpion display pod.

Basic Orientation Tracking Filter

The Extended Kalman Filter (EKF) for the Hob IT is greatly simplified compared to the Vis Tracker. Because the Vis-Tracker had a rolling-shutter image sensor, it had to process each individual fiducial measurement separately at a differ-ent point in time, using a highly nonlinear bearings-only measurement model which was a function of position as well as orientation [7]. Due to the global shutter imager and the much faster processing element (ARM Cortex A8 at 1 GHz), the HOb IT is able to simultaneously capture and decode up to 20 fiducials at frame rate. For every frame, it solves for pose using a modified version of the Open CV pose recovery algorithm, which results in a direct measure-ment of the rotation that can be used to correct gyro drift. Therefore, the head orientation can be tracked independently from position using just gyros and camera pose measurements and a very simple 6- state Complementary Kalman Filter (CKF) to estimate the rotation errors and gyro biases.



Algorithm for tracking relative to i-frame, then converting output to pframe for legacy tracker compatibility

III. FILTER AUGMENTATION FOR COMPENSATING DELAYED INS DATA

The flight test data collection computer was capturing the platform INS data at 25 Hz (which is an acceptable rate because the Hob IT tracking algorithms use head-mounted gyros to directly track pilot head orientation relative to the ground at 200 Hz without using any platform INS data in the primary AR data path). However the data was being delayed by an unknown amount that the pilot estimated as upwards of 200 ms. With that much delay, the measurement updates in the Kalman filter would receive

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measurement errors sig-nificantly larger than the tuned measurement noise matrix resulting in suboptimal performance. Rather than retune the filter to expect vastly more measurement noise, we determined that given the slow dynamics of an aircraft it would be possible to remove most of the error by forward predicting the aircraft attitude if we only knew the amount of latency we needed to compensate. We took the approach of trying to automatically estimate and adapt to the data latency by adding one additional state to the CKF to estimate the error of the prediction interval currently in effect for compensating the measurement data latency.

IV. SIMULATION

The main algorithmic engine for HOb IT, called sf Core, was developed using model-based design in Simulink. There-fore, much effort was spent up front developing a high-fidelity simulation harness so the algorithms could be continuously tested with realistic data. Fig. 9 shows the architecture of the simulation environment. The sf Core algorithm is run as a software-in-the-loop (SIL) block of compiled C code that was auto-generated from a Simulink model and runs within the simulation model. A key aspect of the simulation is the use of splines to generate high sample rate (five KSPS) truth data from the 100 SPS recorded head motion and aircraft motion that was obtained on previous test flights. The high sample rates are needed in order to simulate in detail the internal oversam-pling and integration algorithms of the NavChip IMU in order to produce simulated inertial measurements with the same drift characteristics as the actual HOb IT. Careful verification was performed by generating simulated perfect IMU measurements (D**u** and D**V**) with no noise or error sources, and showing that 6DOF strapdown INS integration algorithms applied to these measurements reconstruct the truth trajectory perfectly.

Analysis

Unfortunately it is not straightforward from this to understand the AR registration errors that the pilot will see when looking in any particular direction, which involves a complicated interplay between the various error sources making up the tracker error budget and the bore sighting process which serves to cancel out the repeatable parts of the tracking error in the frontal direction. Furthermore, pointing error is a two-dimensional error and should be characterized with a distance-RMS (DRMS) metric of the line-ofsight (LOS) vector which is computed from the tracker orientation output and the boresight transformation. The first goal of the analysis in this section is to determine the DRMS pointing accuracy for various helmet azimuth and elevation look directions. A covariance analysis is used to provide a statistical characterization of the system accuracy including both time-varying tracking errors that occur throughout the flight, as well as tracker-to-tracker, install-to-install, and flight-to-flight variations that occur due to one-time errors in calibration, harmonization, bore sighting, etc. This analysis is needed to determine the statistical pointing accuracy of the system because it is not possible to collect and analyze enough different flights with different trackers and different installation parameters to determine the accuracy empirically, even if there were a way to mea-sure the aiming accuracy of the system during flight. The three error terms are not independent because the pilot bore sight procedure adjusts b to make the visible error exactly zero at the location of the bore sighting target, which may be either the watermark in a Head-Up Display (HUD), or the crosshair in a Bore sight Reticule Unit. Let **v**p 1 be the true location of the bore sighting reference mark and **v**^p 1 be the nominal position determined by design or measure ment, which is used in the software to generate the bore sight symbol in the Scorpion. They are not always exactly the same. The alignment accuracy at the center of a commercial HUD is typically þ/-3 mrad, while refractive HUDs with integrated combiners are capable of achieving þ/–1.5 mrad. However, BRUs are not aligned as accurately as HUDs. The novel auto-harmonization algorithm presented makes it possible to consider deploying the HOb IT on these types of vehicles, which are not equipped with a HUD to facilitate traditional methods of harmonization. Of course many of these vehicles do not currently have installed GPS/INS systems, but with the recent developments in the MEMS field, the cost of sufficient performance is falling very rapidly and it may already be practical to add a MEMS GPS/INS unit as part of the vehicular AR package.

V. CONCLUSION

One interesting such application occurs in climates where the snow piles so high that ploughs cannot see the tops of the roadside guidance poles. It seems inevitable that AR guided plows will eventually be deployed. Another very alluring possibility is AR guidance for operators of earthmoving equipment and other heavy construction machinery to help them more efficiently and

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exactly achieve the desired results planned in a CAD model. Obviously AR headsets would also be valuable to provide situational awareness to first responders while they drive to the scene, and after they dismount from the vehicles at the scene.

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