Position: Augmenting Inertial Tracking with Light

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1 INTRODUCTION

Inertial measurement unit (IMU) has been widely used for tracking object motion. Comprising accelerometer, gyroscope, and compass sensors, IMU measures object's acceleration, angular speed, and orientation. As a low-cost, low-power unit with a small form factor, IMU has been commonly included in today's mobile devices (e.g., smartphones, smart watches, drones, VR controllers and headsets) and smart appliances (e.g., robot vacuum).

Despite its popularity, IMU is well known for its drifting problem. Since IMU sensors measure only acceleration and angular velocity, one must *double* integrate these sensor signals to compute object's movement trajectory. The integration of signals also contains sensor errors caused by constant bias (offset measured when the sensor is not moving or rotating), thermal-mechanical and electrical noise, as well as other random noises due to calibration or temperature [11]. These errors cumulate quickly, resulting into a fast growth of the location error [9, 10, 13].

To address IMU's drifting problem, prior studies have proposed various methods to calibrate IMU tracking results by leveraging external landmarks with absolute locations. However, these methods either require human in the loop (e.g., foot steps used in the pedestrian dead reckoning) [4, 8, 11], or rely on cameras [5, 7] that are typically power-hungry, or consider only outdoor scenarios with GPS signals and outdoor landmarks available [3], or leverage coarse-grained landmarks (e.g., landmarks based on Wi-Fi signal strength or building structures) for calibration and thus are unable to achieve centimeter-level accuracy reliably [6, 9, 10, 12].

In this position paper, we propose the use of ubiquitous lights to correct IMU tracking errors and boost inertial tracking accuracy. Specifically, we consider reusing indoor luminaries (e.g., LED or fluorescent lights) to cast passive, imperceptible *light polarization patterns*. Such patterns provide fine-grained (e.g., at centimeter-level) optical landmarks to constrain and correct the integration drift of IMU. To generate the polarization pattern, we exploit the birefringence optical property [2], where we simply cover existing light cover/diffuser with a thin (e.g., 0.18-mm), cheap (<\$1) polarizer film attached with transparent tape stripes in an arranged pattern. Transparent tape stripes disperse a polarized light into color beams in different polarization directions. They result into colorful patterns observed by a color sensor with a polarizer film. The polarization pattern can be projected to the space using a thin (e.g., 0.15-cm center thickness) Fresnel lens. Relying on a thin layer of cheap cover atop existing light cover/diffuser, the whole setup reuses existing lighting infrastructure without requiring active modulation unit, entailing low deployment overhead and cost.

The integration of light and IMU sensors brings three benefits:

- ***High accuracy***: With wavelengths measured in nanometers, visible light can generate landmarks with fine and rich details. Such fine-grained optical landmarks best complement IMU to address its drift error and thus to achieve high tracking accuracy;
- ***Reliability***: While light achieves fine accuracy, it can be easily blocked by other objects, rendering light signals unavailable. IMU sensors, on the other hand, reliably provide a constant stream of readings that can compensate for the loss of light signals upon occasional blockage, allowing the system to be robust against occasional blockage/occlusions in tracking;
- ***Low power and portability***: Both IMU and photodiodes are cheap, small, and low-power (photodiodes consume power in μW). Thus they can be easily embedded in everyday objects to track their locations. Light can be further exploited as an energy source to harvest energy from and power the sensing component attached to the object.

We next overview two main components of the system and discuss key technical challenges.

2 CREATING POLARIZATION PATTERN

The first component is to design light patterns serving as landmarks for correcting IMU drift errors. The key challenge lies in the conflicting goals: on one hand, the light pattern should exhibit strong light intensity contrast to ensure robust detection of the pattern; on the other hand, the pattern should also be imperceptible to avoid affecting lighting. Additionally, the creation of light patterns should require minimal instrumentation to ease practical deployment.

To meet the above goals, we seek to create patterns in light polarization, which are imperceptible to human eyes and yet detectable by photodiodes with a polarizer film. Furthermore, since ambient light is typically unpolarized, light polarization patterns are robust against ambient light interference.

To create polarization patterns, we will reuse existing indoor luminaries (e.g., fluorescent or LED light). These visible light sources typically emit unpolarized light, i.e., a mixture of light waves with different polarizations. To create polarized light, we will attach a thin polarizer film to the light cover/diffuser. The polarizer allows light rays of only a particular polarization to pass through while blocking light rays of other polarization directions. To create a spatial pattern of light polarization, we will exploit the birefringence optical property [2], where an optically anisotropic material rotates the polarization of a light ray by an amount that depends on the

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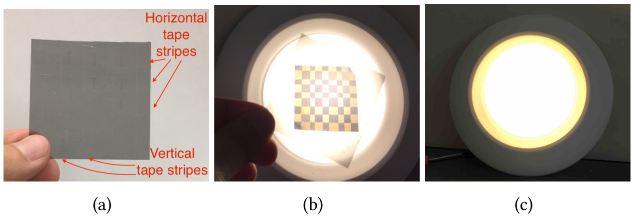

Figure 1: A polarizer film with horizontal and vertical transparent tape stripes arranged in a grid (a). Attaching this film to a light cover and viewing it through another polarizer, we observe colored grids (b). This pattern, however, is imperceptible without a polarizer (c).

light wavelength (i.e., color). Therefore, when polarized light passes through a transparent anisotropic material, the white light will be split to several color light beams in different polarization directions. Then a color light sensor with a polarizer film can perceive a color light beam that aligns with the polarization direction of the polarizer. Interestingly, such optically anisotropic materials are common. Our experiments show that everyday transparent tape is made of such materials. Thus, we can glue transparent tape stripes on a polarizer film to create a spatial pattern of light polarization.

As an example, Figure 1(a) shows a polarizer film, where we glue transparent tape stripes vertically and horizontally on its surface in a grid pattern. It consists of four types of grids: 1) grids not covered by transparent tape; 2) grids covered by both vertical and horizontal tapes; 3) grids covered by a vertical tape stripe; and 4) grids covered by a horizontal tape stripe. Placing this film in front of a light source and viewing it through another polarizer film, we observe different colors in these different types of grids (Figure 1(b)). This is because polarized light is dispersed differently in different types of grids, leading to different colors when perceived through a polarizer. This color pattern, however, is imperceptible to naked human eyes (Figure 1(c)). To project this colored grid pattern to the 3D space, we will add Fresnel lenses (0.15-cm center thickness [1]) along with the polarizer film to enlarge the pattern in the space. As a color sensor (with a polarizer) moves across grids, it will perceive color change during edge crossing, which can serve as landmarks to calibrate IMU drift errors.

The above example demonstrates that both the orientation and number of layers of transparent tape stripes affect their effect in changing light polarization. It leads to the following research tasks: 1) we will model the impact of transparent tape stripes in changing light polarization and examine the set of colors with high contrast that can be generated by judiciously arranging the layer and orientation of tape stripes; 2) we will explore the design of color patterns so that adjacent grids have high-contrast colors to facilitate the detection of grid crossing, while maximizing the likelihood of mapping different moving trajectories to different color sequences.

3 FUSING LIGHT AND IMU SENSORS

The second component is to detect optical landmarks (e.g., color grids) and fuse the landmark information and IMU data to continuously track object location.

To detect the light pattern and thus the edge-crossing event, a color sensor covered by a polarizer monitors its R, G, B channel input for perceived color changes (e.g., detect color changes based on first-order derivatives). The key challenge is to deal with orientation change during movement. The specific grid colors in the color pattern (Figure 1(b)) will change if we rotate the polarizer at the receiver (i.e., color sensor). Therefore, as an object changes its orientation, the perceived changes in color can be due to both location change (i.e., crossing grids) and orientation change. Thus, to identify edge crossing correctly, we need to subtract the color change caused by orientation change. To do so, we plan to model the relationship between observed color and orientation. We will leverage the compass and gyroscope sensor in IMU to infer orientation changes and use the model to derive the associated color change to be subtracted.

To fuse detected landmarks with IMU data, we will consider estimation theory as the theoretical framework on the basis of Bayesian inference. A particular challenge in our context is that the optical landmarks (i.e., edge crossing) do not provide complete 2D/3D coordinates, rather, they indicate only the object crossing a boundary along x or y direction. To best exploit the information conveyed by the landmarks, we will study an optimization framework that jointly optimizes all positions of the object in a sliding time window. We will seek 3D positions that minimize: 1) the discrepancy between the acceleration measured by IMU and the acceleration estimated from the inferred locations, and 2) the distances to the nearest boundary during edge-crossing instances. We will also explore the particle filter method, where we advance current particles (i.e., positions) to the next time step based on IMU measurement (e.g., acceleration, direction), and update the probability density function of particles based on detected optical landmarks.

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