Assessing the Impact of Laser Camera Damage Artifacts on Visual Odometry Algorithms

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ABSTRACT

The convergence of last mile delivery challenges and urban laser proliferation presents a nuanced landscape for navigating aerial vehicles, particularly drones, in urban environments. While drones offer promising solutions to expedite deliveries and reduce operational costs, the hazards posed by lasers, both to aircraft and camera equipment, introduce complex safety and reliability concerns. Laser interference can impair pilot vision during critical flight phases and compromise the accuracy of visual data captured by onboard cameras, impacting navigation algorithms and posing risks to both operational efficiency and public safety. It is shown that corrupting a small patch of the image size can significantly affect optical flow estimates. This attack leads to noisy navigation positioning and deviations far from the intended destination. This necessitates a comprehensive understanding of laser-camera interactions and their implications for aerial navigation systems, highlighting the critical need for robust mitigation strategies to ensure the safe and effective deployment of drone technology in urban last mile delivery contexts.

KEYWORDS

laser, optical flow

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1 INTRODUCTION

The last mile delivery problem, a critical aspect of any supply chain management, is the final stage of distribution where goods are transported from the last distribution center to the end consumer at a specific location. This phase presents various challenges owing to its complex intricacies, including but not limited to road condition and congestion, unpredictable consumer needs, and stringent time constraints [5]. Rapid urbanization and the rise of e-commerce exacerbates this issue leading to increased delivery times and operational costs. Further, consumer are increasing expectations for rapid delivery and accurate tracking which only intensifies the pressure on logistics providers to adapt, innovate and optimize their last mile strategies.

Recent advancements in drone technology have enabled safe indoor drone flights in numerous scenarios, extending far beyond the open spaces and human piloting typically necessary for precision drone operation [4, 6]. In recent years, the rise of drone delivery in support of the last mile delivery has greatly proliferated, both in urban cities and rural countryside. There are many specific examples, including Zipline, a drone operator delivering medical supplies to areas with poor surface infrastructure [1]. In general, drones bring the advantages of greater accessibility, efficiency, and cost-savings while lowering overall pollution [5].

For these use cases, the reliability of navigation is important as a crash can not only cause financial but also environmental losses and harm to individuals. GPS navigation is currently the industry standard, but the accuracy is on the order of metres at best and navigating urban environments greatly increase the error with additional challenges of issues like airspace permissions, takeoff areas, noise restrictions, urban obstacles, and landing requirements[5, 13]. To compliment this, many operators are including the use of vision navigation for positioning. Thus, understanding the weaknesses of navigation by the camera and the correctness and confidence of the input to these algorithm is important.

2 BACKGROUND

In urban environments, the prevalence of lasers is notably higher compared to rural areas due to the density of human activity and infrastructure. The presence of lasers in cities stems from various sources, including entertainment venues, commercial displays, construction projects, and scientific institutions. This elevated concentration of laser activity in urban locales poses distinct challenges and risks, particularly concerning safety of aerial vehicles including piloted aircrafts and the optical sensors present in cameras.

One significant concern regarding lasers in urban settings is their potential interaction with aircraft, particularly with pilots during takeoff, landing, and low-altitude flight. Laser

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pointers, often used for recreational purposes, can inadvertently illuminate cockpit windows, causing temporary visual impairment or distraction for pilots. This phenomenon, commonly referred to as "laser strikes," poses a significant safety hazard, potentially compromising flight crew's ability to operate aircraft safely and navigate effectively, thereby endangering passengers and bystanders alike [15].

Moreover, the proliferation of lasers in urban areas also raises new unknowns regarding their interaction with camera equipment. Lasers can interfere with camera sensors, resulting in artifacts or distortions in captured images or videos [16]. This interference can manifest as streaks of light, halos, or blotches, degrading the quality and reliability of visual data obtained through these devices . Such disruptions can impede various applications reliant on precise imaging, including surveillance, photography, and cinematography. In this scenario, it has the potential to affect the correctness of detecting motion between frames in navigation.

Cameras are also used in other applications including autonomous vehicles and are susceptible to various artifacts and failures [10, 11]. Laser artifacts distinguish itself from naturally occurring elements such as dirt or leaves through a fundamental difference in the mechanics. Laser-induced anomalies in visual data exhibit distinct characteristics, often appearing as precise, geometric patterns or intense, concentrated bursts of light, with remaining artifacts on the sensor appearing as a constant shape of illuminated light, often pink in colour [16]. These features contrast with the random distribution and irregular shapes typically associated with environmental debris of dirt and dust where these is an obstruction of light, a place on the image with no discernible data. Consequently, laser-induced artifacts affect navigation algorithms by presenting itself as an easy and useful point to track for motion due to its distinction both from the background and the precise shape. However, tracking this for navigation can potentially produce wildly erroneous outputs.

3 VISUAL ODOMETRY

Visual odometry (VO) is a technique used in robotics and computer vision to estimate the motion of a camera or a vehicle by analyzing the changes in its visual input over time. It operates by tracking distinctive features in successive frames of a video stream and calculating the relative movement between these frames. By triangulating the positions of these features, visual odometry can estimate the camera's trajectory and, consequently, the motion of the vehicle or the device to which the camera is attached [12, 18].

Visual-inertial odometry (VIO) enhances the capabilities of visual odometry by incorporating data from inertial measurement units (IMUs) along with visual data. IMUs provide measurements of linear and angular accelerations, as well as angular rates, which can complement visual information, especially in environments where visual features are scarce or ambiguous. By fusing data from both sensors, VIO systems can achieve more accurate and robust motion estimation, particularly in dynamic and challenging conditions such as fast movement or low-light environments [12, 18].

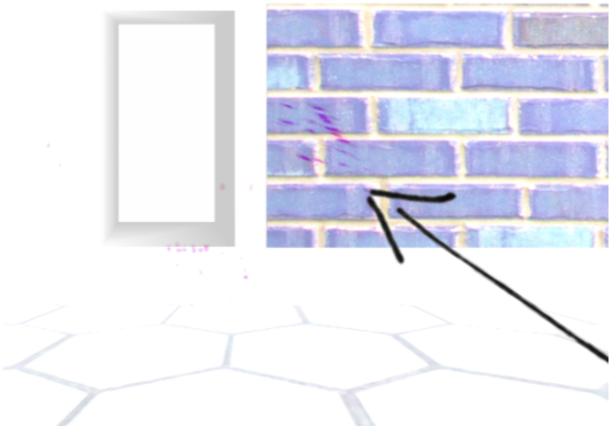
In Stereoscopic VIO, compared to monoscopic, it enhances depth perception by capturing different perspectives of a scene from each camera, allowing for accurate estimation of depth distances and spatial relationships between objects. This depth perception leads to a more accurate detection of movement between frames [9].

Visual simultaneous localization and mapping (vSLAM) extends the principles of visual odometry to simultaneously build a map of the environment and localize the camera within that map [14, 19]. In addition to estimating the camera's trajectory, vSLAM algorithms construct a representation of the surrounding environment by identifying and tracking features, such as landmarks or key points, while the camera moves. This map-building process occurs concurrently with the localization of the camera within the map, enabling real-time navigation and exploration in unknown or GPS-denied environments [2]. vSLAM finds applications in various fields where accurate localization and mapping are essential for navigation and interaction with the surroundings [7]. In this project, the primary focus will be on a stereoscopic VIO system as that is the best possible equipment configuration, and should make this the most resilient to flow attacks.

4 FACILITATING THE ATTACK

To test our attack, we first selected our testing platform to be based on XTDrone for its comprehensive test environments and the preexisting setup for various vehicles and navigation algorithms [17]. It is easily extendable for all UAV simulation with embedded support for the integration of ROS, Gazebo and PX4. Other End-to-End simulators exist as well for complex environments and sensor testing, but they lack formal documentation that allows for the use of them as a platform to extend the project[2]. Further, this platform offers integration of various navigation and path planning frameworks, providing a versatile foundation for our experimentation while ensuring the scalability and repeatability of our findings across various UAV simulations environments. We also limited our scope of testing to stereoscopic vision VIO. This represents the best equipment configuration for optical positioning fused with an inertial measurement unit (IMU). If the attack works on VIO, it is likely to also be capable of attack VO algorithms.

Figure 1: Laser Damage Overlay in Simulator



We further selected the OpenVINS as our algorithm to calculate the positioning of the vehicle. OpenVINS stands out as an attractive option due to its rich array of features and capabilities in the field of visual-inertial navigation systems (VINS). Its open-source nature is helpful in dissecting and tracking how each frame of attack is working. This open-access model not only allows users to tailor the system to our specific needs but also allows for rigourous validation. Moreover, OpenVINS excels in challenging environments due to its integration of visual and inertial sensor data, enabling precise localization in dynamic scenarios.

To create laser damage artifacts, real images were collected from an iPhone camera that has previously been exposed to lasers with affected areas moved onto a transparent canvas. The extension of laser damage overlays was complemented by detailed analysis outlined in a paper detailing the thresholds of silicon 2D imaging arrays, encompassing a spectrum of diverse examples [19]. A sample of 100 different patterns were made and iteratively tested on both camera of the stereoscopic image.

5 THE EXPERIMENT

In crafting the attack, a ROS node was inserted between the vehicle camera and the flight computer with a python3 openCV library to efficiently overlay various images and manipulations to judge the efficacy and resiliency of the odometry algorithms. The overhead of this node was negligible with timing delays of less than one millisecond on a machine running a i9-11900k processor with a Nvidia 3090 GPU. As part of the XTDrone platform, the simulation runs in lockstep, allowing the simulation speed to be adjusted according to the computer performance [17]. The injected image can be precisely managed as with the openCV library tools and then republished back as a topic for the vehicle computer.

Table 1: Arrival Rates for Each Injected Overlay

Injected Overlay	Arrival Rate
None	99.8%
Low	95.2%
Medium	61.0%
Severe	0.9%

Note: Evaluated on 1000 runs of the path for 1m of arrival waypoint

To receive the groundtruth data, another ROS node was built to receive the groundtruth positioning and orientation from the Gazebo simulator and logged. This allows for the detail comparision of relative positioning and mean error over the whole entire flight path. The positioning data from the VIO trip computer system was also collected for comparision. They are both visualized into RViz for a 3-Dimensional graphical representation.

6 EVALUATION CRITERIA

For our experiment, we used intel realsense camera on the stock iris quadcopter to evaluate three different types of flight. The takeoff and vertical ascent, straight and level flight with a camera pointed sideways, and straight and level flight with the camera pointed forwards. The distinction here allows us to precisely evaluate forward facing motion reconstruction and sideways facing and how this interacts with laser damage artifacts. The waypoints for the whole flight are then setup to evaluate these different phases with a record of whether the vehicle has arrived to the waypoint within 1 metre of the waypoint. The entire flight path is 15 metres. The success of a flight is defined as whether of not the quadcopter arrived at the final waypoint without imapcting any of the objects enroute and landed within 1 metre of the final waypoint on the ground. Detailed analysis was also conducted to investigate how to reliable craft an input signal to attempt hijacking control instead of the simple deviation in any random direction.

7 RESULTS AND DISCUSSION

This attack operates similarly to a sensor input spoofing attack [3]. Each laser artifact usually presents itself as a bright coloured patch, and feature point detection finds these points as excellent landmarks to track and calculate motion with. The error that results deviates the vehicle from its planned path where it wrongly considers itself as still on track to the final destination.

With reference to Table 1, it can be seen that with no injections, the vehicle arrives to its final destination consistently high at 99.8% and with low severity injections, more crashes and less arrivals happen. With just a mere 5% covered sensor for medium severity, the arrival rate is reduced significantly, and even more damage prevents the vehicle from completing the journey at all. The protection of the camera to having artifacts that are bright must be corrected either in physical filters or by software implementations that retroactively stops tracking static objects on frame.

To safeguard against enduring sensor impairment induced by pulsed lasers, the adoption of laser protection filters becomes imperative. Nonetheless, when confronted with a laser threat of indeterminate wavelength, conventional fixed filters prove inadequate as they necessitate prior knowledge of the specific wavelength for their design. Consequently, an effective protection filter must exhibit versatility across a broad spectrum of wavelengths while possessing the capability to promptly engage and obstruct the incoming pulse within a timeframe shorter than the pulse duration itself. The resolution to such a quandary is found in optical limiters, which represent self-triggering, intensity-responsive filters designed to dampen high-intensity light while permitting the transmission of low-intensity light [19].

Extending the attack, it is trivial to control the direction of deviation of the vehicle. With laser damage artifacts on the left side of the image sensor, this is interpreted as the left side stationary, while the right side moving. The vehicle then calculates that itself is turning left and corrects the straight line motion with right deviation. This can be used to hijack control of a vehicle in straight line forward motion if it is using vision positioning.

8 RELATED WORKS

Previous research efforts focus on both crafting and attacking LiDAR with specific and malicious laser signals or using infrared to blind and attacking traffic control devices in algorithms such as traffic sign recognition [8, 10, 18]. These optical attacks are generally highly specific to the environment and not persistent across on the vehicle. Attacking a stop sign will stop the vehicle from obeying that specific traffic control devices, but it will resume normal operation at the next stop sign. This attack extends that by directly affecting the camera onboard with artifacts that are easily recognized by feature point detection of various filter-based visual estimators. The preliminary results show that this attack occurs under a similar mechanism as the sensor spoofing attacks [3] where drift is possible on downward positioning cameras on drones.

9 CONCLUSION

The intricate interplay between last mile delivery challenges and the proliferation of lasers in urban areas underscores the complexities of integrating aerial vehicles, such as drones, into these environments. Despite their potential to streamline deliveries and reduce costs, drones face significant safety and reliability obstacles due to laser interference, which can impair positioning vision and compromise visual data accuracy. The demonstrated susceptibility of onboard cameras to laser attacks emphasizes the importance of developing robust mitigation strategies where little laser artifacts can together cause deviations far from the original flight path. To enable the safe and efficient deployment of drone technology for urban last mile delivery, it is imperative to deepen our understanding of laser-camera interactions and implement effective measures to safeguard camera systems both as improved hardware filters and robust software navigation.

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