Vision Based UAS Navigation For RFI Localization

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BIOGRAPHIES

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ABSTRACT

Radio frequency interference (RFI) is a challenge that has, and continues to be, faced by the aviation industry today. This is especially true for GNSS in aviation as these signals are particularly weak. Interference comes in many forms ranging from short transient events to longer duration events, and are often caused by unintentional radiators, however all of these scenarios have the possibility to pose a risk to GNSS users. Many techniques exist to localize a signal source, however, these techniques typically rely on knowing the position from which a set of measurements are made. Therefore, when the source being localized creates a GNSS denied environment there become two problems to solve: localizing the interferer and navigating in the denied environment caused by the interferer. An unmanned aerial system (UAS) built on a multirotor platform, known as JAGER, is being developed to solve these two challenges [1].

This paper focuses on the development of a navigation system for JAGER to enable operation in a GNSS denied environment, resulting in improvements to the RFI localization capabilities that are JAGER's core mission. Enabling operation in the denied environment opens up new possible flight trajectories that result in significant improvements in time to localization of the RFI source. This paper presents the design, development, and flight testing of a vision based navigation system for JAGER. The resulting navigation performance is demonstrated to enable improvements in the RFI localization performance through enabling flight trajectories that take JAGER closer to the RFI source into a potentially GNSS denied environment. To quantify the improvements to the RFI localization, this paper uses the existing system's strategy of maintaining a necessary standoff distance to an interferer to execute the mission with a GNSS position throughout the flight as a baseline. Against this baseline, this paper demonstrates the improvements possible through the use of new trajectories that bring the vehicle closer to the interferer.

The navigation system is built around the use of a downward facing infrared (IR) camera and the use of optical flow to measure the velocity of the vehicle in flight. These velocity measurements are used in an extended Kalman filter (EKF) that estimates the 2D position and 2D velocity of the vehicle throughout the flight. Flight tests of the system demonstrate an ability to measure the velocity with noise of 0.7m/s resulting in a drift rate of the estimated position of 0.4% of distance traveled. This level of navigation performance enables the separation of the navigation and localization algorithms, enabling the use of two different filters for navigation and localization.

A brief analysis of the effect of the noise in the velocity measurement on the navigation and localization systems is also presented. It is shown that as the noise increases above 1m/s, the localization results are no longer improved with the new trajectories taking JAGER into the GNSS denied environment. Therefore, in those cases, to combat the drift in the position estimate due to the use of velocity only measurements, this paper briefly explores the use of a simultaneous localization and mapping (SLAM) framework to use both the velocity and bearing measurements to the RFI source to simultaneously estimate the vehicle's position and the source's position. In simulation, this paper shows that the inclusion of bearing measurements can cap the position drift of the vehicle's estimate and, with low noise bearing measurements, can provide improvements to the localization system in cases of high velocity measurement noise.

INTRODUCTION

JAGER's core mission is to localize the source of an interferer. Extending the operational environment from only being outside of any GNSS denied environment to being inside the denied environment will enable the use of better trajectories for localization, improving the core mission for JAGER. Therefore, a self-contained navigation system to estimate the position of the vehicle throughout the duration of the flight has been designed and tested.

This paper is broken down into three sections: system design, navigation results, and localization results. In the system design section, the design of the system and approach to solving the navigation problem is described. Each of the results section shows a combination of flight test and Monte Carlo simulation results of localization missions with JAGER in a mix of environments with and without GNSS.

Existing System

The RFI localization system on JAGER is built on the use of a direction finding antenna (beam steering or directional) to provide bearing measurements to the RFI source at a rate of 3Hz and has been demonstrated to be capable of localizing the source of interference when JAGER has a GNSS based position solution throughout the flight [2]. Previous work has demonstrated JAGER's capability of maintaining a standoff distance to a GNSS interferer such that the vehicle was beyond the effective range of the interferer but bearing measurements to the interferer were still possible [3]. This result enables a localization strategy that requires JAGER to circle around the interferer, maintaining the necessary standoff distance, while making bearing measurements.

For example, for a scenario with an interferer at a distance of 1km away from the vehicle's initial position that has a range of influence that is less than 1km, a standoff flight path would look as shown in Figure 1. For this case, it would take the full 20 minute flight duration of JAGER's typical cruise speed of 5m/s to fly a near full circle around the source.

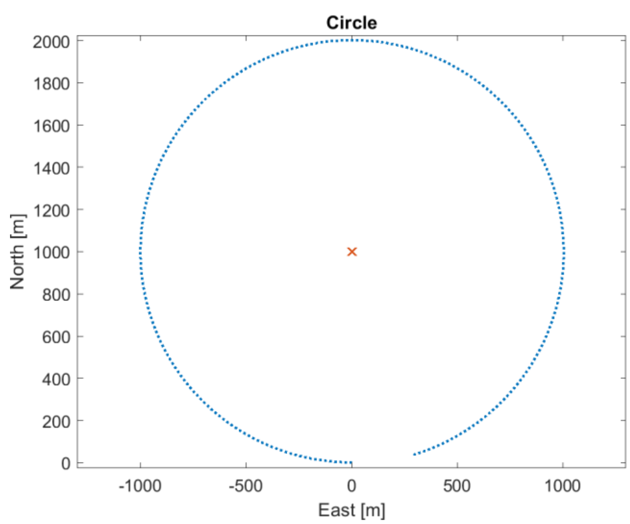

Figure 1: example flight path for standoff strategy

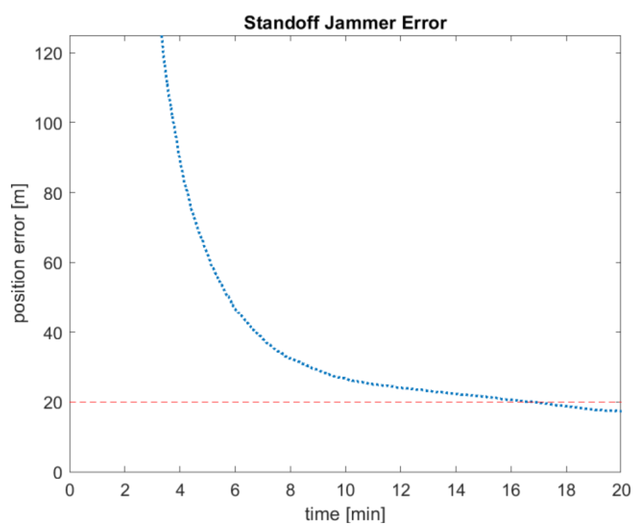

Figure 2: position error of jammer's estimated location throughout standoff flight

Figure 2 shows the resulting performance of the existing bearing only localization performance over time. This example standoff strategy result is used as a baseline for comparing improvements in the localization performance enabled by the navigation system. Figure 2 also shows a 20m error threshold that will be the target threshold for this scenario.

Improved Trajectories

The key element that can be leveraged by creating a navigation system capable of GNSS denied navigation is the ability to get closer to the interferer. For bearing only measurements, both proximity and angular distance traveled around the source are important factors that determine the time to localization. The trajectories shown in Figure 3 demonstrate other possible, easily flown trajectories around the target that satisfy both getting closer to the interferer and increase the angular distance traveled in a given amount of time. For all of these trajectories, the path is chosen by flying a certain angle off of the last measured bearing or the bearing to the current estimated location of the interferer. Immediately, two things can be noticed: first, both of these trajectories get closer to the interferer, and second, the angular speed around the interferer has increased with these trajectories, meaning that, without changing the velocity of the vehicle, the vehicle is tracing out angles around the interferer more quickly, due to the proximity to the interferer. The trajectories also assume a minimum standoff distance to the interferer as the antennas used by JAGER has limited observability when nearly overhead the interference source. It is important to note that these paths are still not optimal trajectories as they are predefined methodologies and are not dynamically computed to solve for an optimal move at every time step given the current state. However, these trajectories are as simple to fly as the circle trajectory and are better than the circle trajectory in terms of proximity and angular distance traveled. These trajectories presented are all spiral trajectories as they are best flown using an angle from the bearing to the current estimated location of the interferer. The localization algorithm uses bearing only measurements with a delayed initialization that typically requires JAGER to fly on average 30 degrees around the interferer to initialize an estimate for the interferer's location, therefore a spiraled approach allows JAGER to travel at least 30 degrees around the interferer before reaching the minimum possible distance.

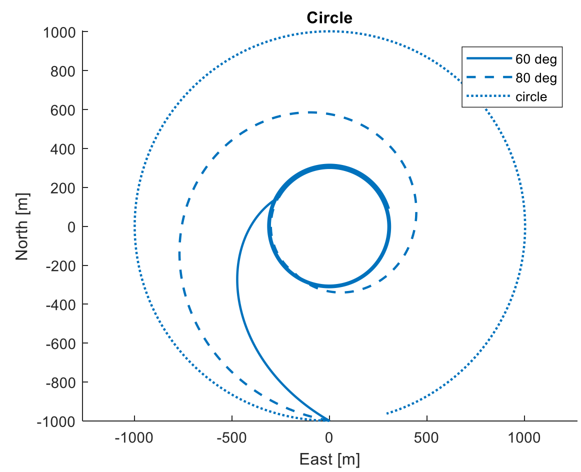

Figure 3: depiction of improved inward spiral trajectories

To illustrate the improvement these trajectories can have on the localization performance, Figure 4 shows the position error in the estimated location of the interferer if JAGER has a GNSS solution throughout the flight. It is immediately noticeable that both new trajectories are superior to the standoff strategy (circle) in both time to the 20m threshold and error in the estimated position of the interferer after 20 minutes. Therefore, while not yet optimal trajectories, it can be seen that these new trajectories can provide tremendous improvements in time to localization.

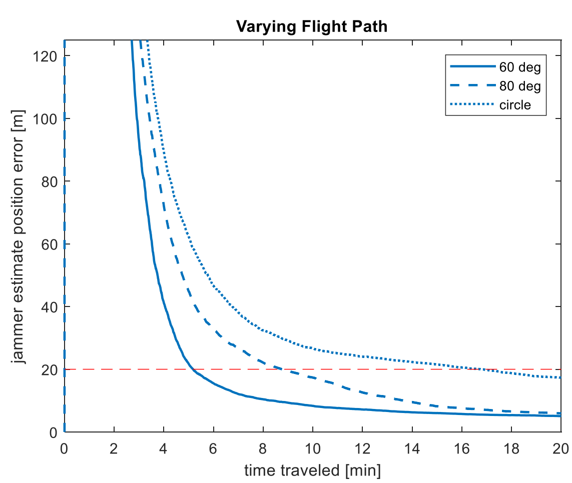

Figure 4: error of the interferer's estimated position throughout the 20 minute flight for each type of trajectory

When it comes to performing the localization mission in a GNSS denied environment, the system will rely solely on velocity measurements. This will result in a drift of JAGER's position estimate and an increase in JAGER's position uncertainty over time. With that in mind, the question becomes whether or not the drift rate is low enough, and the position error is small enough, to be able to execute enough of these trajectories to get the desired localization performance before the error in JAGER's estimated position grows to a point that it no longer helps the localization.

SYSTEM DESIGN

This section of the paper discusses the design of the vision based navigation system. First the sensors being used onboard for both the localization and navigation systems are described, then the process for the flow of information for the visual odometry system is described, and finally the method for evaluation the performance of the navigation system is explained.

Sensors

For the localization system, the key sensor is the electronically beam steered antenna. The electronically beam steered antenna is a custom built, three-element, phased-array antenna [4]. For ease of testing purposes, the current version of the antenna is tuned for 2.4GHz, however a version for the L1 frequency has been built previously [2] . This sensor is capable of providing bearing observations to an interference source at a rate of at least 3Hz. It is mounted upside down on the underside of JAGER to minimize any loss of signal strength to the interference. The bearing measurements from the sensor will also be evaluated for use in a simultaneous localization and mapping approach to improve the performance of the navigation system depending on the noise in the velocity measurements.

For the navigation system, three components on mounted on JAGER: a FLIR Systems Boson IR camera with 4.9mm lens and resolution of 640x512, a gimbal for the camera, and a Lightware SF 11/C 1D LIDAR sensor. The IR camera can provide video data at a frame rate of up to 60Hz, however for the testing done in this paper, that rate was limited to 30Hz. The camera is mounted on a 2-axis gimbal to mechanically remove noise from attitude and vibrations that would otherwise have to be accounted for in the processing of the imagery. The 1D LIDAR provides a measurement of the vehicle's height above the terrain with high precision and accuracy. The combination of these sensors and mounting hardware enable the monocular visual odometry approach used for navigation.

Monocular Visual Odometry

Monocular visual odometry is the technique of estimating position of a vehicle given velocity measurements based on a single camera. At a high level, visual odometry is comprised of the following step: capture images, detect features in the images, make optical flow measurements, convert the flow to world velocity measurements, and estimate the position of the vehicle using a filtering approach [5].

The specific implementation of the visual odometry system on JAGER is outlined in Figure 5. First, each image taken by the camera is stamped with the height information from the LIDAR. Then a Shi-Tomasi corner detector is used on each image to extract a set of up to 500 features to be tracked using Lucas-Kanade optical flow. Both the feature extraction and the optical

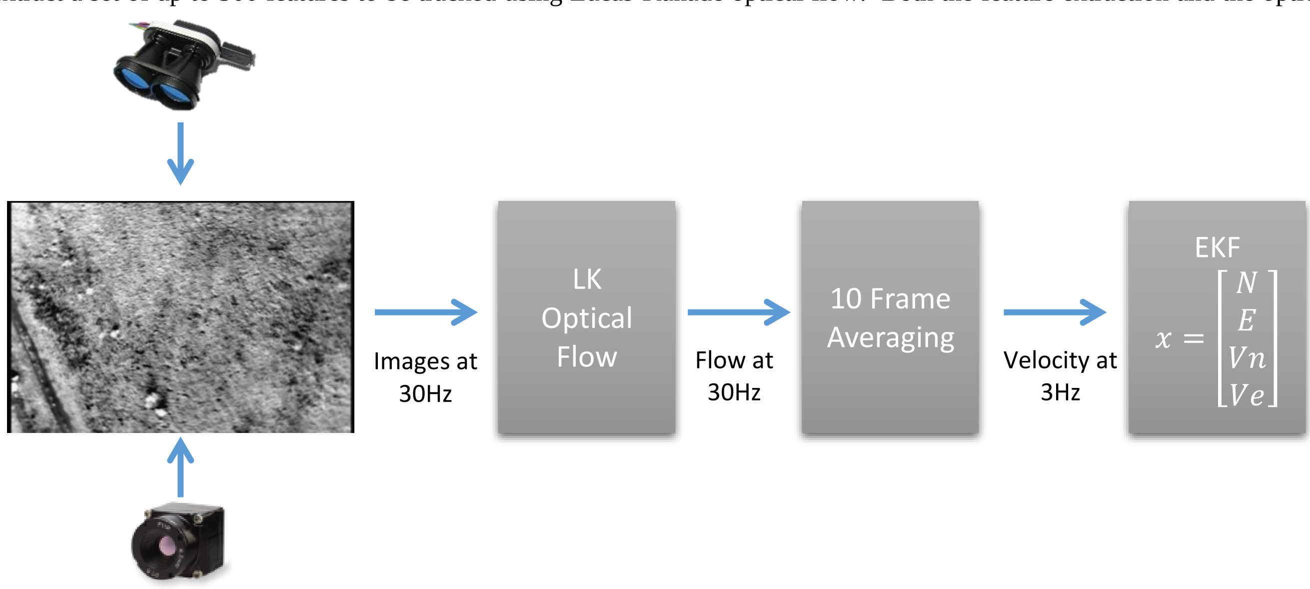

Figure 5: visual odometry pipeline implemented onboard JAGER

flow are implemented using the OpenCV library [6]. The feature detection is implemented with 'goodFeaturesToTrack' which implements a Shi-Tomasi corner detector [7], and the optical flow is implemented with 'calcOpticalFlowPyrLK' which implements an iterative Lucas-Kanade optical flow with pyramids [8]. The optical flow measurements are very noisy, so before using the velocity measurements in the position estimation extended Kalman filter (EKF) the results of the speed as measured by the optical flow are averaged across 10 frames. Finally, these velocity measurements are used in an EKF that estimates the 2D position and 2D velocity of JAGER. The altitude is held accurately with a combination of the onboard barometer and LIDAR and therefore is not estimated. The EKF uses the optical flow determined velocity as a measurement and uses a constant velocity motion model in the prediction step. Additionally, the EKF uses a control input of the desired change in the velocity vector that is being commanded to execute the curved trajectories being flown for the localization missions.

Evaluation

While the standoff strategy has been proven to be possible, it is sensitive to a variety of factors, such as the gain of the antenna on JAGER, the power of the jammer, and the initial distance from the jammer. With a 12dB directional antenna a standoff distance of 1km to a 0.5W jammer was possible, however, the three element antenna has a maximum gain of only 6dB resulting in much smaller maximum distance possible [3]. Furthermore, the jammer may vary its power output which makes the standoff strategy difficult without a large detection gain. Suffice it to say, while the standoff strategy is useful, being able to navigate in a GNSS denied environment makes the system robust to different scenarios or jamming strategies. Therefore the chosen evaluation of the GNSS denied navigation system is by assessing the possible improvements and increased robustness of the localization mission.

NAVIGATION RESULTS

This section presents the results of flight test and simulation data on the optical flow velocity measurements and the full visual odometry. The results are broken down into two section to better highlight the design choices of the information flow and to be able to examine the impact of increased measurement noise on the visual odometry system as a whole. A simulation model for the velocity measurements was created and simulation results are presented to both validate the model and examine the effects of velocity measurement noise on the position estimation performance.

Flight Test Results

With a visual odometry system, it is important to eliminate outliers and reduce noise from the measurements. To reduce noise, a 10 frame averaging of the measurements is employed. Figure 6 and Figure 7 show the magnitude of the velocity measurements before and after the 10 frame averaging is performed for a small stretch of a flight test. Before the averaging, the noise was on the order of 2.5m/s and after the averaging the noise had a standard deviation of 0.7m/s.

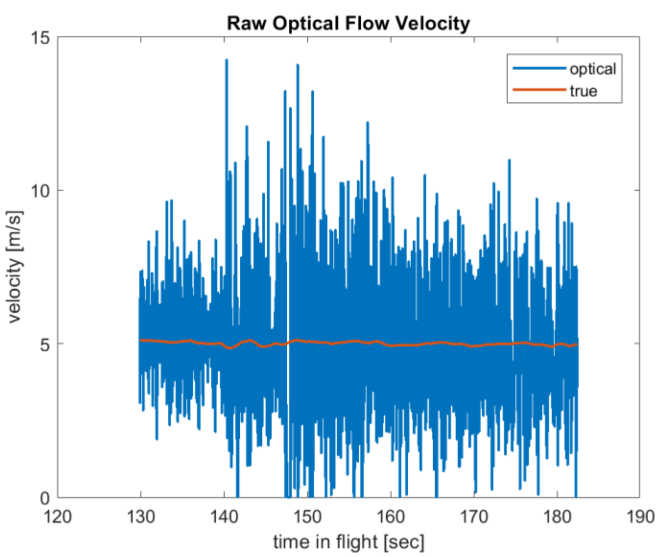

Figure 6: raw optical flow velocity measurements

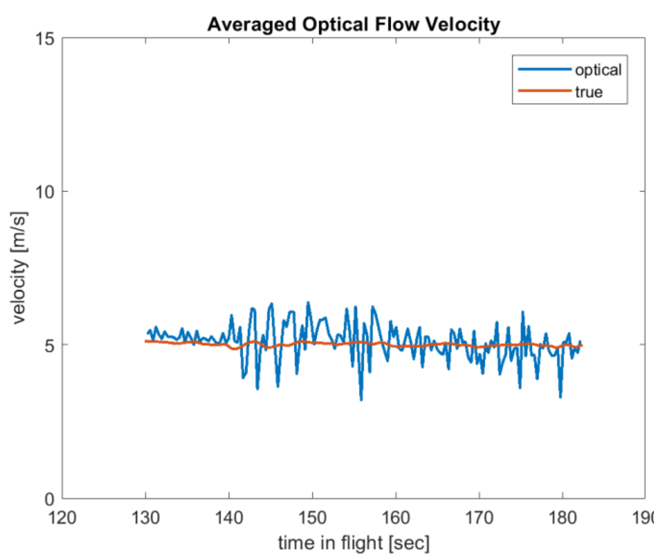

Figure 7: optical flow measurements after 10 frame averaging

For the full test flight, shown in Figure 9, the measured velocity can be seen in Figure 8. Throughout the entire flight, the optical flow was capable of measuring the velocity accurately, resulting in an ability to model the measurement noise as a Gaussian with zero mean and a standard deviation of 0.7m/s.

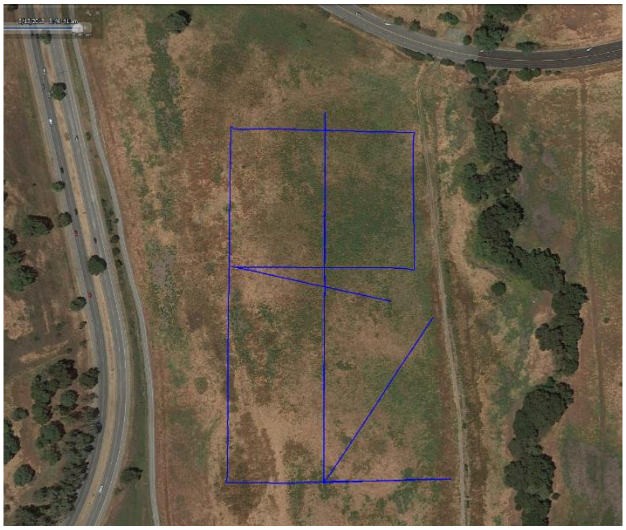

Figure 9: GPS position of test flight path

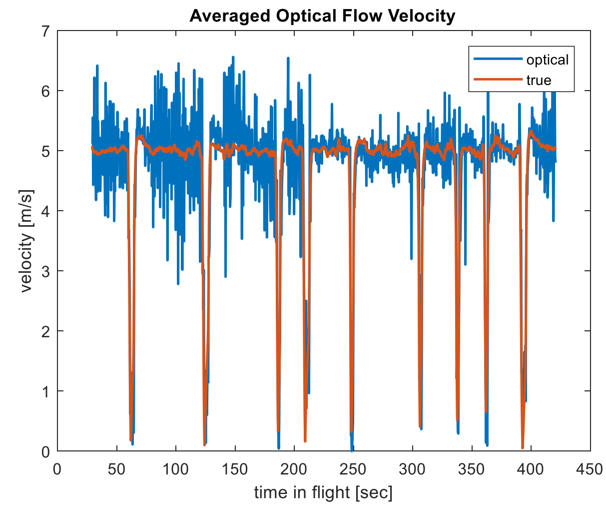

Figure 8: true and measured velocity throughout the test flight

For the same flight, the EKF was run using only the velocity measurements and a known initial position of the vehicle. Running the EKF resulted in the estimated position displayed as the red track in Figure 10, next to the true position in the blue track. As expected, the estimated position does drift over the time of the flight. The 2D position error throughout the flight, comparing the estimated position to the GPS position, can be seen in Figure 11. Once again a general drift trend can be noticed, though it is a obscured by several large jumps in the error. These jumps are a result of the constant velocity assumption in the motion model that breaks down at each of the corners of the pattern, sometimes resulting in smaller errors, other times resulting in larger errors.

Overall, for the duration of the 7.5 minute flight, JAGER flew a total distance of 1.8km and maintained a constant velocity of 5m/s through each of the straight sections of the flight. Throughout this flight, the largest error was ~9m, with the final position

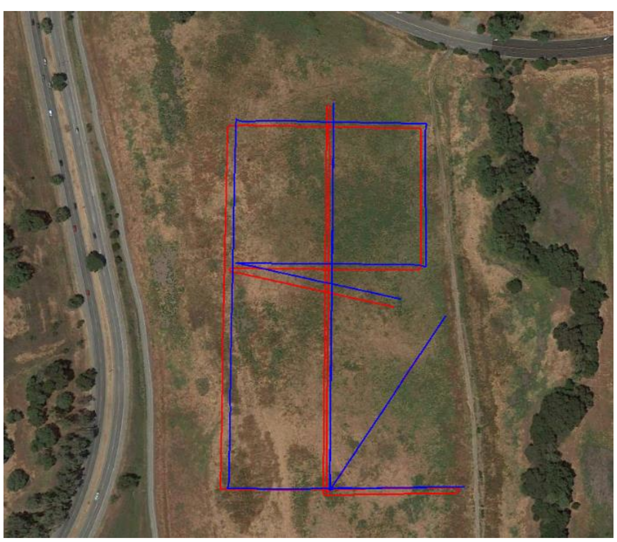

Figure 10: GPS (blue) and estimated (red) position throughout test flight

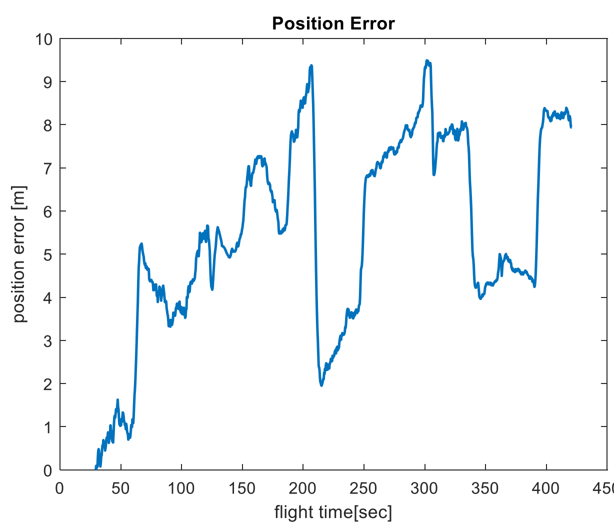

Figure 11: estimated vehicle position error throughout the test flight

error being ~8m, or 0.4% of distance traveled. This level of performance from a visual odometry system is on par with similar techniques implemented on regular vision cameras today [5].

Simulation Results

Due to the limited size of the flight space available and larger distances desired for the localization mission scenarios, a simulation environment was set up to match the performance of the real world flights. This simulation environment uses a velocity model and vehicle model based on the results of flight test data. To validate the models, a set of 1000 Monte Carlo simulations were run on the flight test flight path yielding similar results.

To evaluate the impact of noise in the optical flow velocity measurements on the EKF's position estimates, another set of 1000 Monte Carlo simulations were run on the standoff strategy circle flight with a radius of 1km. Figure 12 shows the vehicle position error results for varying levels of velocity noise (ranging from the flight test result of 0.7m/s to a much noisier 1.5m/s) over the full 20 minute flight capability of JAGER at a flight speed of 5m/s. As expected from velocity only measurements, an increase in the noise of the velocity measurements result in an increase in the drift of the filter. In addition to the increased drift, it is important to also note that the initial slope of the error increases as the velocity noise increases.

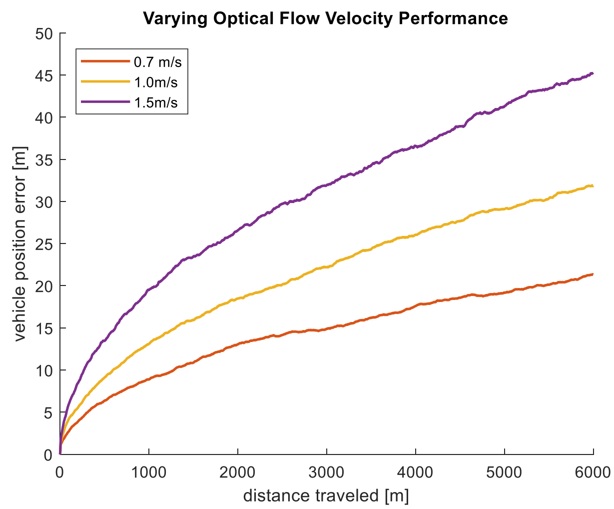

Figure 12: estimated vehicle position error in simulated flights with varying velocity measurement performance

LOCALIZATION RESULTS

For localization, the current algorithm is designed around a two-step approach: first a Gaussian sum filter (GSF) is used to initialize the estimate of the RFI source and then an EKF for estimating the 2D location of the source. This two-step approach is used as the system relies on bearing only measurements and the current implementation uses a delayed initialization technique, where the initialization is done using a Gaussian Sum Filter (GSF) to approximate the uncertainty from a bearing only measurement [9]. Once initialized, an EKF based on the highest weighted filter in the GSF is used for continuing the localization. Other filters are possible (e.g. a particle filter), but that is beyond the scope of this paper.

This section presents Monte Carlo simulation results of the localization performance in a completely GNSS denied environment for the scenario of an interferer that is 1km away from JAGER's initial position. Once again, all the models used in the simulation environment (velocity, bearing measurement and vehicle motion) are based on flight test data. For each scenario simulated, 1000 Monte Carlo simulations were performed to generate the results presented. It is important to note that in all the simulation results presented, the only information being used throughout the flight is the initial position of JAGER, the velocity measurements, and bearing measurements. Results are shown for each of the three different trajectories (circle, 80 degree inward, and 60 degree inward), with each trajectory being flown initially based on the most recent bearing measurement and then, once an estimate is initialized, on the bearing to the current estimated position of the interferer. Therefore, the resulting trajectories are not as smooth as those depicted in Figure 3, however for every simulation run, JAGER is successfully able to circle around the interferer without significantly violating the minimum approach distance.

This section is broken into two parts: first results are presented for the case of separating the navigation and localization systems and second, results are presented for a SLAM approach to the problem.

Localization with Separate Navigation System

Here the results presented assume the visual odometry performance seen in flight testing. Therefore the navigation system is separate of the localization system, with the localization system using the bearing measurements to the interferer, the current position estimate for JAGER for the measurement, and the JAGER's position uncertainty.

Figure 13 compares the difference in the localization performance between the case of JAGER maintaining a GNSS position solution throughout the flight and the case of JAGER operating in a GNSS denied environment. In this figure, the error in the estimated position of the interferer over time of the duration of the flight for each of the 3 different trajectories is plotted. These results show that due to the low drift rate of the vehicle position estimation, the system is able to yield interferer localization performances similar to that of the case of finding an interferer in a GNSS available environment. Most importantly, this means that JAGER is capable of realizing a near 3x improvement in time to reaching the 20m error threshold. Looking at the final position error over the full span of the possible flight time, the GNSS denied case does not perform as well as the GNSS available case for each of the trajectories. This is to be expected as the drift of JAGER's position estimate, along with the increased uncertainty, begin to negatively impact the performance of the bearing only measurements. However, it is also important to note the 2 inward spiral trajectories in a GNSS denied environment do perform better than the standoff strategy's circle in a GNSS available environment after the full duration of the flight.

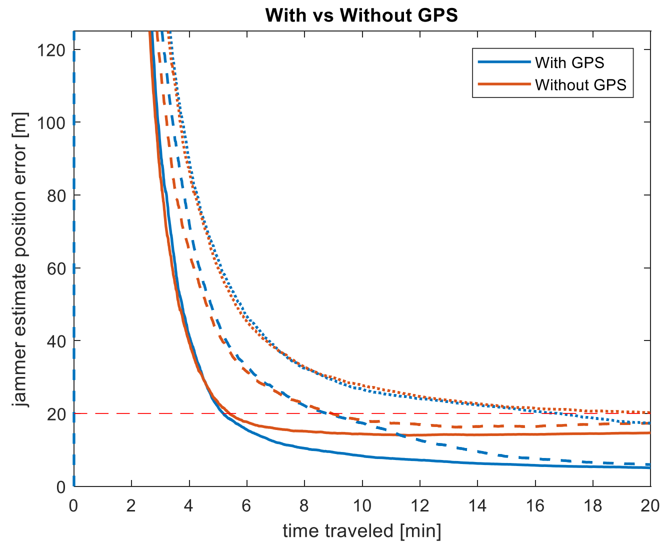

Figure 13: error in the estimated interferer's position in simulation flying the three different trajectories (circle [dot], 80 [dash] and 60 degrees [line]) with and without GPS for an interferer 1km away

The possible improvements to the localization system will also be a function of the initial distance from the interference source. Therefore the same simulations have also been run on scenarios with an interferer at an initial distance of 500m and 1.5km. These results are shown in Figure 15 and Figure 14, respectively. Note that in these cases, to highlight the performance difference between the baseline standoff strategy (circle) and the inward trajectories, the only result shown in a GNSS available environment is the circle trajectory.

In these figures, it can be seen that in every case the 60 degree inward trajectory improves the time to the 20m error threshold. Furthermore, as the initial distance to the interferer increases, the relative benefit of the 60 degree inward path also increases. In the scenario with the interferer 500m away, it can be seen that the relative benefit of the 60 degree inward trajectory may not be worth the loss in performance over the full duration of the flight when compared to the standoff strategy, making the

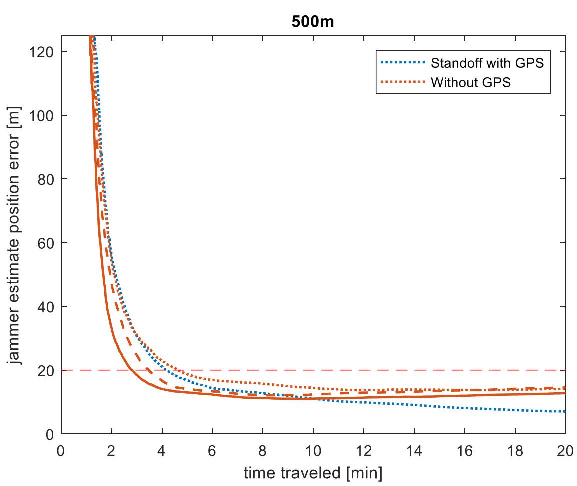

Figure 15: error in interferer's estimated position in simulated flights of all 3 trajectories without GPS compared to standoff strategy at a distance of 500m

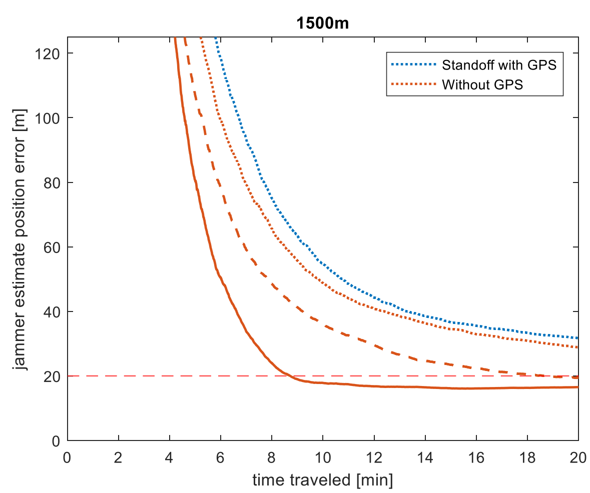

Figure 14: error in interferer's estimated position in simulated flights of all 3 trajectories without GPS compared to standoff strategy at a distance of 1500m

standoff strategy potentially the better strategy in that case. However, for it to be the better strategy, that assumes that JAGER is capable of having a GNSS solution at a distance of 500m from the interferer, which is quite unlikely with the typical GNSS interferer power levels [10]. Therefore, it can be seen that if JAGER is already in a GNSS denied environment at 500m, the best strategy would most likely be the 60 degree inward trajectory over trying to fly outside of the GNSS denied environment to execute the standoff strategy. In the other scenarios, it can be seen that the 60 degree inward trajectory is better in all metrics (time to 20m error and final error after the full 20 minute flight).

Simultaneous Localization and Mapping

In the navigation results presented above, it was seen that as the noise in the velocity measurement increased, both the drift in JAGER's estimated position and the initial drift rate increased. To evaluate these effects on the localization performance, a set of simulations were performed with varying the velocity measurement noise levels. As it was seen that the 60 degree inward trajectory was the best for the 1km scenario, the results presented here focus on flying the 60 degree inward trajectory with an interferer at an initial distance of 1km.

The effects of increasing the velocity measurement noise pose two potential problems to the localization error: first, the final achievable error after the 20 minute flight will get worse due to the higher overall drift rate, and second, the initial error growth may be too fast for the localization filter to ever achieve the 20m error localization target. Both of these effects are shown in Figure 16, where it can be seen that velocity measurements with noise >1.0m/s result in an inability achieve the 20m error target, making the standoff strategy the better strategy in those cases. Therefore, when designing and testing the system, to decouple the navigation and localization filters, the velocity measurements need noise of <1.0m/s in order to attain the benefits possible from the inward trajectories. If velocity measurements with that noise threshold is not possible, the better strategy for localization will be the baseline approach of maintaining a standoff distance to the source large enough to be able to achieve a GNSS position solution for the duration of the localization mission.

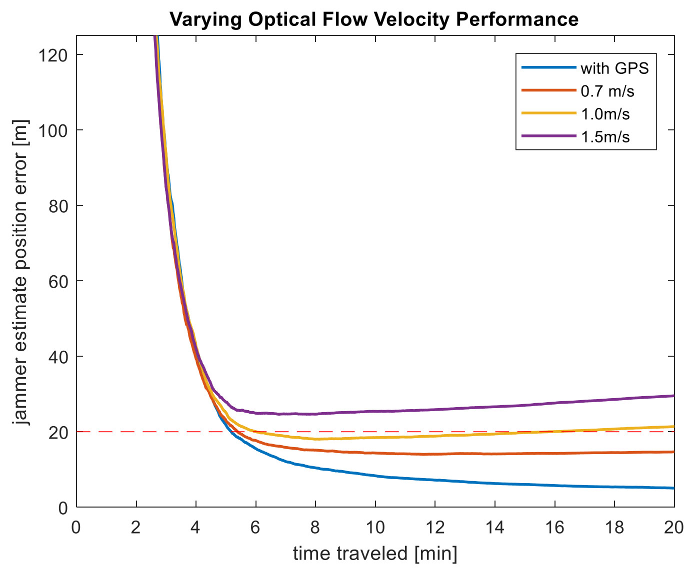

Figure 16: error in interferer's estimated position in simulated 60 degree inward flight trajectory at a distance of 1km with varying velocity measurement noise

Another possible approach is the use of an EKF-SLAM framework to use the velocity and bearing measurements to simultaneously estimate JAGER's position and the interferer's position. Framing the problem in this way allows the bearing measurements to cap the position drift seen with velocity only measurements. Results of this can be seen in Figure 18, where it is seen that the inclusion of bearing measurements to an interferer, even when needing to estimate the position of the interferer simultaneously, caps the maximum position error of the vehicle. In this figure, JAGER's position error is displayed for varying levels of bearing sensor performance (noise levels of 20 degrees, 10 degrees and 5 degrees). However, it can also be seen that the initial slope does not decrease due to the fact that until the interferer's 2D position is initialized, the EKF-SLAM approach does not use the bearing measurements.

Looking at the resulting localization performance in Figure 17, it can be seen that a bearing measurement with noise of <10 degrees can result in the 60 degree inward trajectory once again meeting the 20m localization error target and does so with the significant improvement in time compared to standoff strategy's circular flight path. However, it is also shown that if the sensor noise is too large, the localization performance is actually worse. This is due to the fact that the high initial drift rate means that the initialize phase for the interferer's position takes longer than the 30 degrees of angular travel. In the simulations with the 20 degree bearing measurement noise, several simulations resulted in JAGER not fully circling the interferer, resulting in a significant reduction in the angular distance traveled around the interferer and therefore worse interferer position estimates. These results indicate that while the EKF-SLAM approach can be used to improve both the navigation system and the localization system, it is very sensitive to both the noise in the measurements and the trajectory flown, indicating that more optimal trajectories may be needed to get the best performance from the EKF-SLAM approach.

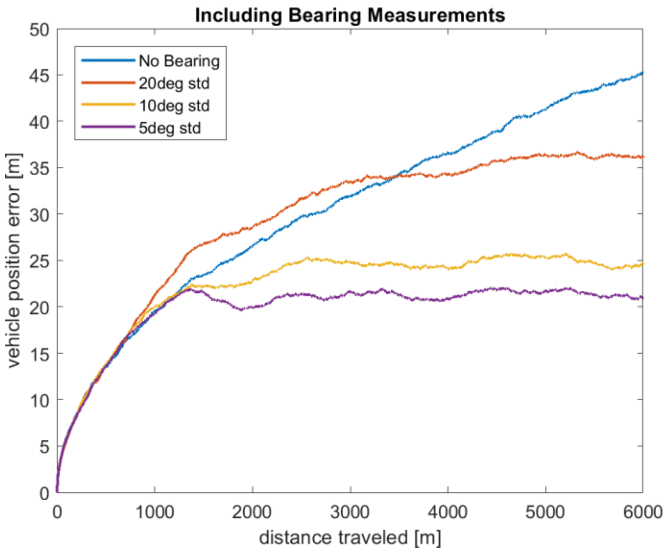

Figure 18: error in the vehicle's estimated position using velocity only and velocity + bearing measurements

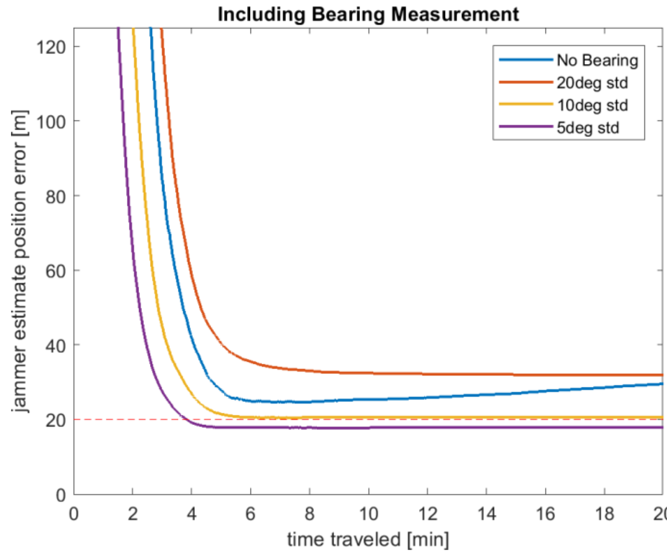

Figure 17: error in interferer's estimated position in simulated 60 degree inward flight trajectory using the SLAM approach

CONCLUSION

This paper has demonstrated the design, development and testing of a visual odometry navigation system to enable JAGER's flight into GNSS denied environments. In flight tests, the optical flow on the IR vision was shown to measure velocity with a noise of 0.7m/s which, when used in an EKF for position estimation, resulted in a drift rate of 0.4% of distance traveled. This navigation performance is both enough to be able to enable a flight into a GNSS denied environment (or through one) and enable better flight trajectories for localization. The ability to fly improved localization trajectories have resulted in a significant improvement in the time to localize an interferer within 20m compared to the baseline standoff strategy.

This paper has also provided a brief sensitivity analysis on the effect of the noise in the velocity measurements on the performance of the navigation and localization systems. It was shown that as the noise increases, separating the navigation and localization problems results in a performance that is worse than the baseline standoff strategy. However, framing the problems as an EKF-SLAM problem with low noise bearing measurements results in capping the drift of the vehicle's position estimate quickly enough to once again enable the improvements in the localization performance over the baseline standoff strategy.

FUTURE WORK

As development of this system continues, one key area of continued improvement is stress testing the vision system in many environments. So far standard, out of the box optical flow algorithms work really well with IR images during the day. At night, previous results have shown a reduction in the total number of features, and distribution of features, so testing the optical flow performance and tuning in those environments are important to provide true robustness to time of day.

The current implementation of the visual odometry system has no step to remove outlier measurements. In the current flight test environments, the number of outliers was very small and did not greatly impact the resulting velocity measurements. However this may not always be the case (e.g. cases with fewer overall features will result in a higher relative percentage of outliers), so work is ongoing to determine the best, light weight, outlier rejection algorithms to be able to minimally impact processing time and improve performance as needed.

The localization algorithm currently uses a prescribed path. While this paper has demonstrated the superiority of the inward spiral path to the circle path, this inward spiral is not necessarily optimal, especially in cases where EKF-SLAM may be necessary. Therefore, methods for determining an optimal trajectory given the current position and uncertainty of the vehicle and interferer and the most recent bearing observations will be explored and evaluating.

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DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or any other person or organization.

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