

Unmanned Aerial System for RFI Localization and GPS Denied Navigation

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ABSTRACT

Radio frequency interference (RFI) has and continues to be a challenge faced by the aviation industry today. Short transient events, or longer duration interference, often caused by unintentional radiators in the vicinity of airports, all have the possibility to pose a risk to the industry, especially for systems such as GPS. In an effort to minimize the impact RFI sources, an unmanned aerial system (UAS) built on a multirotor platform, known as JAGER (Jammer Acquisition with GPS Exploration and Reconnaissance), is continuing to be developed as a means of autonomously and rapidly localizing GPS RFI.

Three main elements make up the system: sensing and measurement, path planning, and navigation. This paper discusses the continued improvements in the sensing and navigation elements of JAGER. For sensing, a three-element beam steering antenna has been developed to enable electronic rotation replacing the need for physically rotating the vehicle. For navigation, an infrared (IR) vision system has been developed to enable real time velocity measurements of the vehicle.

JAGER's approach to the problem through using bearing information for localization of a single fixed jammer has been successfully demonstrated using a single directional antenna and the vehicle's ability to rotate as the sensing system. In order to greatly increase the rate of bearing measurements and remove the need for a physical rotation, a three-element beam steering antenna has been developed, enabling the electronic rotation of the antenna allowing for a near 100x improvement in the observation rate (from about 30 seconds for a rotation to about 0.35 seconds for a rotation). With a near continuous observation of bearing, new techniques for source localization and navigation are enabled. Of great interest is the sensor's ability to enable simultaneously localizing the source of the RFI and the position of the vehicle in a GPS denied environment. This paper describes the development of the beam steering antenna and the IR vision system that will enable the use of simultaneous localization and mapping techniques to solve the RFI localization and navigation problem. Both systems are tested in several real world environments with commercial GPS jamming equipment and results are discussed.

As the system is intended to localize the source of GPS interference, JAGER needs to be capable of navigating in a GPS denied environment. To augment the information from the RFI source, an infrared (IR) camera system is used to measure the velocity of the vehicle during flight. This paper discusses the use and performance of using optical flow techniques of IR imagery to obtain velocity measurements. Live day and night exercise results are presented and discussed.

INTRODUCTION

As GNSS is used more ubiquitously, there is an increased need to protect, toughen, and augment GNSS to maintain its reliable use. To assist with protecting users of GNSS, this research focuses on minimizing the impact an RFI source can have on nearby GNSS systems. Our approach is to develop a system capable of localizing the source as quickly as possible to minimize the duration of impact the source may have on GNSS systems. The Stanford GPS Laboratory developed JAGER, a bespoke research vehicle based on a commercially available octocopter platform built to test navigation and localization packages to quickly localize source of GNSS interference. To achieve this, JAGER is designed to autonomously localize the RFI source using bearing only measurements in a potentially GPS denied environment. The end goal for JAGER is to provide both a GPS location of the RFI source and an overhead image of the location in a timely manner. The mission duration is a function of the distance to the source, however, the target is to complete the mission within the typical battery capacity of about 20-30 minutes, which dictates the desired performance of the localization and navigation systems.

JAGER is designed with three core systems: sensing and measurement, path planning, and navigation. Each of these systems work together to successfully localize an RFI source while navigating in a GPS denied environment.

Previous Work

The previous version of JAGER used a single directional antenna and leveraged the multirotor's capability to rotate to make bearing observations. This method was demonstrated to be successfully able to localize the source, however all the observations were made using a GNSS position solution [1]. Live trail exercises also demonstrated the range capabilities of the directional antenna. The 12dBi antenna was capable of detecting, and making bearing observations of, a 0.5W jammer at ranges of at least 800 meters, well outside of the jammer's effective range of about 500 meters [1]. This long range capability enabled JAGER to successfully localize the source of a commercial GPS jammer while still maintaining a GNSS based solution, demonstrating the performance of the localization algorithms developed. Essentially, JAGER can maintain a standoff distance where it can still track GPS signals while still being able to measure the jamming.

For navigation, the goal was to use two main elements: visual odometry and the many signals of opportunity that may be found near an airport. Since this original goal, improvements have been made to JAGER's systems that simplify some of the techniques required for successful localization and navigation.

UPDATED APPROACH

Instead of relying on different signals of opportunity, which may be on different frequencies and have different characteristics from one location to another, the new approach to navigation in a GPS denied environment is to use a guaranteed signal of opportunity, the interference signal source itself. An RFI source is no different than a beacon which can be used for navigation. However, for this to be possible, the bearing observations must occur at a much higher rate, driving the need for the development of an electronically steered antenna, increasing the observation rate from at most once every 30 seconds to almost 3 times a second.

Coupled Problem

Typically, to use a beacon for navigation, the location of the beacon must be known, which is not the case here. However, the problem of localizing the signal source (or mapping the environment) and self-localization at the same time is a common problem known as simultaneous localization and mapping (SLAM). By combining all the observations from the sensors onboard JAGER – bearing, velocity, and IMU data – a SLAM problem can be formed and solved in real time. Once again, this method is only possible with the increased bearing observation rate provided by the development of a beam steering antenna.

Search Strategy

In addition to enabling the use of the signal source for navigation, the increased bearing observation rate enables the use of simpler approaches for path planning. Previous JAGER relied on complex search strategies and localization techniques to get fast localization. Now the near optimal strategy is to fly a circle around the signal source, or even a circular spiral inwards towards the signal source. This simplified path is not just more computationally friendly to ensure real time operations, it also

simplifies the necessary maneuvers JAGER needs to make, increasing the robustness of the visual odometry used in the navigation system, discussed further in the IR Navigation section.

BEAM STEERING ANTENNA

To improve the rate of bearing observations a three element phased array (beam steering) antenna has been developed, called BeaSt [2], shown in Figure 1. BeaSt is comprised of three patch antenna laid out in a triangular grid pattern that are steered with three phase shifters. Using the phase shifters, the beam, or null, can be steered and the power can be measured by the onboard power detector. For a more detailed description of the construction of the board, see [2]. Two different versions of the beam steering antenna have been developed, summarized in Table 1.

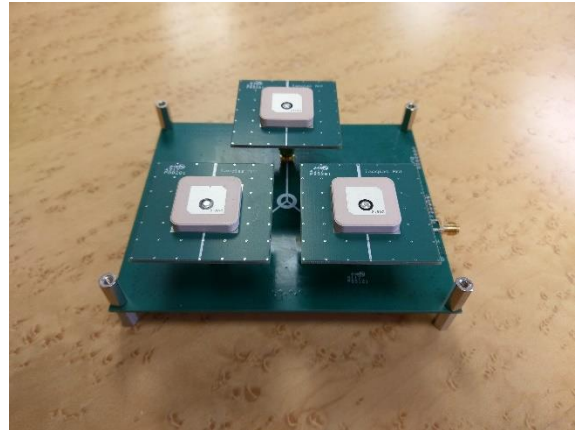


Figure 1: BeaSt v2 board with three patch antennas

Table 1 compares three useful metrics for each of the antennas: the measurement rate, the rotation rate, and the observation rate. The measurement rate is the rate at which the power detector is being read to make signal strength measurements. The rotation rate is the rate at which the antenna is steered, physically for the directional antenna and electronically for the BeaSt versions. Finally, the most important, the observation rate is the rate at which bearing observations are made, which requires a full 360 degree rotation.

Table 1: performance of directional antenna and two version of beam steering antenna

	Measurement Rate [kHz]	Rotation Rate [deg/sec]	Observation Rate [Hz]
Directional Antenna	0.05	12	0.03
BeaSt v1	0.5	500	1.4
BeaSt v2	1000	1000	2.8

The key improvement from the directional antenna to BeaSt is the greatly increased rotation rate, and therefore bearing observation rate. For the directional antenna, the rotation rate is dictated by the rotation rate of the vehicle, while BeaSt's rotation rate is determined by the speed of the phase shifters. In addition to the faster rotation rate, BeaSt also provides a higher density of measurements in a gain pattern as measurements are made at every degree of azimuth, while the directional antenna made measurements at about every 7 degrees, depending on the rotation of the vehicle. With the rotation being dependent on

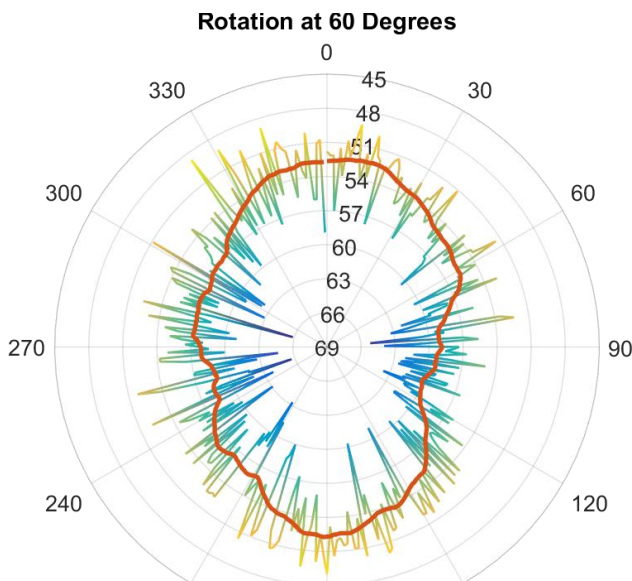


Figure 3: BeaSt v1 raw gain pattern and smoothed pattern

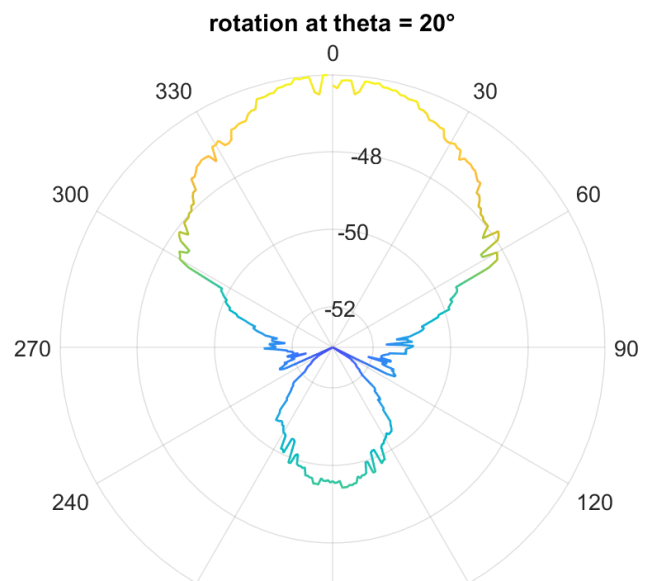


Figure 2: BeaSt v2 gain pattern

the vehicle itself and decoupled from the measurement rate, weather conditions, such as strong winds, could result in a non-constant rotation rate and therefore an uneven density of measurements. This uneven density of measurements can result in errors in bearing if there are not enough measurements to capture the beam's proper peak location.

From BeaSt v1 to BeaSt v2, the major change is the measurement rate, which is several orders of magnitude greater for BeaSt v2. For v1, a single measurement was made at each steered angle which resulted in a very noisy pattern, as shown in Figure 3. The noise seen in the pattern is a result of both white noise on the board and elements in the environment. For v2, 1000 measurements are averaged at each steered angle to help reduce some of the noise in the pattern, as shown in Figure 2. By averaging over the 1000 measurements at each angle, the white noise of the board and the environment noise can be averaged out, resulting in a cleaner pattern.

Note that the steered elevation angle is quite different between the patterns in Figure 2 and Figure 3 which is why there is a second lobe visible in Figure 3. As the steered elevation angle gets larger a larger back lobe forms which is what is being seen, which is an additional challenge posed by an electronically steered antenna that was not present with the directional antenna. This secondary lobe results in a second bearing observation, which is removed by filter used for localization.

When evaluating the performance of BeaSt, there are two key metrics: ability to handle noise and precision in the steering. If the steering can be demonstrated to have similar performance to rotating the physical antenna, then the antenna's performance in localization will be no different than with the directional antenna. Once a gain pattern is produced from the antenna, whether from a rotated directional antenna or a steered electronic beam, the same algorithms are being used to calculate the bearing.

Noise Reduction

Moving from a rotating directional antenna to an electronically steered antenna introduces another potential source for noise: the electronics on the board itself. Reducing the effects of noise in the pattern can greatly reduce errors in determining the bearing to the signal source, therefore the focus from BeaSt v1 to v2 was noise reduction. There are two different types of noise to be considered: board component noise and environment noise.

Analyzing the two different types of noise shows that each type requires a different averaging window, or number of signal strength measurements to make at each steered angle. The power detector used on BeaSt has a bit of white noise which can be seen in the deviation of the averaged signal strength for a variety of different window sizes shown in Figure 4. From here it can be seen that a window size of 50 samples is more than enough to remove most of the effects of the noise.

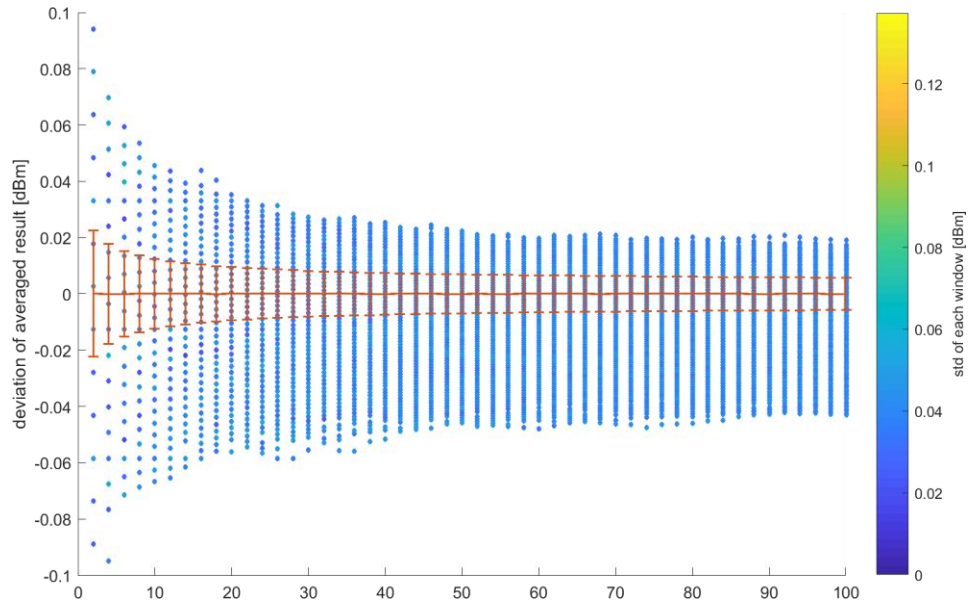


Figure 4: deviation of averaged signal strength for different window sizes

The power detector used on BeaSt has a bit of white noise which can be seen in the deviation of the averaged signal strength for a variety of different window sizes shown in Figure 4. From here it can be seen that a window size of 50 samples is more than enough to remove most of the effects of the noise.

The environment noise is a function of the frequency and environment. Figure 5 shows the impact of the background noise on 2.4GHz in a typical office type environment. Note that BeaSt v2 is built for 2.4GHz for ease of testing, but the same principles and algorithms apply to any other frequency. Notice that since data is being transmitted across nearby WiFi networks, the antenna periodically measures much higher signal strength than expected. This noise is time dependent, therefore in this environment, it is best to average over 1ms, or 1000 samples given the sample rate is 1 Mhz. By analyzing some measurements over time, BeaSt can be configured to determine the appropriate number of samples to average over based on the current environment conditions.

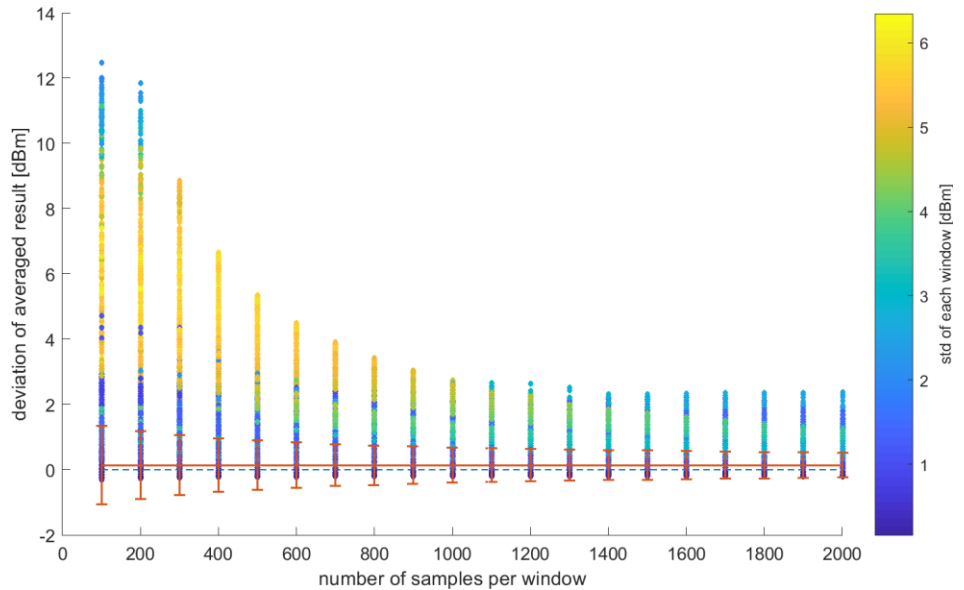


Figure 5: deviation of averaged signal strength for different window sizes in real environment

Steering Performance

If the steering can be demonstrated to have similar performance to rotating the physical directional antenna, the antenna’s performance in localization will be no different than with the directional antenna since the same bearing calculation methods are being used. Therefore it is important to analyze BeaSt’s pointing accuracy. The beam steering board’s performance is driven by two key elements: the geometry and the phase shifters being used to control the phase of each of the elements.

The array is comprised of three patch antenna elements arrayed in a planar triangular grid pattern [2]. When combined in this way, there is a limit on the maximum steerable elevation angle of about 30 degrees, shown in Figure 7. This figure shows that there is a non-linear mapping between the desired elevation angle and the actual resulting elevation angle. This is a limitation of using a small number of patch style antenna elements [3]. The geometry for the most part does not affect the performance of the azimuth angle, shown in Figure 6.

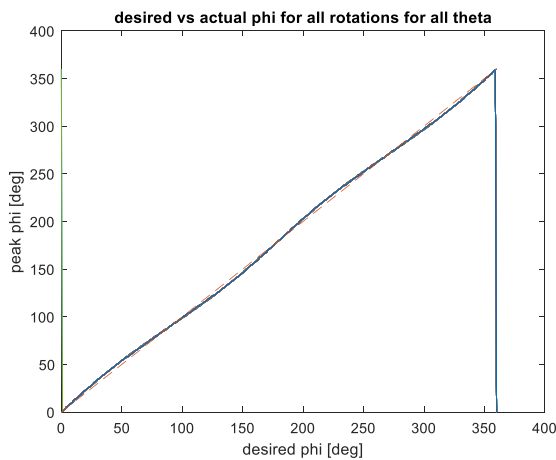


Figure 6: desired vs actual azimuth angle for all steered elevation angles

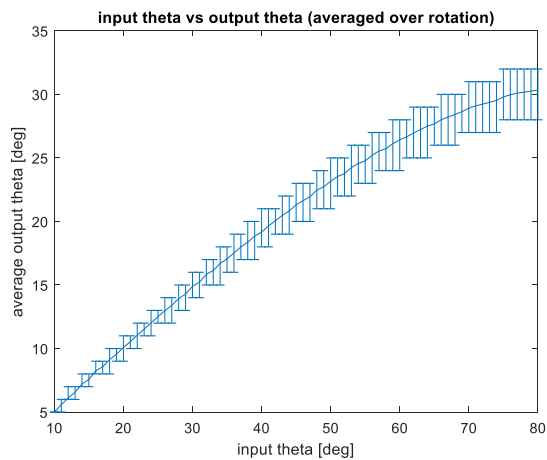


Figure 7: desired vs actual steered elevation angle

To steer the antenna, each element is connected to an 8 bit phase shifter [2]. In order to steer the beam of the antenna to a specific location, defined as (ϕ, θ) , where ϕ is the azimuth angle and θ is the angle off vertical (a spherical coordinate systems), the phase shifter values (ψ_0, ψ_1, ψ_2) are determined as follows for this antenna array:

$$\begin{aligned}\psi_0 &= \pi \sin(\theta) \left(\cos(\phi) + \frac{1}{2} \sin(\phi) \right) \\ \psi_1 &= -\pi \sin(\theta) \left(-\cos(\phi) + \frac{1}{2} \sin(\phi) \right) \\ \psi_2 &= 0\end{aligned}$$

On the board, the phase shifts are set using an 8 bit phase shifter. Each 8 bit phase shifter breaks down the 360 degrees of phase shifts between each antenna element into 256 discrete values, limiting the achievable set of phase shifts and therefore limiting the exact steering angles BeaSt is capable of achieving. The limitation is mostly dictated by the elevation angle, with steering accuracy in azimuth degrading below 10 degrees of elevation and degrading in elevation above about 65 degrees, as shown in Figure 8 and Figure 9.

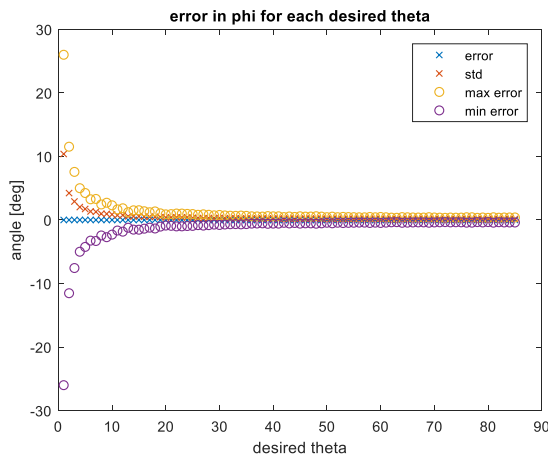


Figure 8: error in desired azimuth angle for all desired elevation angles due to phase shifter rounding

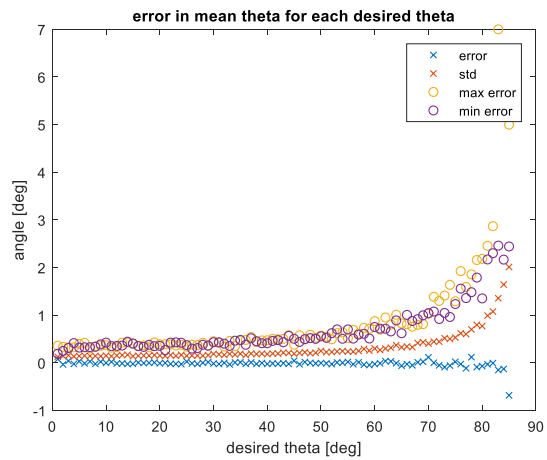


Figure 9: error in desired elevation angle due to phase shifter rounding

After accounting for the mapping from desired to actual steering angles, the limits become about 5 and 28 degrees, respectively. While this may seem limiting, the 80 degree beamwidth of the antenna means that signals on the horizon will still be detected with a steering angle of only 28 degrees, albeit with some loss in gain.

Being able to understand and know the limitations the mission profile to be designed in the most successful possible way. It is important to note than none of these constraints make the mission impossible.

Steering Modes

In addition to being used as a beam steering antenna, this antenna can also be used for null steering, which allows for much better precision on the bearing, since the null is much sharper than the beam, as can be seen in Figure 10 and Figure 11 comparing beam steering and null steering to a source at a bearing of 0 degrees. Furthermore, as JAGER gets closer, or higher, to the signal sources, the null provides elevation information as well as azimuth information. With an estimated ground plane, this effectively provides bearing and distance to the signal source, which can tremendously improve the filter’s accuracy in localization.

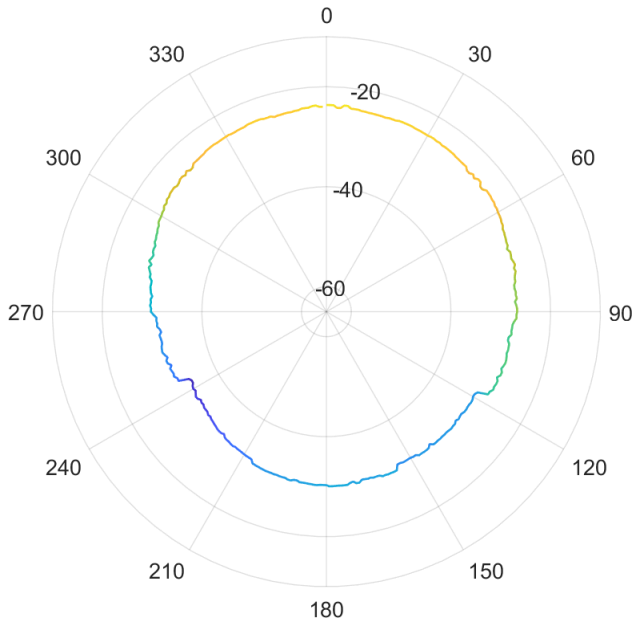


Figure 10: gain pattern of beam steering antenna for source at 0 degrees

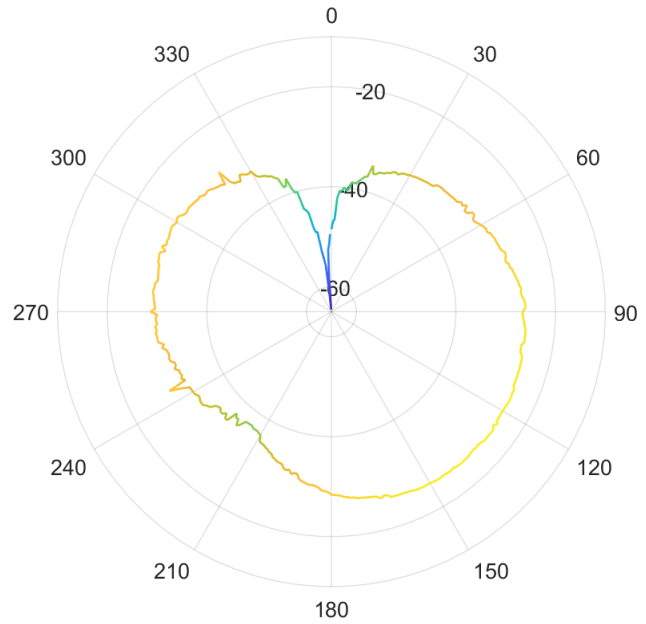


Figure 11: gain pattern of null steering antenna for source at 0 degrees

However, null steering is not as robust to errors in the phase shift, meaning that the accuracy of the null varies considerably even with small distortions between expected and actual steered angles. Therefore null steering can only be used within the steerable limits of 5 degrees and 28 degrees, requiring JAGER to either be close to, or high above, the source location to successfully use null steering to provide elevation information.

INFRARED VISION NAVIGATION

The main sensor used for navigation is a gimbal stabilized, downward facing IR camera used to measure JAGER's velocity in flight. This camera also serve a dual purpose of being able to provide imagery of the source location. The navigation system relies on a technique known as optical flow to determine the velocity, which can then be integrated to get a position estimate. The use of optical flow for position estimation board UAVs has become more common as the cost of computation and image sensors has decreases, as seen in [4] and [5].

Visual Odometry and Optical Flow

Using optical flow, the system can measure the vehicle's velocity based on motion in successive frames in the video and integrate that velocity to get position. Figure 12 and Figure 13 show some sample flow vectors and demonstrate the benefits of using IR. Figure 12 is during the day while Figure 13 is at night, but for both cases there are enough features being detected to generate a flow field for some horizontal motion. Currently the approach being used is to average all of the vectors and use that averaged flow vector to calculate the velocity.

Currently, JAGER uses Lucas-Kanade optical flow to determine the flow vector and velocity of the vehicle. This is a very lightweight (computationally efficient and fast) algorithm that is capable of providing fairly robust optical flow to be used for visual odometry [3]. In addition to the calculation optical flow, different techniques (such as outlier rejection) are being explored to help reduced the noise of the calculated velocity vectors, and therefore improve the velocity only position solution being calculated.

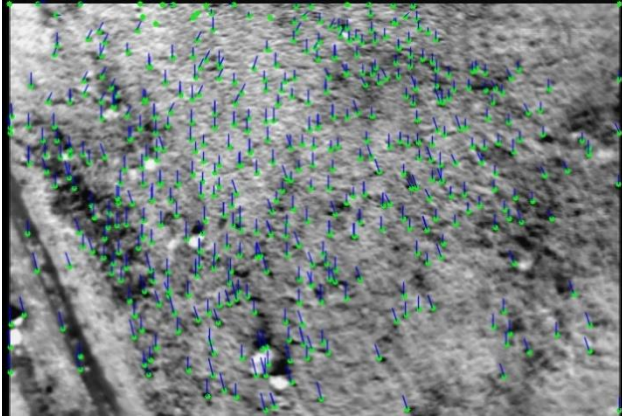


Figure 12: optical flow field during daytime flight

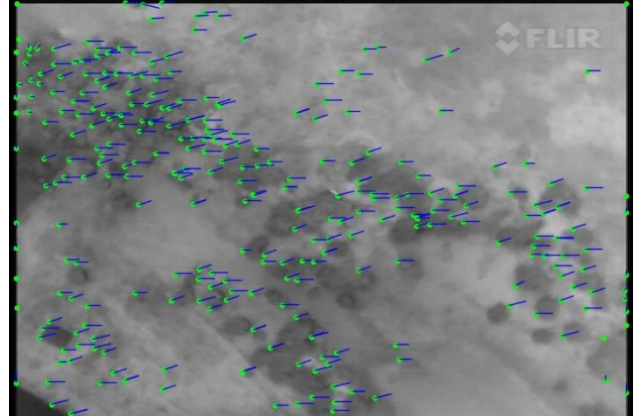


Figure 13: optical flow field during night flight

JAGER's downward facing IR camera is gimbal stabilized to remove effects from attitude changes, leaving three distinct flow types: horizontal, vertical, and rotational. For position estimation, the only flow element of interest is the horizontal velocity, therefore the effects from vertical and rotational motions need to be removed from the flow field. Using the pressure sensor and magnetometer onboard the autopilot, the vertical and rotational motions are estimated and removed from the flow. In addition to using these sensors, the simplified flight path requirement for localization allows JAGER to fly with additional constraints, such as constant heading, constant velocity, constant altitude, and a smooth path, further improving velocity measurements and therefore position estimates.

Test Results

The IR system was tested in both day and night environments. Here are results from night time tests at Edwards Air Force Base. In these tests, the vehicle was flown to maintain a constant altitude (using the onboard pressure sensor) and was flown with a variety of different velocities while executing a square box pattern. It will be seen that the square box pattern is not the easiest for the optical flow method to work on and posed some extra challenges with drift.

Figure 14 and Figure 15 show the results for measuring velocity from the camera, broken down into the north and east components, respectively. One of the major challenges with an IR camera is the need for the camera to periodically recalibrate its sensor due to temperature changes over time. This recalibration process is an internal process to the camera that temporarily pauses the video feed from the camera. This results in brief delays in the imagery resulting in the spikes seen in the velocity estimates. A filter is being developed to reduce the noise caused by that event to get a cleaner velocity measurement.

In Figure 14 and Figure 15, there are also some periods where the velocity is not being calculated; these are periods of time that additional information from either the pressure sensor or magnetometer must be used to remove excessive vertical and rotational motion.

To get the position estimate, the velocity measurements are integrated and result in an estimate as shown in Figure 16. With just straight integration, the position errors are about 10% of distance traveled, leading to the need for techniques to improve the position estimate. Note that during the straight segments, able to do fairly well with

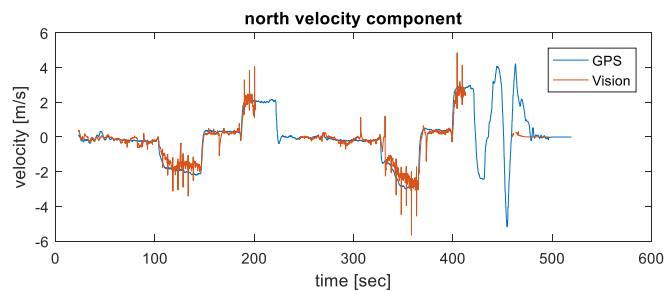


Figure 14: north velocity component, GPS and vision based

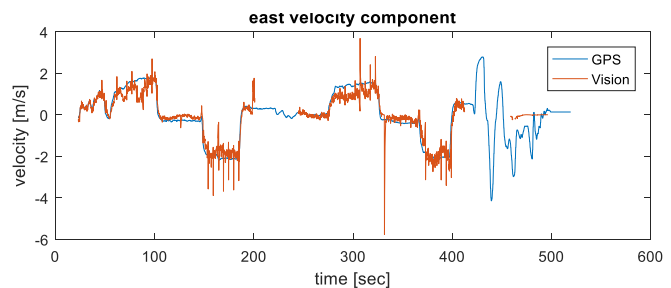


Figure 15: east velocity component, GPS and vision based

the position estimate. One of the biggest challenges were the sharp corners taken, where JAGER was standing still at each corner before changing direction. The vehicle's heading was not altered, but a short pause was taken at each corner, resulting in large error growth at each corner.

Visual odometry, even coupled with inertial measurements, will always drift over time. Techniques can be used to minimize that drift as much as possible such as improved velocity estimates or the use of external information, such as bearing to a signal source. The high rate of bearing observations from the beam steering antenna enables the use of that information to help correct for the drift in the position solution calculated by the visual odometry.

CONCLUSION

The development of a three element beam steering antenna onboard will greatly improve the localization and navigation performance of JAGER. The reduced noise in the beam steering antenna compared to previous versions greatly improves the bearing accuracy, bringing it on par with the previous directional antenna. With each of the core system elements being near complete, JAGER needs to undergo full system testing and then all is done.

For navigation in a GPS denied environment, off the shelf optical flow techniques have demonstrated to be capable of being used to measure velocity in both day and night environments with the IR camera. The position estimate through direct integration of the velocity resulted in a higher amount of drift than desired due to noise in the velocity measurements. Going forward, several techniques are being explored to reduce the noise in the velocity measurements. Additionally, the bearing observations to the signal source will be integrated into the navigation system in order to use all the information available to reduce the drift in the position solution.

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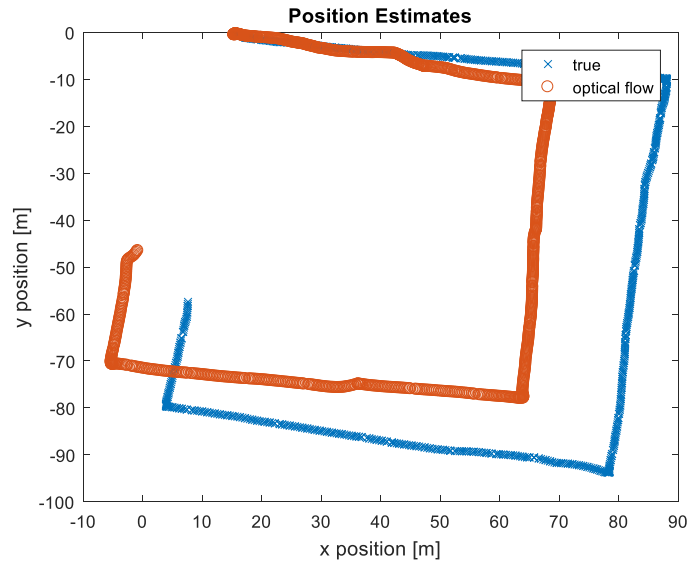


Figure 16: estimated and GPS position of JAGER during box flight

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