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Vision Based Control for Fixed Wing UAVs Inspecting Locally Linear Infrastructure using Skid-to-Turn Maneuvers

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Abstract The following paper proposes a novel application of Skid-to-Turn maneuvers for fixed wing Unmanned Aerial Vehicles (UAVs) inspecting locally linear infrastructure. Fixed wing UAVs, following the design of manned aircraft, traditionally employ Bank-to-Turn maneuvers to change heading and thus direction of travel. Commonly overlooked is the effect these maneuvers have on downward facing body fixed sensors, which as a result of bank, point away from the feature during turns. By adopting Skid-to-Turn maneuvers, the aircraft is able change heading whilst maintaining wings level flight, thus allowing body fixed sensors to maintain a downward facing orientation. Eliminating roll also helps to improve data quality, as sensors are no longer subjected to the swinging motion induced as they pivot about an axis perpendicular to their line of sight. Traditional tracking controllers that apply an indirect approach of capturing ground based data by flying directly overhead can also see the feature off center due to steady state pitch and roll required to stay on course. An Image Based Visual Servo controller is developed to address this issue, allowing features to be directly tracked within the image plane. Performance of the proposed controller is tested against that of a Bank-to-Turn tracking controller driven by GPS derived cross track error in a simulation environment developed to simulate the field of view of a body fixed camera.

Keywords Image Based Visual Servoing · Guidance and Control · Fixed Wing UAVs

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1 Introduction

Recent years have seen a steady increase in the use of Unmanned Aerial Vehicles (UAVs) in civilian applications, particularly those involving inspection and surveillance [1,8]. In many of these roles, fixed wing platforms are chosen for their endurance, range and payload capabilities, however are faced with a challenge when attempting to follow straight ground based features as the platform is unable to directly generate a lateral force required to correct for cross track error. Over the past two decades a number of controllers have come forth seeking to address this issue, minimizing the time taken to acquire a desired track [4,9].

Commonly overlooked by these controllers however, is the effect maneuvers have on onboard sensors. Even though the primary objective of these systems is to collect data over a target, aggressive roll angles and sharp bank maneuvers are employed to rapidly converge with a desired track, potentially causing motion blur and features to leave the field of view (FOV). Steady state conditions can also have undesired effects, as residual pitch and roll angles maintained while the aircraft is over the feature can point the principal axis of sensors away from the target. Of those controllers that do recognize this problem, typically one of two approaches is taken; compensation through a gimbaled sensor mount or through the limited use of maneuvers.

Stolle and Rysdyk develop an algorithm that generates path guidance and synchronous angle commands for a pan and tilt camera to observe a ground based targets [11,12]. The disadvantage with gimbaled cameras is the limited range of rotation and thus compensation available. This point is acknowledged by the authors and compensated by defining maneuvers to maximize target exposure. Holt and Beard also employ a gimbaled camera, however present a proportional navigation solution based on a Skid-to-Turn (STT) kinematic model mapped to a Bank-to-Turn (BTT) Miniature Aerial Vehicle (MAV) with a single axis gimbaled camera [5]. The main problem with these solutions is that rather than removing the unwanted motion, motion is compensated. A far more desirable solution is too remove unnecessary motion altogether, thus avoiding the additional weight and complexity of a gimbaled sensor mount.

Egbert and Beard take this approach and introduce roll constraints given the altitude of their BTT MAV in an attempt to maintain the footprint of the strap down camera over the pathway [3]. Although an effective solution for BTT only MAV and UAVs, it introduces an unwanted trade-off between altitude and turn radius. In addition, the effect of roll on sensors is not addressed. Rathinam et al. take a vision based approach, using visual feedback to locate and update the ground coordinates of the feature being tracked [10]. This information however is not used to directly maintain the feature in the image plane, rather to update the path required to fly over the feature.

The following paper proposes a novel use of Skid-to-Turn (STT) maneuvers for fixed wing UAVs to reduce unwanted motion and maintain the FOV of downward facing, body fixed sensors whilst tracking linear infrastructure. An Image Based Visual Servo (IBVS) Controller is implemented to directly track features in the image plane thus account for inaccuracies in infrastructure location and robustness in camera calibration. Controller performance is evaluated against that of a position based lateral track controller employing Bank-to-Turn maneuvers, using a powerline corridor as example.

The paper is structured as follows. Problem Formulation details the step by step design of the IBVS controller and how STT maneuvers are managed. Experiment introduces the simulation environment developed to test the performance of the proposed controller and how images were generated to simulate a downward facing camera. Additionally, this chapter discusses the test scenarios developed to evaluate performance under expected operating conditions. Results presents the outcome of simulation tests and discusses findings. Finally, a short summary concludes the paper, with some discussion of future research.

2 Problem Formulation

The conventional means of altering the heading of a fixed wing aircraft is through a Bank-to-Turn (BTT) maneuver. By rolling the aircraft about the longitudinal axis and inducing a bank angle, the resultant lift vector produces the necessary horizontal force to turn. Given the magnitude of the lift vector and angle of bank achievable, a considerable amount of turning force can be generated. This does however have a significant impact on those sensors mounted orthogonal to the longitudinal axis (ie. downward facing cameras), which are now subjected to a panning motion that can not only can introduce motion blur, but angles the sensor away from the direction of turn. Alternatively, Skid-to-Turn maneuvers can be used to change heading, yawing the aircraft to produce a sideslip angle, β, between the longitudinal axis and relative airflow. The resultant thrust vector produces a component of force perpendicular to the relative airflow, coupled with additional aerodynamic force created by the now exposed fuselage and vertical stabilizers, accelerating the aircraft into a turn. As rotation is only required about the yaw axis, the aircraft can maintain wings level flight during the maneuver, thus allowing sensors to maintain their FOV [14]. As with BTT, STT maneuvers have their disadvantages, particularly with larger manned aircraft, as drag is increased due to the exposed fuselage, while the lateral acceleration passengers are subjected to can cause discomfort. The amount of turning force that can be generated is also limited by the inherent directional stability of the platform that restricts the maximum β angle the rudder can hold in steady state, thus the limited use of STT maneuvers under normal operating conditions.

Any number of control techniques can be used in conjunction with STT maneuvers to improve data collection and in this instance Image Based Visual Servo (IBVS) control has been chosen to track features directly from the image plane. Originally developed to control serial-link robotic manipulators fitted with cameras mounted on end effectors [2], error measurements are taken directly from the image plane between the observed and desired pose of image features. Not only can IBVS handle inaccuracies in real world models, it is inherently robust to camera calibration [6]. Identifying suitable features for tracking is essential and considering the case of locally linear infrastructure, the feature can be modeled as a straight line within the image plane. Figure 1 illustrates this with a section of powerline imaged from a low flying UAV (approx. 100ft) where the feature has been modeled by a single straight line and its position and orientation defined by track error, T_e, and observed line angle, θ_o. This approach can be used to model any infrastructure once appropriate feature extraction algorithms have been applied. For the purpose of this paper, it is assumed that images have been preprocessed.

Ideally the feature is to remain centered in the FOV for the duration of the inspection process, which from a control perspective implies driving T_e to zero and flying at a track angle equal to the features orientation with respect to Earth. It should be noted that this does not imply the aircraft maintains a ground track over the feature, as steady state pitch and roll angles may require the aircraft to fly slightly off center for the feature centered in the FOV. Considering the case where the aircraft is operating in no wind and sensor alignment is with the body axis, the feature can be expected to run vertically through the image plane, or more specifically, the observed line angle, θ_o, would be zero. Thus in this instance the controller seeks to drive T_e and θ_o to zero. This however only applies to the ideal situation

Fig. 1 Representation of Linear Features identified in the image plane through the use of, Track Error, T_e, and Observed Line Angle, θ_o

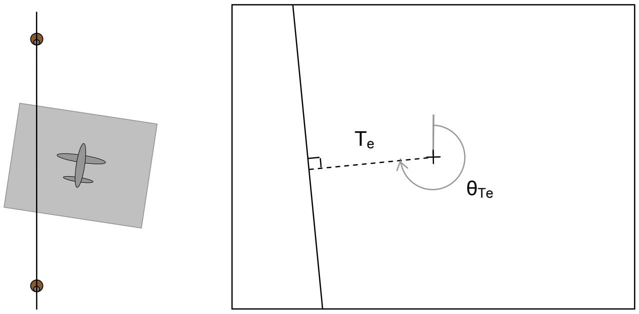
where the aircraft operates in no wind. When introduced to wind, the aircraft's heading and track over ground become separated by a drift angle, or wind correction angle (*WCA*) as more commonly referred to when course is corrected for wind. This angle between body fixed and inertial coordinate frames translates through to the camera frame and under steady state conditions will see the line pass diagonally through the image center, with an observed line angle, θ_o, equal to *WCA*. Although weather predictions and ground track from GPS can provide an estimate of *WCA*, ideally the IBVS controller will compensate with no prior knowledge.

Having identified control features and their desired pose, the next step in development looks at how STT maneuvers can control pose. Although minimizing track error is the primary focus, T_e alone provides insufficient information to account for current approach angle, which is critical for rapid convergence and limited overshoot. This research proposes the use of current track error to derive a desired line angle, θ_d, that once established, will set the UAV on a trajectory that minimizes T_e. Figure 2 illustrates this with an example of an aircraft flying, wings level, over a powerline attempting to maintain it centered in the FOV. Figure 2(a) shows the initial position of the aircraft and a simulated image as would be captured by a downward facing camera. From the image one can infer the aircraft is right of the feature and flying away, based on line angle. To bring the feature towards the center of the image, the heading of the aircraft must be altered in a similar fashion to that of Figure 2(b), which would see the feature captured as the solid line, referred to as the desired line angle, θ_d, for which the controller must drive the aircraft towards. This however forms but one case and if extended for all values of T_e produces a relationship similar to that of Figure 3(a). Note, $+T_e$ and $-T_e$ refer to the line in the right and left halfs of the image respectively, or more specifically, the angle with respect to vertical, θ_{Te} as shown in Figure 2(a), is between 0 and π or 0 and $-\pi$ respectively. Similarly, $+\theta_d$ refers to the line angle measured clockwise over 0 to π, while $-\theta_d$ is measured from 0 to $-\pi$. When tracked over time the aircraft can be expected to follow a path similar to that shown in Figure 3(b).

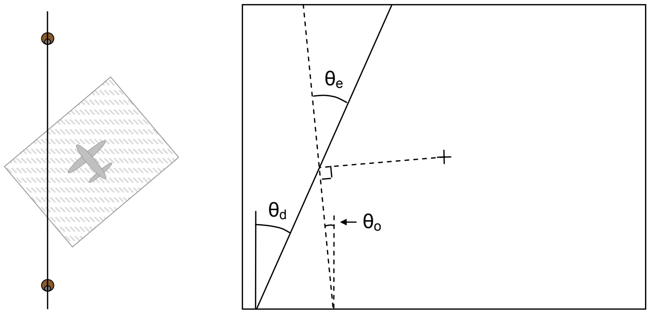
Mathematically, the curve shown in Figure 3(a) can be described by the sigmoid function,

$$f(T_e) = \frac{\pi}{\left(1+e^{\frac{T_e}{k_s}}\right)} - \frac{\pi}{2} \tag{1}$$

Where k_s defines the slope of the function through the transition and thus can be used to adjust the rate at which the aircraft approaches the target. Desired angle can then be ex-

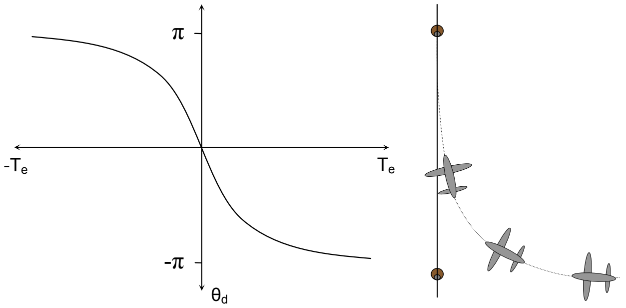


(a) View of aircraft and feature from above (*left*) and image plane (*right*).



(b) Desired heading and line angle as would be seen from above (*left*) and in the image plane (*right*).

Fig. 2 Establishing desired line angle, θ_d, from track error, T_e, as observed in the image plane.



(a) Desired Angle versus Track Error (b) Desired Trajectory

Fig. 3 A sigmoid relationship between track error and desired line angle is adopted to generate a converging trajectory.

pressed as follows with the inclusion of residual track error and approach velocity feedback for wind conditions,

$$\theta_d = \frac{\pi}{\left(1 + e^{\frac{T_e}{k_s}}\right)} - \frac{\pi}{2} + V_a + R_{Te} \tag{2}$$

Where V_a, the compensation for approach velocity and R_{Te}, compensation for residual track error, are expressed as follows,

$$V_a = k_v \frac{dT_e}{dt} \tag{3}$$

$$R_{Te} = k_r \int T_e \, dt \tag{4}$$

Maneuvering the aircraft to so that θ_o equals θ_d is achieved through rudder deflections generated by a PID controller drivne by angle error, θ_e, given as,

$$\theta_e = \theta_d - \theta_o \tag{5}$$

Under this design, ailerons and elevators are free to operate independently of the IBVS controller and thus can be used to maintain altitude and hold wings level. In this way, a conventional autopilot can be used to navigate the aircraft to the inspection sight, where the IBVS controller can then take over control of the rudder, issuing a command to the autopilot to maintain altitude and wings level. The overall system architecture is illustrated in Figure 4.

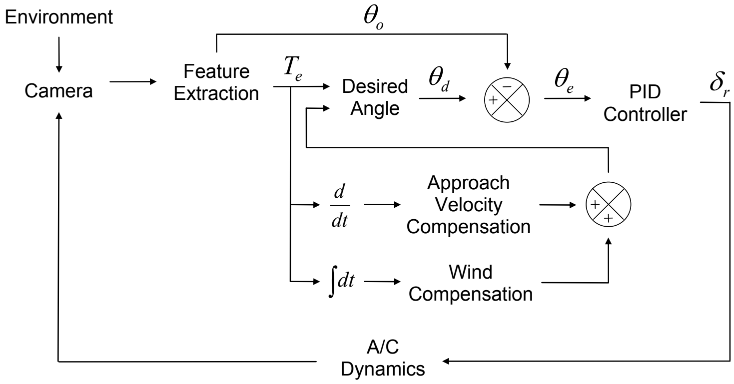


Fig. 4 System Diagram of Skid-to-Turn Image Based Visual Servo Control Scheme

3 Experiment

To test the performance of the STT IBVS controller, a simulation environment was built upon Matlab Simulink that could replicate the FOV of a body fixed, downward facing, image sensor. To generate images, the location of turning points in the simulated linear infrastructure where transformed from Earth Centered Earth Fixed (ECEF) coordinates to camera image plane coordinates through a series of standard photogrammetric transforms [7, 13]. By then connecting the turning points within the camera image plane, T_e and θ_o could be estimated and used as input to the IBVS controller. The response of the aircraft to rudder commands generated by the controller are then simulated using a nonlinear, 6 degree of freedom, dynamic model of an Aerosonde UAV, which in turn provides the state variables required for ECEF to image plane coordinate transformations. Separate controllers were developed to maintain airspeed, altitude and wings level, emulating an autopilot that would operate independent of the IBVS controller.

To compare the performance of the proposed controller to that of a conventional BTT controller, a GPS driven lateral track controller was implemented. Although many controller options exist in this area, the use of BTT maneuvers is common throughout and subsequently the behaviour on sensor FOV is expected to be reflected by all. The controller implemented in this instance applies a simple variation on waypoint navigation, using both future and previous waypoints to define a course over ground from which cross track error can be established. This cross track error is then reduced through the use of a PID controller that alters the current desired heading, directed at the future waypoint, bringing the aircraft on track.

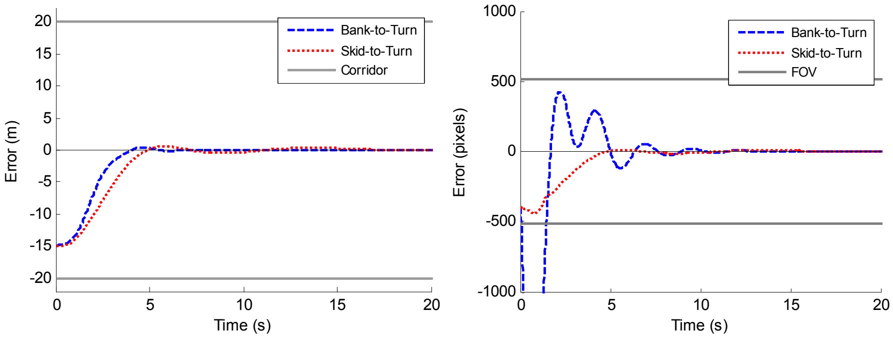
A series of scenarios were then developed to test the performance of these controllers under typical operating conditions. Powerline inspection is used as an example to set real world parameters, modeling a three wire distribution line with 20m easements and 10m poles spaced at 100m. Initially the aircraft is positioned off to one side of the line, flying parallel, from which position it must maneuver back over the line. Corners and bends are not considered at this stage. Flight parameters including autopilot gains, desired altitude and airspeed are all held constant for the duration of each scenario. Selection of altitude during these missions is highly dependent on camera parameters, with angular FOV and spatial resolution limiting the lower and upper limits respectively. The camera model used in this instance has a 50° horizontal angular FOV and a resolution of 1024 x 768 pixels, effectively limiting the lower altitude at which the aircraft can fly and still capture the full corridor to 50m, while the ability to see the lines limiting the highest altitude to approximately 100m.

Airspeed selection is less constrained, with lower speeds favored to avoid motion blur and increase image overlap, with higher speeds favored to increase efficiency and range. With respect to the Aerosonde, the slowest speed at which the aircraft can still maintain altitude is approximately 70km/h, while increased efficiency can be achieved around 100km/h. The final test condition would introduce wind and whilst initial tests would be performed under no wind conditions, subsequent tests would introduce a worst case scenario of a direct cross wind acting across the powerlines, in this instance a 15kt (7.7m/s) wind. Test cases would then be developed to test the full combination of height, airspeed and wind, bounding the expected working conditions of the system. After initial tuning, IBVS controller gains would remain constant for all scenarios, as would be required in practice.

4 Results

Parameters for the first series of tests were selected to reflect ideal operating conditions, with altitude and airspeed set to 50m and 70km/h respectively. To evaluate and compare performance, two metrics, Track Error and FOV Track Error, were introduced, both providing a relative measure of aircraft position with respect to the feature. Track Error in this instance refers to the perpendicular distance from the aircraft to the feature centerline and is a common performance metric for lateral track controllers. FOV Track Error on the other hand, previously referred to as track error, T_e, provides a measure of the features position in the image plane. It should be noted that the two controllers tested are not directly comparable in that the BTT based controller seeks to reduce GPS derived track error while the STT IBVS controller seeks to minimize FOV Track Error. This is useful however to highlight the general perception of lateral track controllers and the typical approach to design.

Initially the aircraft is positioned 15m to the right of the line, a distance chosen to ensure the feature begins within the sensor FOV. Results for the first test, performed under no wind, are shown in Figure 5. As would be expected, the BTT controller performs well in repositioning the aircraft over the line, with faster convergence and less overshoot than the STT controller. Traditionally this result would favor the use of the BTT controller, what is not considered though, is the impact on sensor FOV. Plotting FOV Track Error, as shown in Figure 5(b), it becomes clear the effect roll has on the image plane. Immediately the bank required to change heading results in the sensor pointing away from the feature, in this instance, at a sufficient angle to loose sight of the feature. As the plane levels out, the feature comes back within the FOV, only to then swing away again as the aircraft attempts to align with the feature. At this point the bank has a positive effect on the image plane, pointing the sensor towards the feature while it has yet to cross the line. Finally a small series of oscillations are seen as the aircraft reaches steady state. Another issue, not immediately obvious from Figure 5(b), is the rapid movement of features in the image plane, evident by the rate at which FOV Track Error changes, which would very likely result in motion blur during those frames. Considering now the STT controller, it can be seen that a more desirable response is seen from the point of view of the image plane. Momentarily the feature moves away from the centre, caused by a sudden increase in lift on one wing as the aircraft begins to sideslip that takes the bank controller a moment to counteract. From this point on, FOV Track Error is slowly minimized and the feature is brought into the centre of the image with minimal overshoot or oscillations.

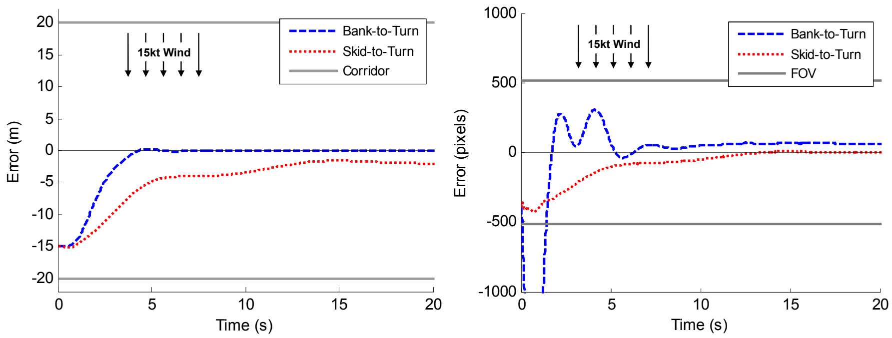


(a) Track Error with respect to feature centerline (b) Track Error as measured in the image plane

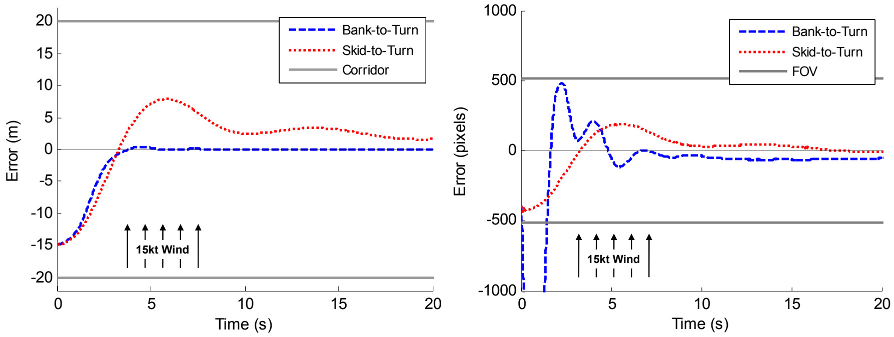
Fig. 5 Performance of Bank-to-Turn versus Skid-to-Turn controllers under ideal operating conditions (No Wind, 70km/h, at 50m altitude)

Although the STT controller displays better performance than the BTT controller in this scenario, a critical factor not considered is the effect of wind. Wind is a particular challenge for the IBVS controller as inertial data is not available for use and must be compensated for based on the features response within the FOV. The worst case scenario during operation is in the event of wind directly perpendicular to the line. This can have two effects, depending on the approach of the aircraft, either pushing the aircraft over the lines, or working against the aircraft making it harder to converge. To test both scenarios, a moderate wind of 15knots (7.7m/s) was applied from both directions.

Figures 6(a) & 6(b) show the response of the aircraft to winds working against it, while Figures 6(c) & 6(d) show the response for winds working with the aircraft. As we would



(a) Track Error with respect to feature centerline (b) Track Error as measured in image plane



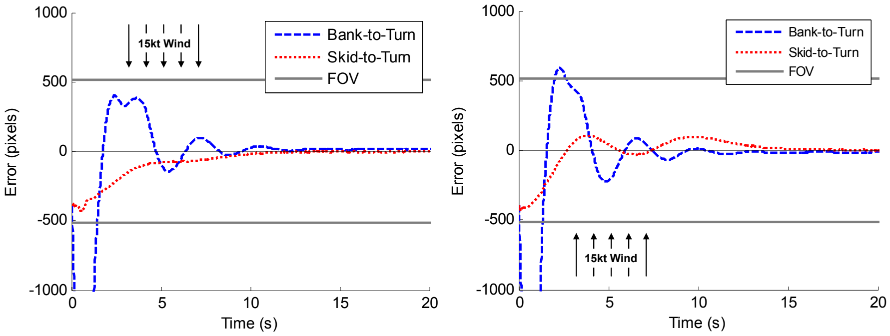
(c) Track Error with respect to feature centerline (d) Track Error as measured in image plane

Fig. 6 Performance of tracking controllers in the presense of a 15knot (7.7m/s) cross wind. Wind working against the aircraft (a,b) and wind working with the aircraft (c,d). (70km/h, 50m altitude)

expect given no actual feedback for track error with respect to the feature centerline is provided to the STT IBVS controller, the response to re-positioning the aircraft over the line is far from ideal, while BTT has almost an identical response in both scenarios to that with no wind. However the effect on the image plane is quite clear, where the STT controller once again produces a far more desirable response. With the wind working against the aircraft the desired angle calculated by the STT controller to re-center the feature actually sees the aircraft draw short of the feature, creating a residual FOV Track Error that is slowly reduced over a 10sec period. A similar effect is seen with the wind working with the controller, although in this instance the desired line angle generated by the IBVS controller causes the aircraft to overshoot before compensation for wind can be made. To assist in this situation, velocity compensation is used to slow the rate of convergence, and thus avoid overshoot. An interesting result of the BTT controller is seen after it reaches steady state, where the feature is slightly off center in both instances, an issue not observed during the initial scenario with no wind. This can be put down to pitch required to maintain altitude, which due to the WCA means the aircraft flies with a heading offset from track, thus pointing the sensor away from the line, instead of further along the line for the case of no wind. It can be seen from Figures 6(a) & 6(c) that the IBVS controller accounted for this by maintaining steady state track error.

Having established that the controller can handle wind conditions, test scenarios were then introduced to evaluate the controller's response to changes in flight parameters. Although controller gains could be modified to account for these alterations, ideally the tracking controller would be robust over the full range of flight parameters that would be used during operation. The first flight parameter of concern that is likely to change is airspeed, both directly and indirectly, as the aircraft is flown faster or slower adjusting for weight, sensor requirements and efficiency, to small changes due to variations in wind.

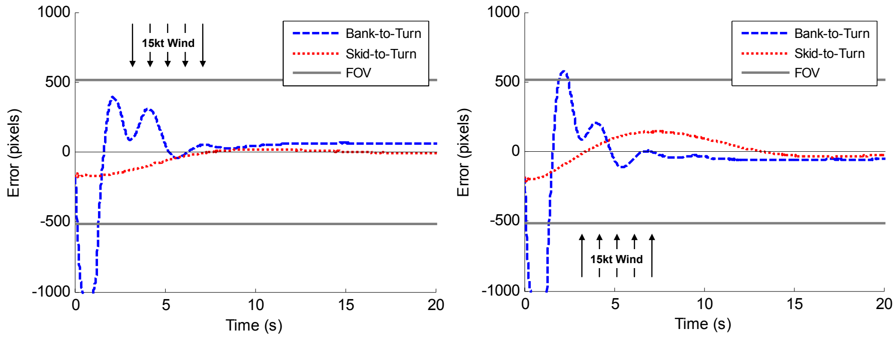
Figure 7 shows the results when airspeed is increased to 100km/h, with FOV Track Error shown for both cross wind conditions. It can be seen that the increase in velocity slightly improves the performance of the STT IBVS controller, which can be attributed to a greater influence of the approach velocity compensator. One downfall is minor oscillations as the aircraft attempts to reduce residual track error, although after approximately 15secs the response has died down. One thing to note with the BTT controller is that the steady state FOV Track Error is effectively eliminated as not only the angle of attack required to maintain altitude is reduced but faster airspeed results in a smaller WCA, both having a positive in this instance on the image plane.



(a) Wind working against aircraft (b) Wind working with aircraft

Fig. 7 Effect of increasing airspeed from 70km/h to 100km/h, with controllers both using original gains. Results show track error as measured in the image plane with +15kt winds (a) and -15kt (b). (50m altitude)

The final parameter to be considered is that of altitude, another which is likely to vary both directly, to meet the requirements of a mission, and indirectly due to variations in terrain height not accounted for by the autopilot. To test the performance, altitude was increased to 100m, with results shown in Figure 8. From the image perspective, the increase in height effectively reduces the scale of features, with a 15m offset resulting in a feature that appears closer to the FOV centre. Thus from the controller perspective, this requires small correction even though the same amount of cross track error exists. Working against the wind, the response is desirable and the controller effectively brings the feature into the image center. Working with the wind, the response is less favorable as the residual track error compensator provides too much compensation, with the aircraft taking over 20secs to converge. Gains in this instance could be modified to improve this response, although in practice it is unlikely that variations of this scale would be expected in a single flight.



(a) Wind working against aircraft (b) Wind working with aircraft

Fig. 8 Effect of increasing altitude from 50m to 100m, with controllers both using original gains. Results show track error as measured in the image plane with +15kt winds (*a*) and -15kt (*b*). (70km/h)

5 Conclusion

This paper set out to highlight the benefits of Skid-to-Turn maneuvers over traditional Bank-to-Turn maneuvers for the tracking and inspection of locally linear infrastructure, and the importance of including visual feedback in control. Aside from the principal advantage of features remaining visible in the field of view of onboard body fixed sensors, STT maneuvers were shown to eliminate rotation that can lead to degraded data quality. Controller performance was demonstrated through a series of simulations, with performance out comparing that of a BTT controller using GPS derived cross track error. The controller was also shown to be robust to variations in wind, airspeed and altitude with no modification of controller gains necessary over a range of flight parameters likely to be encountered.

From a practical point of view, the proposed controller should lend itself well to integration with operational UAVs, as the guidance controller is able to operate independent of any onboard autopilot. The addition of a suitable feature extraction algorithm to pre-process image data has not been considered here, although will be necessary to close the overall control loop. In addition an interface between guidance controller and autopilot will be required to allow the IBVS controller to indicate when tracking is in progress and for the autopilot to hold altitude and airspeed while maintaining wings level flight. Future work will investigate controller robustness to errors in the feature extraction process, as well as tracking linear infrastructure through discontinous bends, as is present in powerlines and pipelines.

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