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Image Based Visual Servo Control for Fixed Wing UAVs Tracking Linear Infrastructure in Wind

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Abstract—This paper presents an Image Based Visual Servo control design for Fixed Wing Unmanned Aerial Vehicles tracking locally linear infrastructure in the presence of wind using a body fixed imaging sensor. Visual servoing offers improved data collection by posing the tracking task as one of controlling a feature as viewed by the inspection sensor, although is complicated by the introduction of wind as aircraft heading and course angle no longer align. In this work it is shown that the effects of wind alter the desired line angle required for continuous tracking to equal the wind correction angle as would be calculated to set a desired course. A control solution is then sort by linearizing the interaction matrix about the new feature pose such that kinematics of the feature can be augmented with the lateral dynamics of the aircraft, from which a state feedback control design is developed. Simulation results are presented comparing no compensation, integral control and the proposed controller using the wind correction angle, followed by an assessment of response to atmospheric disturbances in the form of turbulence and wind gusts.

I. INTRODUCTION

The inspection of ground based infrastructure is a task well suited to the unmanned aerial vehicle (UAV), although poses the challenge of providing guidance and control that not only allows the UAV to follow the feature, but ensure the viewing angle of onboard sensors allows for the collection of data. While maintaining a ground track directly above a feature may prove effective for helicopters, quadrotors and airships, many of the maneuvers employed by fixed wing aircraft utilize body rotations that directly impact fixed inspection sensors, thus requiring careful selection of maneuvers [1]–[4]. This is further complicated in the presence of wind as the course over ground flown by the aircraft no longer aligns with aircraft heading.

While the effects of wind on the capture of fixed targets have been investigated [5]–[7], the treatment of tracking in the presence of wind for locally linear infrastructure is generally concerned with reducing cross track error and neglects the impact of maneuvers on data collection [8]–[10]. One technique that allows the tracking task to be posed directly from the perspective of inspection is through the use of Image Based Visual Servoing (IBVS), a technique that has been seen in both relative positioning of fixed wing aircraft with respect to fixed targets [11], [12] and linear infrastructure [13], [14]. By relating motion of a feature within the image plane to motion of the camera through an interaction matrix, a controller can be developed that focuses on achieving the desired pose of image features. In the context of inspection, this allows the goal of the tracking task to focus on centering the feature for the purpose of data collection, as opposed to a secondary effect of flying directly over the feature on a pre-planned path.

In the ideal case of no wind, the IBVS task can be generalized as one of centering the feature vertically within the image plane for a downward facing imagining sensor aligned with the longitudinal axis of the aircraft. However, with the introduction of wind, the course over ground flown by the aircraft no longer aligns with aircraft heading and subsequently can introduce steady state error. This is addressed in [14] where a IBVS controller is developed for automatic landing through a forward facing camera, where integral control is introduced to reduce the steady state error introduced by wind. This can also be achieved for a downward facing camera, as was previously presented for a Skid-to-Turn IBVS controller for which this work builds upon [15]. Although integral control offers a sound solution in the case of unknown wind, lag and overshoot are often introduced given the nature of compensation.

In this work, a solution is sort to improve performance given an estimate of wind is available, possible through a number of techniques including vision [16]. By modeling the effects of wind on the interaction matrix and linearizing about a steady state condition of a centered feature it is shown that the desired line angle required to perform tracking is equal to the Wind Correction Angle as would be flown to correct aircraft heading for a desired course. The interaction matrix is then augmented with the lateral dynamic equations of motion from which an LQR control design is developed for full state feedback, allowing simultaneous tracking and positioning of the feature.

The paper begins in Section II with a development of an interaction matrix for a line feature taking into account the effects of wind through the camera velocity screw that lead to selection of the desired feature pose. The linearized interaction matrix is then augmented with the lateral dynamics of the aircraft in Section III such that a state feedback controller can be developed. Section IV details the simulation environment that was used to test the controllers. Results are then presented in Section V, first comparing the response given no compensation, integral control and the use of wind correction angle, the second assessing response of the
The proposed design in the presence of atmospheric disturbances. The paper concludes in Section VI with a summary of findings and discussion of future work.

II. PROBLEM DEFINITION

Developing an Image Based Visual Servo control design begins by generating an interaction matrix, \( \mathbf{L} \), such that feature motion in the image plane can be resolved as a function of camera motion expressed in the form,

\[
\dot{s} = \mathbf{L} \mathbf{T}_c
\]

where \( s \) denotes the set of image features, and \( \mathbf{T}_c \) the camera velocity screw that defines the translational \(( \mathbf{V}_c )\) and rotational \(( \Omega_c )\) velocity of the camera.

For locally linear infrastructure the logical choice of feature is a line feature which can be expressed as perpendicular distance from the image center, referred to as Sensor Track Error \(( T_v )\), and orientation with respect to the image vertical, defined here as Line Angle \(( \Theta_1 )\), as illustrated in Fig. 2. Mathematically the feature is then described as,

\[
T_v = -X_v \sin \Theta_1 + Y_v \cos \Theta_1
\]

The feature can be likewise expressed in the 3D camera frame as the intersection of two planes, given by,

\[
L = \begin{cases}
    a_1 x + b_1 y + c_1 z + d_1 = 0 \\
    a_2 x + b_2 y + c_2 z + d_2 = 0
\end{cases}
\]

The resulting interaction matrix can be derived using the techniques of [17] resulting in,

\[
\begin{bmatrix}
    \dot{T}_v \\
    \dot{\Theta}_1
\end{bmatrix} = \begin{bmatrix}
    -K_o \Theta_1 & -K_e \Theta_1 \\
    K_a \Theta_1 & K_e \Theta_1 \\
    -K_a K_d & -K_e K_d \\
    K_a \Theta_1 & K_e \Theta_1 \\
    K_b \Theta_1 & -K_e \Theta_1 \\
    0 & -1
\end{bmatrix} \mathbf{T}_c
\]

where \( C_\phi \) \(( S_\phi )\) represents \( \cos \phi \) \(( \sin \phi )\), respectively, and terms \( K_x \) are given by,

\[
K_a = \frac{f(c_s + T_v(b_s \Theta_1 - a_s \Theta_1))}{d_i}, \quad K_b = \frac{f^2 + T_v^2}{f}, \quad K_e = \frac{a_s \Theta_1}{d_i}, \quad K_d = \frac{T_v}{f}
\]

where \( a_s, b_s, c_s \) & \( d_i \) are taken from either of the two planes that define the line feature in the 3D camera frame. At this point, motion of the camera is generally assumed to be directly inherited from aircraft motion, thus the camera velocity screw \( \mathbf{T}_c \) is equal to the aircraft velocity and angular rates expressed in the body axes. However in the presence of wind, the camera’s motion with respect to the feature not only sees motion of the aircraft, but as the feature is fixed to the Earth, also sees the relative motion of the Airmass.

In this work, compensation for wind is sort for mean wind conditions, i.e. steady, constant, movement of the Airmass with respect to the ground reference frame. For an aircraft flying under such conditions the consequence is that ground track and aircraft heading no longer align, and thus to achieve a desired ground track the aircraft must be altered by a factor commonly referred to as a Wind Correction Angle \(( WCA )\), as illustrated by Fig. 1. The resultant ground velocity vector is the summation of free stream velocity incident on the aircraft, \( \mathbf{V}_0 \), and the wind vector \( \mathbf{V}_w \), leading to

\[
\mathbf{V}_g = \mathbf{V}_0 + \mathbf{V}_w
\]

Relating motion of the airmass to camera motion requires the velocity of the airmass to be expressed in body coordinates of the aircraft. This can be achieved using the Euler Angles that express the orientation of the aircraft with respect to the reference frame in the form of a Direction Cosine Matrix \(^b\mathbf{R}_c\) \(( DCM )\) given by,

\[
^b\mathbf{R}_c = \begin{bmatrix}
    C\Phi C\Psi & C\Phi S\Psi & -S\Phi \\
    S\Phi S\Theta - C\Phi S\Psi & C\Phi S\Theta S\Psi + C\Phi C\Psi & C\Phi C\Theta \\
    S\Phi S\Theta C\Psi + S\Phi S\Psi & C\Phi S\Theta C\Psi - S\Phi C\Psi & C\Phi C\Theta
\end{bmatrix}
\]

where the notation \(^b\mathbf{R}_c\) is used to express the transformation of Frame \(( e )\) to Frame \(( v )\), so in this instance, from the Body Frame to the Reference Frame. This allows the velocity component of the camera velocity screw to be expressed as,

\[
\mathbf{V}_c = \mathbf{V}_{ac} + \mathbf{R}_c \mathbf{V}_w
\]

where the aircraft is assumed to be flying about a steady state condition such that motion of the aircraft is described by small perturbations about a steady state condition resulting in,

\[
\mathbf{V}_{ac} = \begin{bmatrix}
    U_0 + u \\
    V_0 + v \\
    W_0 + w
\end{bmatrix}, \quad \Omega_{ac} = \begin{bmatrix}
    P_0 + p \\
    Q_0 + q \\
    R_0 + r
\end{bmatrix}
\]

Likewise, Euler Angles can be expressed as,

\[
\Phi \triangleq \Psi \Phi_0 + \Phi, \quad \Theta \triangleq \Psi \Theta_0 + \Theta, \quad \Psi \triangleq \Psi \Psi_0 + \Psi
\]

One such steady state flying condition that would suit the tracking task is Straight \(( \Theta_0, \Phi_0, \Psi_0 = 0 )\), Level \(( \Phi_0 = 0 )\), Symmetric \(( \Psi_0 = 0 )\) flight. Furthermore, if a Horizontal

\(^1\text{Note: Order of rotation is Yaw (}\Psi\text{), Pitch (}\Theta\text{), Roll (}\Phi\text{)}\)
flight path is selected and stability axes are adopted such that the body fixed longitudinal axis \( ax_b \) is rotated such that it is parallel to the free stream velocity vector, \( V_0 \), then pitch angle, \( \Theta_0 \), and vertical velocity, \( W_0 \) go to zero, and longitudinal velocity, \( U_0 = V_P \), where \( V_P = |V_0| \).

The resulting DCM assuming small angle approximations \((\cos \alpha \approx 1, \sin \alpha \approx \alpha)\) and the products of perturbations are negligible \((\alpha^2 \approx 0, \alpha \beta \approx 0)\), then becomes,

\[
bR_e = \begin{bmatrix} C\Psi_0 - \psi S\Psi_0 & S\Psi_0 + \psi C\Psi_0 & -\theta \\ -(S\Psi_0 + \psi C\Psi_0) & C\Psi_0 - \psi S\Psi_0 & \phi \\ \theta C\Psi_0 + \phi S\Psi_0 & \theta S\Psi_0 - \phi C\Psi_0 & 1 \end{bmatrix}
\]

For the purpose of this work, the vertical component of wind is assumed negligible such that the wind vector, \( V_w \), is expressed as \([V_{wx} \ V_{wy} \ 0]^T\). The resulting camera velocity screw is then given by,

\[
T_c = [V_P + K_{w1} + u + K_{w2}\psi \ K_{w2} + v - K_{w1}\psi \ w + K_{w1}\theta - K_{w2}\phi \ p \ q \ r]
\]

where,

\[
K_{w1} = V_{wx}C\Psi_0 + V_{wy}S\Psi_0 \\
K_{w2} = V_{wy}C\Psi_0 - V_{wx}S\Psi_0
\]

(5)

This can then be linked back to the interaction matrix of (3) that can be simplified by observing that the feature may be assumed to lie in a plane horizontal to the aircraft wind axes \((x_w, y_w)\) at a distance \( h \) below the aircraft, as depicted in Fig. 2, a plane described \( z = h \), or in the form of (2); \( a = 0, b = 0, c = 1, d = -h \). While \( h \) is unknown, the desired height at which the aircraft will be commanded to fly at will be used as an approximation. Constant terms \( K_a \) and \( K_c \) of (4) then simplify to,

\[
K_a = -\frac{f}{h} \quad K_c = 0
\]

Given motion of the aircraft is assumed to take place about a steady state flying condition, the same approximation is extended to the motion of features within the image plane, with \( T_c \triangleq T_{c0} + t_c \) and \( \Theta_l \triangleq \Theta_{l0} + \theta_l \), where \((t_c, \theta_l)\) represent perturbed motion about the reference position, \((T_{c0}, \Theta_{l0})\). In terms of inspection and observation tasks, the overall goal is to center the feature, thus desired sensor track error, \( T_{c0} \), will be zero. Terms \( K_b \) and \( K_d \) of (4) are likewise approximated leading to,

\[
K_b = f \\
K_d = \left(\frac{1}{f}\right) t_c
\]

The interaction matrix of (3) then becomes,

\[
t_c = -K_a(S\Theta_{l0} + \theta_lC\Theta_{l0})(V_P + K_{w1} + u + K_{w2}\psi) + f(C\Theta_{l0} - \theta_lS\Theta_{l0})p + f(S\Theta_{l0} + \theta_lC\Theta_{l0})q + K_a(C\Theta_{l0} - \theta_lS\Theta_{l0})(K_{w2} + v - K_{w1}\psi) - K_aK_d(w + K_{w1}\theta - K_{w2}\phi)
\]

†Airspeed is defined as \( V_P = |V_0| \), where \( V_0 \) is the free stream velocity, not to be confused with steady state lateral velocity component \( V_0 \).
While aircraft heading angle $\Psi_0$ can not be measured directly from the image plane, it can be seen from Fig. 3 that the relative angle between aircraft heading and desired ground track $\chi_d$ (given the extracted feature) can be directly measured within the image plane as $\Theta_i$, thus,

$$\Theta_{i_0} = \chi_d - \Psi_0 \quad (8)$$

Recognizing $\cos(\alpha \pm \beta) = \cos \alpha \cos \beta \mp \sin \alpha \sin \beta$ and $\sin(\alpha \pm \beta) = \sin \alpha \cos \beta \mp \cos \alpha \sin \beta$, (7) then becomes

$$V_P S \Theta_{i_0} = (V_{wy} C \chi_d - V_{wz} S \chi_d) \quad (9)$$

If the wind is then expressed in terms of magnitude and direction ($V_w = V_u \angle \theta_u$, Fig. 1), i.e. $V_{wx} = V_u \cos \theta_u$ and $V_{wy} = V_u \sin \theta_u$, (9) simplifies to,

$$V_P S \Theta_{i_0} = V_u S (\theta_u - \chi_d)$$

However inspecting the vectors of Fig. 1 it is seen that the wind correction angle is given by,

$$\theta_{wc} = \arcsin \left( \frac{|V_w|}{|V_0|} \sin (\angle V_w - \angle V_g) \right)$$

Thus for visual tracking our desired line angle, and thus steady state feature property $\Theta_{i_0}$, should be set to the wind correction angle,

$$\Theta_{i_0} = \theta_{wc}$$

Given that (8) provides a relationship between aircraft heading and desired ground track, it is also observed that perturbations of aircraft heading are directly related to line angle as desired ground track will remain constant, thus,

$$\theta_l = -\psi$$

The interaction matrix of (6) then becomes,

$$\begin{bmatrix} i_e \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{f}{h} S \theta_{wc} & -\frac{f}{h} C \theta_{wc} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} f C \theta_{wc} & f S \theta_{wc} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} + \begin{bmatrix} 0 & V_P C \theta_{wc} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_e \\ \theta_l \end{bmatrix} \quad (10)$$

### III. CONTROL

As previously discussed, a desirable steady state flight condition during tracking is *Straight, Level, Symmetric* flight that leads to a decoupling of longitudinal and lateral equations of motion. While longitudinal motion of the aircraft is seen to effect feature motion through (10), it is noted that the contribution is proportional to $\sin \theta_{wc}$ and that with longitudinal control decoupled the perturbations will be minimal. For this reason the longitudinal contribution of motion to the interaction matrix will be assumed negligible, thus allowing the interaction matrix to be augmented with the lateral dynamic equations of motion given by,

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} Y_v & 0 & -V_P \\ L_v & L'_v & L'_r \\ N'_e & N'_p & N'_r \end{bmatrix} \begin{bmatrix} v \\ p \\ r \end{bmatrix} + \begin{bmatrix} Y_{\delta_a} & Y_{\delta_r} \\ L'_{\delta_a} & L'_{\delta_r} \\ N'_{\delta_e} & N'_{\delta_p} \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}$$

$$L'_e = L_e + \frac{I_{xz}}{I_{zz}} N'_e \quad N'_e = N_e + \frac{I_{xz}}{I_{zz}} L'_e$$

$$L'_e = \frac{L_e}{1 - I_{xz}(I_{zz} - I_{zz})^{-1}}$$

For the purpose of work, full state feedback is assumed available for control, from which an LQR control design is developed that minimizes sensor track error and roll rate to reduce unwanted sensor motion. Longitudinal control is achieved through two PID controllers, regulating altitude through elevator and airspeed through throttle.

### IV. SIMULATION ENVIRONMENT

To assess the performance of the IVBS controller with the inclusion of wind, a simulation environment was developed in Matlab Simulink that could simulate both aircraft motion and data capture of a downward facing, body fixed camera. The aircraft model used in this instance is a 6 DoF nonlinear model of the Aerosonde UAV provided by Unmanned Dynamics in the AeroSim Blockset. Synthetic imagery is generated as would be captured if the aircraft were flying over powerlines, which is simulated by transforming two points of the line from the reference frame to the camera frame given aircraft location and orientation. The concept is further extended to powerpoles, cross bars and a corridor surrounding the powerline $(\pm 20m)$ to provide visual cues for illustration, as seen in Fig. 4.

![Fig. 4. Synthetic images as generated in the simulation environment.](image-url)
Operating conditions for the simulation were selected to reflect a flight envelope as would be chosen in practice. This included selecting a slow cruising speed for the given airframe, in this instance 100 km/hr (54 kn). The camera itself is modeled on a generic sensor of 1024 x 768 resolution, with a horizontal field-of-view (FOV) of 50° and a focal length of 5 mm. The height is selected at 50 m to enable the aircraft to capture the full width of the corridor.

The scenario under which the controllers would be tested was developed to reflect that of an aircraft tracking a feature with steady state cross track error of 10 m. In such a situation the sensor would see the feature offset in the image plane initially as shown in Fig. 4a, from which position the controller would attempt to recenter as seen in Fig. 4b. In addition to mean wind conditions, the simulation would also introduce atmospheric disturbances in the form of both turbulence, modeled on the von Karman spectral form, and discrete gust disturbances modeled on a “1-cosine” [18].

V. RESULTS

The first series of results presented in Fig. 6† show the response of three separate control designs in the presence of a 18.5 km/h (10 kn) cross winds. Sensor Track Error, $T_e$, is shown here as a percentage of frame width from image center, e.g. $T_e = 50\%$ infers sensor track error of 256 pixels for a 1024 × 768 sensor. No Compensation shows the response of the IBVS controller designed under the assumption of no wind and thus has desired line angle set to zero ($\Theta_{i_0} = 0^\circ$). The response is far from ideal, with initial overshoot that sees large steady state sensor track error. The impact of this is highlighted in Fig. 5a that shows the simulated FOV during tracking, where the feature is seen to be both off center and viewed at an angle.

![Fig. 5. Simulated FOV at t = 30 s in 18.5 km/h (10 kn) cross wind with (a) No Compensation (b) Integral Control (c) Wind Correction.](image)

Integral shows the response with integral control added to track error. This is seen to successfully recenter the feature within 10 s, although as would be expected, introduces overshoot. Rather than returning to wings level flight however, the controller is seen to maintain steady bank of approximately 20° that is not only inefficient, requiring aileron and rudder deflections of -14° and +15° respectively, but from Fig. 5b, seen to result in the feature being viewed at an angle, even if centered. The final response, Wind Correction, is that of the new controller that takes into account the wind correction angle, $\theta_{w.c}$. The controller is not only seen to recenter the feature within 5 s with no overshoot, but is also seen to return to wings level flight ($\Phi = 0^\circ$) which is a preferable for inspection, as is evident from Fig. 5c.

![Fig. 6. Control response in a 18.5 km/h (10 kn) cross wind.](image)

The second series of results shown in Fig. 7 show the response of the proposed controller in the presence of stronger, 37 km/h (20 kn), mean wind conditions and the introduction of atmospheric disturbances in the form of turbulence and gusts. Wind now acts at 70° with respect to north, introducing a component of wind along the feature. Turbulence adds a continuous disturbance upon all three axes of the aircraft, while gusts introduce discrete horizontal variations to mean wind in the form of isolated gusts (-25% at $t = 50$ s and +50% at $t = 100$ s) and longer gusts lasting 60 s with magnitudes of -10% and +20% introduced at $t = 150$ s and $t = 210$ s respectively. A second tuning of the controller (FS2) is also included to highlight the potential benefit of using higher gains in rejecting atmospheric disturbances.

The proposed controller is seen to maintain the feature in the FOV during each of the discrete gust disturbances, while turbulence is seen to have only minor influence on sensor FOV, with only slight variations of sensor track error observed. A delay of approximately 3 s is observed between isolated gusts and their impact on sensor FOV, where improved disturbance rejection is seen by the higher gain controller, FS2. The effect of longer gusts is seen to be less ideal, resulting in steady state tracking error during those periods, although is expected given no means for compensation of unknown wind is included. In this instance, the addition of integral control is likely to improve control response, although does highlight the controllers ability to adequately handle errors of mean wind estimates up to 20%, maintaining the feature within the sensor FOV allowing continued tracking and data collection.

†A supplementary video file is available for Figures 6 & 7.
This paper has presented an IBVS controller for fixed wing UAVs tracking ground based infrastructure in the presence of wind. The effects of wind on the IBVS control design were shown to alter the desired line angle from vertical alignment to that of an angle equal to the wind correction angle for continuous tracking to be performed in a Straight, Wings Level, Symmetric steady state flight condition.

Through simulation it was shown that without compensation the IBVS controller would no longer center the feature, which in strong winds could see the feature leave the field of view altogether. While the addition of integral control was found to improve tracking, it was subject to significant overshoot and tracked the feature at a constant bank angle that resulted in the feature being viewed at an angle. With the inclusion of the wind correction angle as the desired line angle for the IBVS controller, the response was shown to improve considerably, avoiding overshoot and excessive control surface deflections, while allowing the aircraft to return to wings level flight during tracking.

Future work aims to include uncertainties in the direction and speed of wind used for the wind correction angle and the estimation of the wind from observed line angle during steady state tracking.

VI. CONCLUSION

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