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Attitude Estimation of Launch Vehicles Using GPS/INS and Periodic Yaw Maneuvers

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Abstract

This paper proposes a novel attitude angle estimation technique for low-cost GPS/INS of small launchers. Unlike legacy launchers, low-cost commercial launchers benefit from the more cost-effective option of GPS/INS navigation integrated with a lower-grade IMU, provided that the vehicle attitude can be accurately determined. Unfortunately, the attitude motion of space launchers is very slow and limited, so GPS/INS navigation does not have sufficient observability to accurately determine attitude angles, especially with roll angle. Since roll angle errors do not produce significant trajectory error, they are not easily detected. Using additional sensors can be helpful but the sensor calibration process can be tedious or unreliable. Instead, we propose an observability improvement method based on intentional perturbation of the ascending trajectory. It is found that periodic yaw maneuvers significantly improve the accuracy of attitude estimation while minimizing the additional propellant required for additional motion. Since load reduction is a major concern during first-stage burn, the proposed method is only applied during upper-stage burns. If there is a roll attitude error, the yaw maneuver will produce INS position and velocity outputs that are different from the GPS measurements. These trajectory errors help the onboard navigation filter estimate the roll angle error and roll gyro bias. We chose a sinusoidal yaw motion to improve observability for the following reasons: First, the sinusoidal guidance command ensures that the perturbed trajectory remains close to the nominal trajectory. Since the reference ascending trajectory is optimized as the minimum-fuel trajectory, in general, the perturbed trajectory produced by additional maneuvers should remain close to the reference trajectory to save the additional fuel amount. Second, the yaw maneuver is more efficient than the pitch maneuver since the nominal pitch angle changes significantly along the ascending trajectory but the nominal yaw angle remains small. Since an analytical method is not currently available for determining the optimal maneuver to improve the observability, we rely on a 6-degree-of-freedom simulation of a realistic launcher model including the attitude control and explicit guidance algorithms. The navigation and orbit insertion performance of the proposed method are then compared with those obtained by applying other maneuvers or pure SDINS navigation. The simulation results show that the proposed low-frequency periodic yaw maneuver strategy significantly improves the accuracy of roll angle estimation while the additional propellant consumption is less than 0.1% of the total upper stage propellant.

INTRODUCTION

As the New Space era dawns, launch vehicle technology is receiving more attention than ever. One of the most significant challenges in space economics is the launch cost per unit mass. Many launch vehicle companies, including SpaceX and Rocket Lab, have reduced their cost by recovering the vehicle using reusable rocket technology or by downsizing and focusing on the small payload market. In fact, the cost of navigation equipment accounts for a large portion of launch expenses. Historical disposable rockets typically relied on high-precision navigation-grade IMUs for navigation, without any external assistance. However, this approach may be inappropriate for modern low-cost commercial launch vehicles. A more cost-effective solution could be using GPS/INS navigation integrated with a tactical-grade IMU.

By using loosely coupled integrated GPS/INS navigation, the accuracy of position and velocity estimation can be significantly improved. However, the performance of attitude estimation has its own limitations due to the lack of observability (Rhee 2004, Hong 2005, Beaudoin 2015, 2018). Specifically, it is much more difficult for the launcher to estimate the roll angle than to determine the pitch and yaw angle, because the variations in the roll angle do not significantly affect the trajectory change that could be detected by the GPS measurement. This point has been studied in detail by (Hong et al. 2005) and the author described the lack of observability of the gyroscope bias, especially aligned with the direction of the specific force.

Previous studies have proposed several techniques to improve the limited observability in integrated GPS/INS navigation. One of the simplest methods is to use additional measurement data. (Theil 2008, 2009) used a star tracker for the launcher and (Barczyk 2010) used a magnetometer for an unmanned aerial vehicle as an additional attitude sensor. In addition, multi-antenna GPS (Cohen 1992) can also be used. However, these approaches can be vulnerable to sensor failures and noise, and can increase the complexity of the system. In addition, the calibration process is demanding. (Madsen 2003, Hong 2020, Sanwale 2022) used GPS signal strength or carrier signal phase to estimate attitude, however, these methods require additional GPS signal processing which can be quite a challenging task. (Beaudoin 2015, 2018) studied the observability analysis of different approaches to improve the estimation. The author stated that the roll angle estimation improves with reference sensors and the reference attitude data can help to reduce the standard deviation of the roll error estimation, but the reference data may be unreliable due to various uncertainties during the ascending flight.

In this paper, the "periodic yaw maneuver" method based on the in-flight alignment (IFA) concept is used to avoid additional sensors or reference attitude data. The changes in acceleration and attitude can affect the observability of the system and this is called IFA. (Rhee 2004) analyzed simple cases of linear acceleration and lever rotation and (Hong 2005) studied scenarios with constant angular velocity. There are few studies on IFA-based methods to improve the observability of integrated GPS/INS navigation systems, especially with launchers. Intuitively, one may think that the IFA-based method is not desirable for launchers because the predefined trajectory is optimal in terms of fuel and the deviation from the trajectory can increase the fuel consumption (Beaudoin 2018). However, we will show that a small trajectory perturbation does not significantly increase fuel consumption and can improve estimation performance.

In the following section, we explain the rationale for choosing periodic yaw maneuvers as an appropriate motion for launch vehicles and discuss the parameters of these maneuvers. In the RESULT AND DISCUSSION section, we describe how we correctly select the parameters and discuss the need for additional maneuvers in the closed-loop guidance phase. As a result, it is shown that the additional fuel cost for an additional maneuver is only less than 0.1% of the total fuel consumption during upper stage burn.

METHOD

Periodic Yaw Maneuver for Observability Enhancement

Launch vehicle usually estimate its initial attitude precisely using initial attitude alignment procedure right before ascent flight. However, when we use tactical-grade IMU, non-trivial gyro bias can affect this procedure and make attitude estimation inaccurate before and during launch. Since launch vehicle experiences a large axial force during ascent, the pitch and yaw angles are observable but the roll angle is not observable at all. Unless the vehicle has transversal forces such as normal and side force, no information on roll motion is provided to the navigation filter since roll motion does not cause any change in the velocity measurement of GPS. In detail, this property is hard to prove by observability analysis but can be explained heuristically as follows: The normal force produces normal acceleration, and by altering the roll and pitch angles, the acceleration vector modifies the velocity and position trajectory. This enhances the observability of the roll and pitch angles. Similarly, lateral acceleration caused by a lateral force improves the observability of the roll and yaw angles.

Although the normal or lateral force is necessary for roll angle observability, generating transverse forces using arbitrary maneuver during climb is undesirable for the following reasons. First, when the vehicle passes through a high dynamic pressure region, arbitrary maneuver may significantly increase the aerodynamic load and threaten the structural stability. Since the design of the climb trajectory during first stage burn is mainly concerned with load reduction with fuel minimization, additional maneuver may cause the mission to fail. Second, since the vehicle does not know its own attitude, excessive maneuver may increase the possible instability of the attitude control loop. This is because the attitude error feedback information differs from the actual error, and when this deviation exceeds the control authority, the control system may easily fail. Third, excessive attitude maneuver may cause the vehicle to deviate from the nominal trajectory that is optimal in terms of fuel, which may decrease the launch delta-V and increase the fuel cost. Trajectory perturbation must be minimized for launch performance when designing the maneuver. Finally, excessive maneuvering during upper stage burn can adversely affect the stability and performance of the explicit guidance algorithm. This can increase burn time, consume a lot of fuel, and degrade performance.

In this study, we propose a periodic or sinusoidal yaw maneuver to improve observability. We assume a typical 3-stage launch vehicle for this study. The vehicle consists of a first stage and an upper stage, which includes both the second and third stages. To avoid additional aerodynamic loading during endoatmospheric flight, the proposed method is only applied to the upper stage burns. The periodic yaw maneuver is characterized by two parameters due to its sinusoidal property: maneuver amplitude and frequency, A_Ψ [rad] and f_Ψ [Hz] for each.

$$\Psi_{\text{pert}} = A_\Psi \sin(2\pi f_\Psi) \tag{1}$$

This perturbed yaw angle command is added to the original yaw angle command of the open-loop nominal pitch program. One advantage of this maneuver is that the perturbed trajectory can stay close to the nominal trajectory. This can reduce the additional fuel required for intentional maneuvers by staying around the fuel-optimal trajectory. Moreover, since the nominal pitch angle already changes significantly during launch unlike the nominal yaw angle, perturbation with the yaw angle is much more effective for better observability. In the pitch program, the nominal pitch angle changes from 90 degrees to -40 degrees relative to the launch frame, but the nominal yaw angle is between -10 and +10 degrees. Since excessive trajectory perturbation is undesirable, a slight change in the yaw angle can be much more effective than perturbation of the pitch angle. Finding the optimal yaw maneuver for enhancing attitude estimation performance is very challenging due to the complexity of the observability analysis. Therefore, in this study, we rely on a 6-DOF simulation of a high-fidelity launcher model including attitude control and an explicit guidance algorithm for orbit insertion. The IMU specification we used in this study is given in Table 1.

Table 1. Specification of IMU Gyroscope

Specification of Gyroscope	Unit	Value
Bias Instability	[deg/hr]	3.3
Angular Random Walk	[deg/$\sqrt{\text{hr}}$]	0.18
Bias Repeatability	[deg/sec]	0.02

RESULT AND DISCUSSION

Parameter Selection for Periodic Yaw Maneuvers

In the simulation study, we evaluate the performance of the attitude angle estimation of the navigation filter under different parameter values for periodic yaw maneuvers. First, we need to select appropriate parameter values for the perturbed yaw control Eq.(1). As mentioned earlier, in order to ensure the stability of the explicit guidance algorithm of the 3rd stage, it may be desirable that the perturbed yaw control is added only to the predefined open-loop yaw program for the 2nd stage, where the proposed maneuver starts at the separation of the 1st stage and ends at the separation of the 2nd stage. The separation of the 1st stage occurs at 128 seconds and the separation of the 2nd stage occurs at 276 seconds. The parameters of each yaw maneuver are given in Table 2.

Table 2. Parameters of Each Yaw Maneuver for 2$^{\text{nd}}$ Stage

Method ID	Amplitude (A_Ψ) [deg]	Frequency (f_Ψ) [Hz]
Method 1-1	1	0.05
Method 1-2	5	0.05
Method 1-3	10	0.05
Method 1-4	5	0.02
Method 1-5	5	0.1

The amplitude values are proposed based on a minimally deviated trajectory for fuel optimization. A larger amplitude results in a more noticeable trajectory perturbation, but it may lengthen the time required for orbit insertion, which results in increased fuel consumption. In this simulation, the amplitude is limited to 10 degrees. As for the command frequency, the system response can affect the value. Although a shorter period command can improve observability by causing drastic changes in the trajectory, limiting the actuator speed prevents the controller from following the maneuvering command. The frequency parameter is limited between 0.02 and 0.1 Hz.

Figure 1 illustrates the attitude estimation error for three different maneuver amplitudes, all performed at the same frequency of 0.02 Hz described in Figure 2. As a nominal case, the “No Yaw Maneuver” scenario is included, where no intentional yaw maneuver is performed except for the predefined yaw program. The pitch and yaw angle estimation error remains within 0.5 degrees after 30 seconds even in the nominal case, but the roll angle estimation is inaccurate and does not converge if there is no significant trajectory change. Figure 1 clearly shows that all three maneuvers are reliable enough to reduce the roll angle estimation error after the maneuver start at 130 seconds, compared to the nominal case. However, as we can see in Figure 3, the trajectory perturbation can be larger depending on the amplitude of the maneuver. The speed trajectory using Method 1-1 remains the closest to the reference trajectory with "No Navigation Error", except for the "No Yaw Maneuver" scenario.

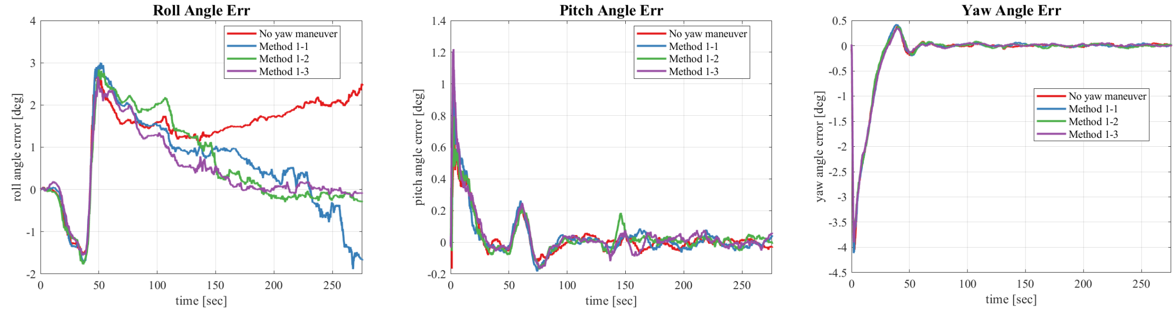

Figure 1. Attitude Estimation Error for Method 1-1, 1-2, and 1-3

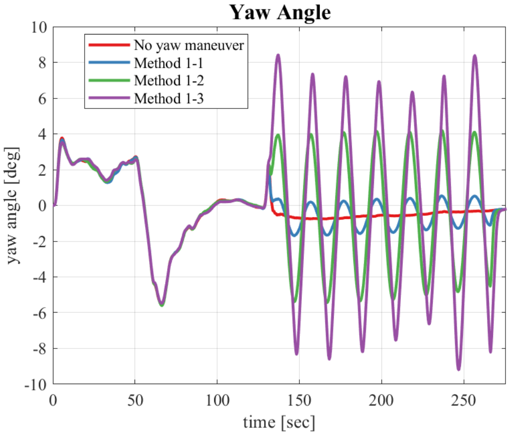

Figure 2. Yaw Angle Before 2nd Stage Separation

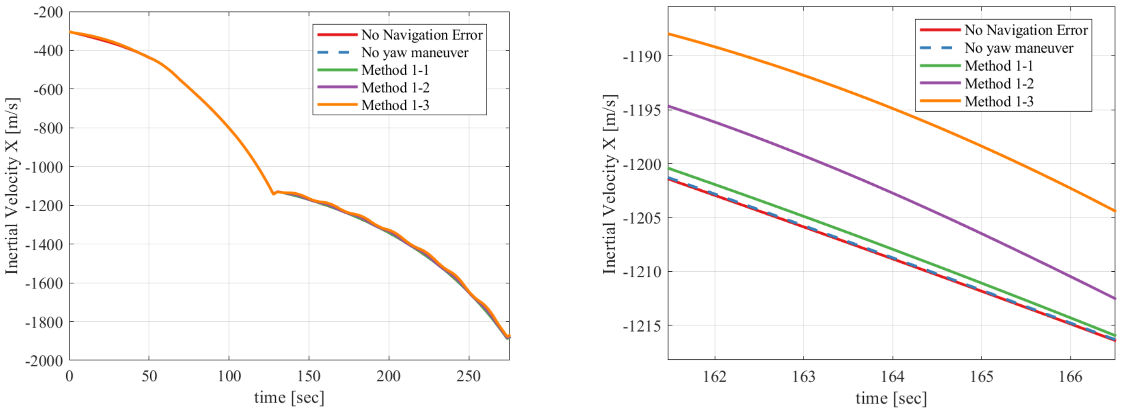

Figure 3. Velocity Trajectory for Method 1-1, 1-2, and 1-3

Figure 4 shows the attitude estimation error for three different maneuvering frequencies, all performed at the same amplitude of 3 degrees. All three methods show better performance for roll angle estimation than the nominal case. The pitch and yaw angle errors are limited during launch, and the roll angle error also converges to zero. Among the three cases, Method 1-2 makes the roll angle error converge to zero stably. Especially for Method 1-5, since the system response cannot keep up with the maneuvering speed, the maneuver amplitude is smaller than the desired amplitude, 5 degrees. Therefore, considering the trajectory disturbance and stable performance, we can conclude that Method 1-2 is the most suitable maneuver among these 5 parameters in Table 2.

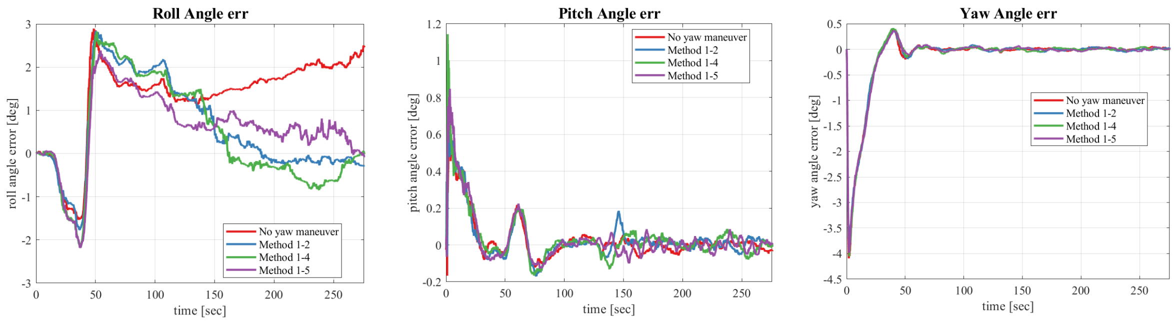

Figure 4. Attitude Estimation Error for Method 1-1, 1-4, and 1-5

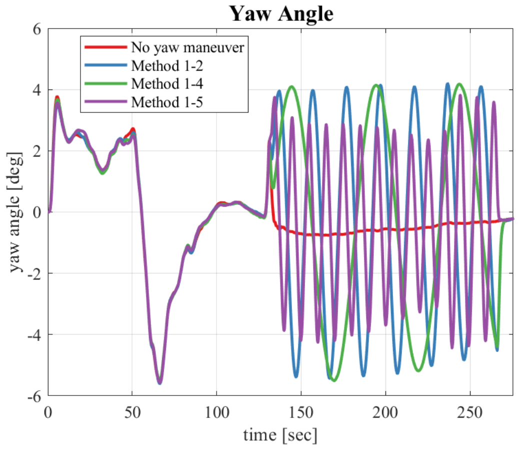

Figure 5. Roll Angle Before 2nd Stage Separation

Periodic Yaw Maneuvers for 3rd Stage Burn

The upper stage of the launch vehicle needs to fly for a few minutes using explicit guidance for orbit insertion after stage separation. The vehicle model in this study is no exception, and this may result in significant roll angle estimation errors due to the long flight time. Figure 6 shows that assuming no intentional maneuver, the roll angle estimation error may diverge by more than 5 degrees and this may be fatal for the stability of the system. Therefore, a periodic yaw maneuver with an appropriate level should be added to the explicit guidance without compromising the stability and performance of the algorithm. We found that integrating periodic yaw maneuvers into the whole explicit guidance process results in a delay in orbit insertion time and an increase in fuel consumption. A proper timestamp for the yaw maneuver in the 3rd stage is necessary, so we will compare the results of several different maneuver-time programs shown in Table 3.

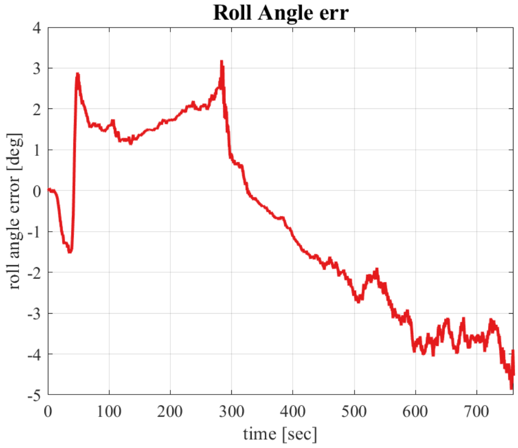

Figure 6. Roll Angle Estimation Error Until Orbit Insertion for "No Yaw Maneuver" Case

Table 3. Timestamps for yaw maneuver in explicit guidance

Method ID	t_{go} (sec)
Method 2-1	All time during explicit guidance
Method 2-2	400-320 / 240-160 / 80-10
Method 2-3	400-320 / 80-10
Method 2-4	240-160
Method 2-5	80-10

Method 2-1 adds a yaw maneuver during the entire explicit guidance process, and the other methods add it within the time prescribed in Table 3. For example, in Method 2-3, when t_{go} is between 400 sec and 320 sec, the yaw guidance command is added to the original guidance command. After t_{go}=320 sec, it stops and restarts when t_{go} is between 240 sec and 160 sec. Note that the yaw maneuver is already added to the 2nd-stage burn, and the parameters of Method 1-2 are used.

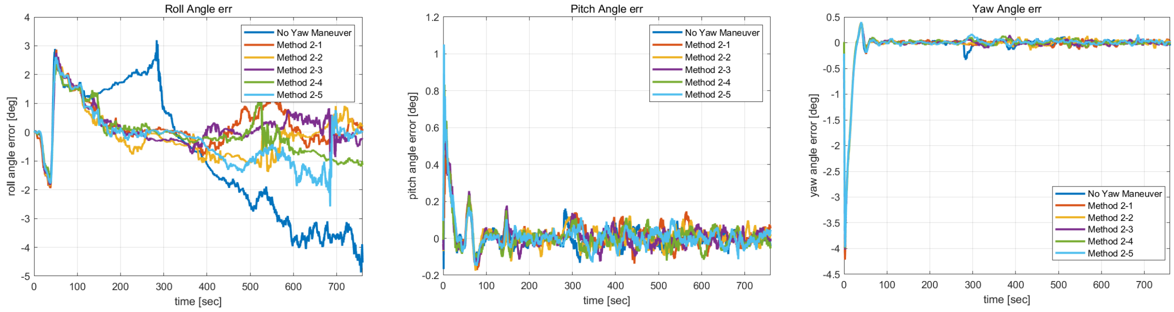

Figure 7. Attitude Estimation Error for Method 2-1 ~ 5

Figure 7 shows that all methods are quite effective for preventing attitude estimation error from diverging. However, Method 2-4 and 2-5 exhibit a lack of observability over extended periods. Attitude estimation errors diverge by more than 1 degree before and after the maneuver for each method. This means Method 2-4 and 2-5 is not adequate for this tactical IMU. Figure 8 illustrates Method 2-1 consumes relatively lots of fuel due to delayed orbit insertion. We observe that Method 2-4 is the most-efficient in terms of fuel cost because it has no maneuver in final time and the stability of explicit guidance is enhanced. Therefore, Method 2-3 can be middle ground for estimation performance and fuel usage. Additional fuel cost for this method is only less than 0.1% of total fuel consumption during upper stage burn.

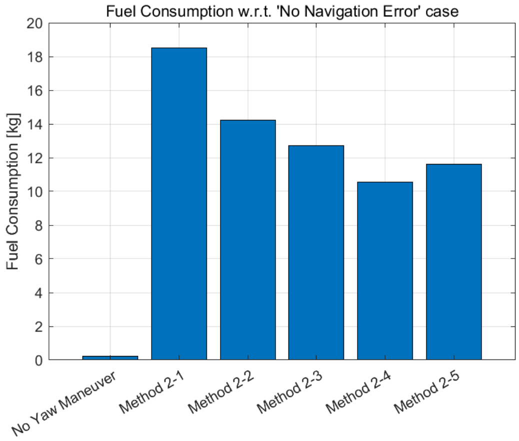

Figure 8. Fuel Consumption w.r.t. “No Navigation Error” Case

CONCLUSION

This paper proposes a novel approach using a periodic yaw maneuver to estimate attitude angles with the launcher's GPS/INS navigation. To improve the observability of roll angle estimation, a periodic yaw maneuver is added to the pre-designed yaw program and explicit guidance. By comparing the estimation performance and trajectory deviation, proper parameters are selected and applied to upper-stage guidance. Arbitrary maneuvering with explicit guidance may degrade the algorithm performance, so multiple timestamps are tested in terms of fuel consumption and estimation performance. It is shown that the additional fuel consumption due to the yaw maneuver is quite small compared to the fuel cost during upper stage burn. Note that the chosen parameters may differ for each tactical IMU specification. How to choose proper maneuver parameters for general tactical IMU using a theoretical analysis will be the subject of future work.

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