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Atmosphere Tolerant Acquisition, Tracking and Pointing Subsystem

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ABSTRACT

For high rate communications such as optical communications, tracking loss can result in substantial reduction of average data rate and the total data volume of the transmitted data. For optical communications, which transmits laser beam through atmosphere, atmospheric induced fades of the beacon signal can vary significantly as observed in ground-to-ground optical experiments. In this paper, we propose a new scheme of compensating the atmospheric induced fading effects using inertial sensors. By measuring the platform vibrations, the beacon movements on the Focal Plane Array can be deduced even if the beacon is lost due to fading. By avoiding the new cycle of reacquisition and tracking, high rate communication can be maintained. The allowable period of beacon fade depends on the inertial sensor noise characteristics and acquisition and tracking Field-Of-View. We will present the results of our analysis for the planned Altair UAV-to-Ground optical communications demonstrations using an accelerometer.

Keywords: Optical communications, Acquisition, tracking, Pointing, Atmosphere, Fade

1. INTRODUCTION

In any optical beacon based pointing system whose beacon travels through atmosphere, atmospheric induced fade occurs with various fade periods depending on the driving phenomenon. In the recent ground-to-ground optical link demonstrations, fade depth of more than 10 dB and mean numbers of fades per second of more than 1000 were observed for more favorable night time and the multi-beam beacon comprised of eight laser beams [1]. During such fade periods, the tracking terminal loses the line-of-sight to the receiver. These fades are generally caused by atmospheric conditions (scintillations, beam wandering, clouds, rain), but may be caused by other situations (blocked line-of-sight due to objects, trees, buildings, etc.). The fades affect all three stages (Acquisition, Tracking, and Pointing) of optical communications.

The conventional Acquisition, Tracking, Pointing (ATP) systems are vulnerable to the fades. Therefore, additional margin is usually built into the system to tolerate the fades. However, this approach has limitation for severe fades or completely blocked beacon beam. During acquisition and reacquisition stages, the severe fades re-initialize the search procedure, causing additional time for acquisition. During tracking/pointing stage, those systems simply lose the communication link if the fade depth exceeds the designed margin. Consequently, data transmission is interrupted until reacquisition of the beacon and handover to tracking is completed. Over the whole communication period, each atmospheric induced fade can potentially disrupt communication link. As the number of fades increases, the average data rate decreases, thereby, requiring an increase in the transmission period to complete the transfer of the planned total data volume. This problem is exacerbated for high data rate (multi-Gigabit/second) optical communications systems, where a short (millisecond) fade can cause delay or loss of Megabits of information per fade. For example, this would be equivalent to 24 seconds of loss time to be ready to re-transmit data in the worst case for the optical communications system designed for an experiment onboard International Space Station, or maximum data volume of 60 Gigabits [2].

Since the fades doesn't necessarily change the LOS of beacon beam, the pointing information from the beacon beam position from the Focal Plane Array (FPA) can be substituted by measuring the relative platform position with respect to the last seen beacon position on the FPA. This is the basic principle of our approach. This can be executed with the novel application of inertial-sensors. Information from the inertial-sensors can be combined with the existing beacon tracking algorithms, yielding a compensating tracking algorithm that provides the necessary pointing information to maintain a stable, uninterrupted optical communications link for a longer period of time than the current state-of-the-art systems. This new technology adds the capability, to the ATP system, to tolerate fades during optical communications transmissions.

The tracking scenarios of the new fade tolerant ATP system are as follows:

a) Substitution beacon position on FPA with angular displacement estimates from inertial sensor measurements when beacon beam is not present or below the threshold level required for the accuracy,
b) Utilize beacon beam centroids when beacon beam is present and exceeds the threshold level, with option of using angular displacement estimates from inertial sensor measurements for high bandwidth tracking.

The advantages are:

a) Stable tracking during fades
b) Feasible data transmission during fades
c) Increased ranges of communication for the same beacon power
d) Requires lower beacon power to maintain link for the same range

The disadvantages are:

a) Added mass of inertial sensors
b) Added complexity of the new tracking algorithm

The innovation of our approach is the application of inertial sensors to mitigate ‘random’ fade effects to the ATP system while, in contrast, many conventional inertial sensor based tracking concepts use inertial sensors to increase tracking bandwidth for the ‘steady’, low intensity beacons [4].

The objective of this paper is to discuss the added benefits of the new technology to the current ATP systems and to present the supporting analysis. Section 2 discusses our approaches to the atmospheric fade problems. Section 3 shows the analysis results using Honeywell’s QA-3000 linear accelerometers. Section 4 summarizes the paper.

2. OUR APPROACHES

2.1 Problem description

Figure 1 conceptually describes the weakness of the existing beacon based pointing system for a fade problem. A typical beacon based optical communications acquisition, tracking and pointing (ATP) system requires presence and successful detection of a beacon all the time from acquisition to pointing stages. Relative difference between the measured beacon position and the transmit laser position on the FPA gives the necessary pointing information (pointing direction and magnitude) to command the fine steering mirror. Failure in this fundamental operations causes additional acquisition time in acquisition and re-acquisition stages due to re-initialization and loss of communication link/or deterioration of pointing performance during tracking/pointing stages. Atmospheric induced fade lowers beacon intensity due to intensity attenuation. In some cases, beacon beam can be completely blocked due to objects such as buildings and trees. Update rate of beacon position is usually low at acquisition stage (typically, tens of Hertz). However, this is typically done at a relatively high update rate (few KHz) during tracking/pointing in order to compensate for platform vibrations.

2.2 Approaches

The atmospheric fades cause loss or inaccuracies of beacon detection in ATP operations. If the platform were not moving at all, the position of beacon on FPA would always be identical. Then, one-time beacon detection would be sufficient for all ATP process. However, this is not the case in reality. Beacon position on FPA varies due to several factors: atmospheric induced beam wandering on the order of micro-radians and platform vibrations typically on the order of tens of micro-radians or larger [5]. Host vehicle’s slewing motion also varies the beacon position slowly. However, this is normally compensated by coarse tracking control that uses a gimbal. Accurate measurements of this dominant platform vibration would yield good estimates of beacon positions on the FPA, which can be used to substitute the beacon centroiding measurements and closing the tracking control loop. This would enable continuous data transmission without interruption. This is our key concept to mitigate atmospheric induced fading in ATP system operation and depicted in Figure 2. The measurements of platform vibration can be done using various inertial sensors: gyros, angle sensors, angular rate sensors, and accelerometers. The requirements on the vibration measurements are accuracies (random error and bias) and update rates that are determined by fade durations. Deduced beacon position estimated from the platform vibration deviates from the true position as a function of time. At a certain time when the error exceeds the allocated error budget, the tracking performance, hence, the pointing performance deteriorates beyond the design numbers. This forces either a) reduction of data rate, or b) interruption of data transmission until more accurate tracking can be restored. Further deviation from the beacon position can yield total loss of tracking when the beacon spot moves out of FPA field-of-view (FOV). This activates re-acquisition. While a typical atmospheric fade period is on the order of 1 millisecond [1], the maximum duration that the inertial sensors can keep accurate pointing ('blind' compensation), can be much longer period depending on the pointing error budget.

Analysis results presented in the section 3 shows that it can maintain tracking up to 3 seconds for the proposed Altair UAV-to-ground lasercomm system [3]. The limitation as to how long the 'blind' compensation can be maintained is limited by the inertial sensor induced error in pointing from the last real observation of the target (external beacon).

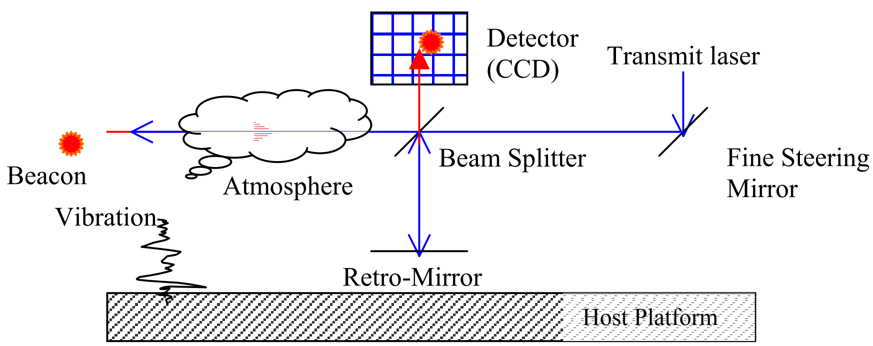

Figure 1. Typical optical communications acquisition, tracking, and pointing system is vulnerable to atmospheric induced fades.

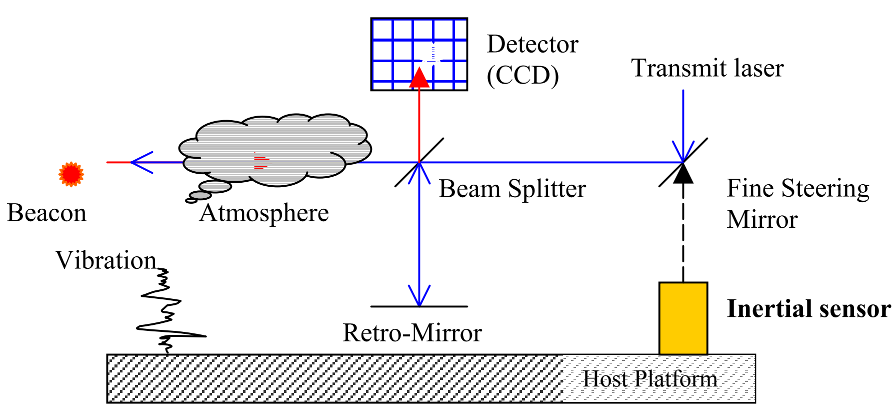

Figure 2. Atmospheric Fade Tolerant ATP System using inertial sensors – even without beacon on detector, inertial sensors measure the platform vibrations and deduce the beacon motion, thereby can command the fine steering mirror for accurate pointing beyond the duration of fades. Inversely, we can lower the beacon power for the required pointing accuracy, still with all the benefits of fade tolerant features.

3. ANALYSIS ON BEACON FADE TOLERANCE

Mitigation of beacon fades is critical to the stability of both pointing operation and accuracy. Without the help of inertial sensors, this will cause a) larger pointing error than the budget, b) loss of tracking. Of course, fade duration and inertial sensor performance are the key factors.

The objective of this section is to a) Determine the maximum pointing duration during which we can track the ground station without beacon (due to fades) using inertial sensors, for example, QA-3000 accelerometers b) Determine the maximum tracking duration during which the beacon does not exit tracking window when the tracking relies on only accelerometers. The selection of the accelerometers was due to its availability and fairly good performance in terms of both noise and frequency response.

3.1 Assumptions

The two numbers, pointing error budget for accelerometer induced error and tracking FOV, determine the maximum pointing and tracking fade duration for the specified QA-3000 accelerometer performance. We assume the Altair UAV to ground optical communication experiment as a baseline for the following illustrations [3]. The following lists are the assumptions for the analysis.

a) Pointing error budget for accelerometers: the total pointing error budget for jitter is 10% of beam or 20 μrad. Since the major error is from platform vibration and there are about 10 different minor error sources, several micro-radians (less than 5 μrad) would be the maximum allocation for accelerometers.
b) Tracking FOV: The tracking FOV is 5 mrad and divided into two sub-windows: beacon tracking window and transmit laser-tracking window. Each sub-window is 2.5 mrad x 2.5 mrad. So if the nominal beacon position is in the middle of the beacon-tracking window, the maximum displacement is 1.25 mrad.
c) Accelerometer performance: We used the noise measurement (340 μg, rms) of QA-3000 accelerometers in the laboratory to derive the expected performance in angular displacement measurement. This is a conservative estimate since the noise is mostly due to building vibration. Lower noise level is expected in the field demonstrations. Two accelerometers separated by 15 cm gives a single axis angular displacement estimates or three accelerometers give two axis angular displacement estimates. The details of this estimation procedure are explained in the following subsection and summarized in [4]. The sampling rate of 5kHz is assumed.

3.2 Angular displacement estimation using three linear accelerometers

Angular displacements on two axis (α, β) can be obtained using three linear accelerometers as shown in Figure 3.

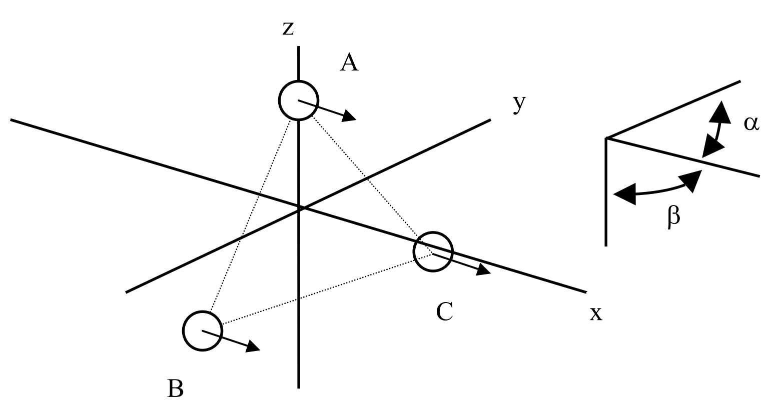

Figure 3. Triangular configuration of three accelerometers

Three accelerometers are placed on the y-z plane. Assume acceleration is in x-direction, and then displacement estimation using accelerations from B and C gives an angular displacement (α) on x-y plane (difference in displacements divided by the separation). Using A and the mean of B and C gives an angular displacement (β) on the x-z plane.

The linear displacement estimates from the linear accelerations are described as follows. We assume that the acceleration to be continuous function as represented as a(t). a(t) is sampled at a fixed rate, producing the samples denoted as a_N for its N^{th} sample, taken at time, T_N. The acceleration sample is assumed to require no integration time. The corresponding estimates for velocity and position are denoted as v_N and p_N, respectively.

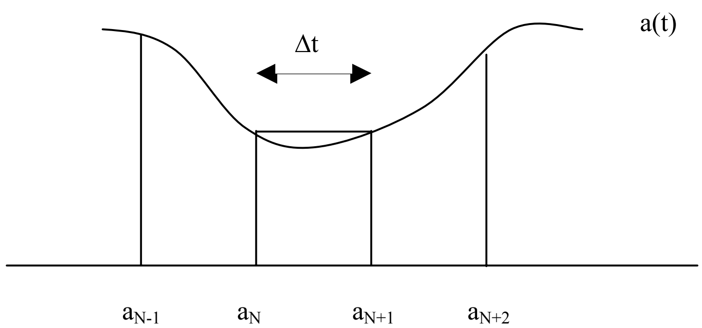

Figure 4. Sampling of continuous acceleration a(t).

Let $a_N(t)$ represent continuous acceleration between sampled accelerations, a_N and a_{N+1}, where t=0 corresponds to the sampling time T_N. Since there is no further information available between two samples, we assume the intermediate acceleration value varies linearly. We introduce the linear interpolation function $a_N(t)$ with sampling interval of [0, Δt] defined by

$$a_N(t) = (a_{N+1} - a_N)t/\Delta t + a_N \tag{1}$$

Note that for t =Δt,

$$a_N(\Delta t) = a_{N+1} \tag{2}$$

Let's consider only two sample points, a_N and a_{N+1}. The integration of $a_N(t)$ from 0 to t gives the corresponding velocity $v_N(t)$:

$$v_N(t) = (a_{N+1} - a_N)\, t^2/(2\Delta t) + a_N t + v_N,\ v_N \text{ the initial velocity at } t = 0 \tag{3}$$

For t =Δt,

$$v_N(t{=}\Delta t) = v_{N+1} = (a_{N+1} + a_N)\,\Delta t/2 + v_N \tag{4}$$

which is the area below the straight line connecting the two points, a_N and a_{N+1} (Figure 4). Notice that the error exists in velocity estimate due to the difference between the true area and our estimate because of our assumption on linearly varying acceleration. This velocity error propagates through position estimates.

Similarly for position estimate, integrating Eq. (3) gives

$$p_N(t) = (a_{N+1} - a_N)\, t^3/(6\Delta t) + a_N t^2/2 + v_N t + p_N,\ p_N \text{ position at } t = 0 \tag{5}$$

For t =Δt,

$$\begin{aligned} p_N(t{=}\Delta t) = p_{N+1} &= (a_{N+1} - a_N)\,\Delta t^2/6 + a_N \Delta t^2/2 + v_N \Delta t + p_N \\ &= a_{N+1} \Delta t^2/6 + a_N \Delta t^2/3 + v_N \Delta t + p_N \end{aligned} \tag{6}$$

The procedure in Eq. (6) is summarized in Figure 5.

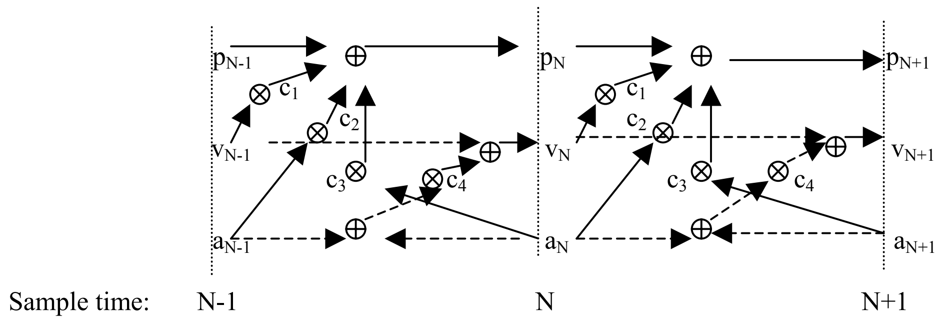

Figure 5. Diagram illustrating the position estimation procedure from acceleration measurements. Multipliers (c_1 to c_4) are: $c_1 = \Delta t$, $c_2 = \Delta t^2/3$, $c_3 = \Delta t^2/6$, $c_4 = \Delta t/2$.

Eq. (6) can be rewritten in terms of acceleration with initial values of velocity and position. From Eq. (6),

$$
\begin{aligned}
& p_1, v_1 \text{ : initial values of position and velocity} \\
& p_2 = a_2\,\Delta t^2/6 + a_1\,\Delta t^2/3 + v_1\,\Delta t + p_1 \\
& p_3 = a_3\,\Delta t^2/6 + a_2\,\Delta t^2/3 + v_2\,\Delta t + p_2 \\
& \quad = a_3\,\Delta t^2/6 + a_2\,\Delta t^2/3 + \\
& \qquad a_2\,\Delta t^2/6 + a_1\,\Delta t^2/3 + (a_2 + a_1)\,\Delta t^2/2 + 2v_1\,\Delta t + p_1 \\
& p_4 = a_4\,\Delta t^2/6 + a_3\,\Delta t^2/3 + v_3\,\Delta t + p_3 \\
& \quad = a_4\,\Delta t^2/6 + a_3\,\Delta t^2/3 + \\
& \qquad a_3\,\Delta t^2/6 + a_2\,\Delta t^2/3 + (a_3 + a_2)\,\Delta t^2/2 \\
& \qquad a_2\,\Delta t^2/6 + a_1\,\Delta t^2/3 + (a_2 + a_1)\,\Delta t^2/2 + (a_2 + a_1)\,\Delta t^2/2 + 3v_1\,\Delta t + p_1 \\
& \qquad \vdots \\
& p_N = \Delta t^2(a_2 + \ldots + a_N)/6 + \Delta t^2(a_1 + \ldots + a_{N-1})/3 + (N-1)\,v_1\,\Delta t + p_1 + \\
& \qquad (N-2)a_1\Delta t^2/2 + \\
& \qquad (2N-5)a_2\Delta t^2/2 + \\
& \qquad (2N-7)a_3\Delta t^2/2 + \\
& \qquad (2N-9)a_4\Delta t^2/2 + \ldots\ldots \\
& \quad = \sum_{i=2}^{N-1} (N-i)a_i\Delta t^2 + (N/2-2/3)a_1\Delta t^2 + a_N\Delta t^2/6 + (N-1)\,v_1\,\Delta t + p_1 \qquad (7)
\end{aligned}
$$

where N is the number of acceleration measurements and Δt is the sampling period such that $N = T/\Delta t$ for the total integration time of T.

3.3 Analysis results

The position estimation error (variance) can be expressed as a function of the random error (1 sigma value) in acceleration, σ_a, assuming the a_i's are iid (independent, identically distributed) random variables. From Eq. (7),

$$\sigma_{pN}^2 = (\Delta t^2)^2 \sum_{i=2}^{N-1} (N-i)^2 \sigma_a^2 + (\Delta t^2)^2 (N/2-2/3)^2 \sigma_a^2 + \sigma_a^2 (\Delta t^2)^2/6^2$$

The standard deviation of position estimation using N samples of acceleration measurements then becomes

$$\sigma_{pN} = \Delta t^2 \sigma_a \left(\sum_{i=2}^{N-1} (N-i)^2 + (N/2-2/3)^2 + 1/36 \right)^{1/2} \tag{8}$$

An angular displacement estimation error can be derived assuming the two linear displacement estimates, d_1 and d_2 are iid random variables with its rms error of σ_{pN} in Eq.(8).

$$\sigma_\theta^2 = (\mathrm{Var}(d_1) + \mathrm{Var}(d_2))/l^2$$
$$= 2\,\sigma_{pN}^2 / l^2$$

or $\sigma_\theta = \mathrm{sqrt}(2)\, \sigma_{pN} / l$, where l is the separation between two accelerometers. (9)

Figure 6 shows the resulting angular displacement estimation error vs. duration (or integration period).

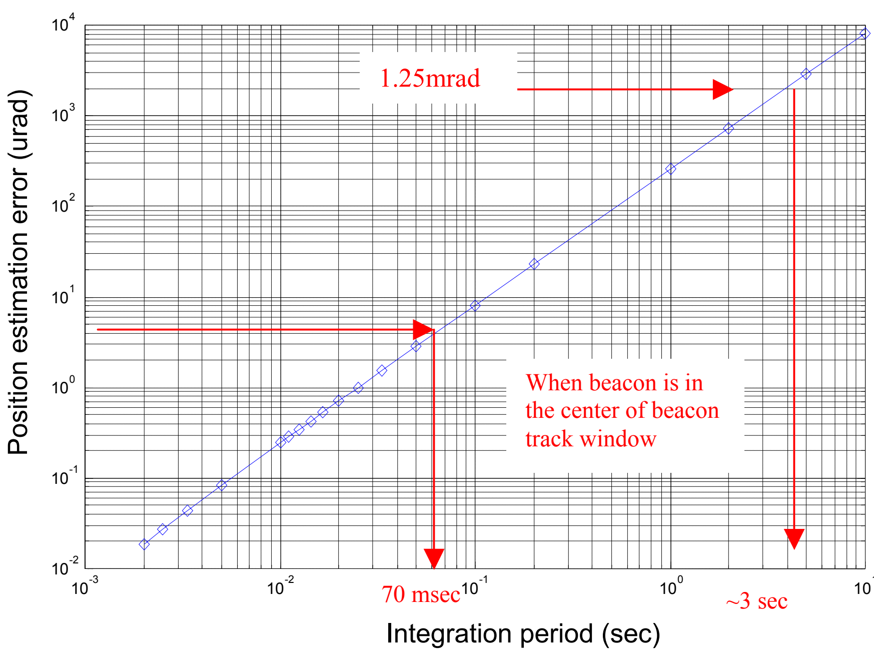

Figure 6. Angular displacement estimation error vs. duration (integration time)

As shown in Figure 6, if we limit the angular displacement estimation error (or pointing error budget for accelerometer induced error) to 5 μrad, the duration is about 70 msec. The maximum duration before tracking loss is 3 sec. This case corresponds to the beacon being centered in the beacon-tracking window [3]. Table 1 and 2 shows the approximate durations for various pointing error budgets for the angular displacement estimation error. Even if the accelerometer-induced error exceeds the pointing error budget in Table 1, it does not necessarily mean link failure. The communication link can still be maintained while increasing BER or reducing data rate.

Table 1. Max pointing duration vs. pointing error budgets (to maintain pointing)

Pointing error budget	Max pointing duration
0.1 μrad	5.5 msec
1 μrad	25 msec
2 μrad	40 msec
3 μrad	50 msec
4 μrad	60 msec
5 μrad	70 msec

Table 2. Max tracking duration vs. accelerometer induced error (to maintain beacon within tracking window)

Accelerometer induced error	Max tracking duration
1.25 mrad	3 sec

4. CONCLUSION

A new technique to mitigate atmospheric induced fades was proposed for ATP system of optical communications. Our approach was to employ inertial sensors to mitigate the fade effects by deducing the beacon positions on FPA by measuring platform vibration, which is the dominant source for beacon movement on FPA. The resulting benefits are stable tracking/pointing, less laser beacon power for the same communication ranges, and higher volume of transmit data. Analysis shows that most beacon fades can be mitigated using commercially available inertial sensors.

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