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Prospects for the Development of Fast-Light Inertial Sensors

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LIST OF ACRONYMS

ARW	angular random walk
CAESAR	Comet Astrobiology Exploration SAmple Return
EDL	entry, descent, and landing
FL	fast light
IMU	inertial measurement unit
JPL	Jet Propulsion Laboratory
LIDAR	light detection and ranging
MSFC	Marshall Space Flight Center
PT	parity-time
RLG	ring laser gyro
SBIR	Small Business Innovative Research
STTR	Small Business Technology Transfer

TECHNICAL MEMORANDUM

PROSPECTS FOR THE DEVELOPMENT OF FAST-LIGHT INERTIAL SENSORS

1. INTRODUCTION

Next-generation space missions are constrained by existing spacecraft navigation systems which are not fully autonomous. These systems suffer from accumulated dead-reckoning errors and must therefore rely on periodic updates provided by supplementary technologies that depend on line-of-sight signals from Earth, satellites, or other celestial bodies (e.g., GPS, star-trackers) for absolute attitude and position determination, which can be spoofed, incorrectly identified, occluded, obscured, attenuated, or insufficiently available. These dead-reckoning errors originate in the accelerometers and ring laser gyros (RLGs) themselves, which constitute inertial measurement units (IMUs).

Increasing the time for standalone spacecraft navigation therefore requires fundamental improvements in the precision of inertial sensors. The conventional method of increasing the precision of an optical gyro is to increase its size, but this is problematic in spaceflight where size and weight are at a premium. One promising solution to enhance gyro precision without increasing size is to place an anomalous dispersion or fast-light (FL) material inside the gyro cavity. The FL essentially provides a positive feedback to the gyro response, resulting in a larger measured beat frequency for a given rotation rate as shown in figure 1.

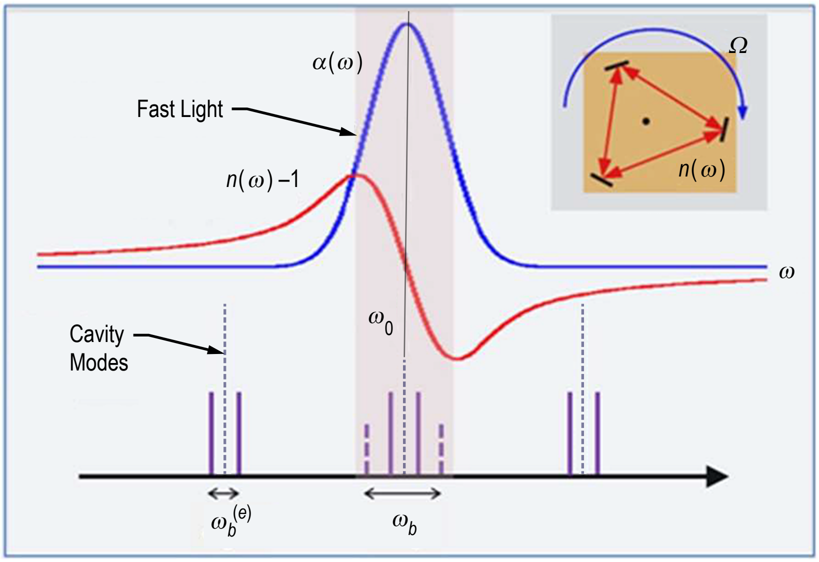

Figure 1. Illustration of how the response of a gyroscope is enhanced by FL. Each cavity mode is split by the rotation of the gyro. In the FL region, the refractive index n decreases with frequency ω, which further separates the modes. The beat frequency ω_b is thus larger than that for the empty gyroscope cavity, $\omega_b^{(e)}$.

Another conventional method to increase precision is to increase measurement integration time. However, this method is problematic in situations where rapid accelerations are required. Under these circumstances a more accurate attitude or position determination is often obtained by taking many quick inertial measurements at a lower precision rather than a few longer ones at a higher precision. Investments in navigation technologies that rely on external signals or celestial landmarks are unlikely to fill this role because they are inherently limited by factors such as large lag times that increase with distance (attitude and position determinations will be in the past) and/or low photon flux (long integration times are required so attitude and position determinations will not be instantaneous). In addition, for sufficiently long integration times, higher-order noise sources, such as bias instability, rate random walk, and rate drift, become dominant and can actually reduce precision. Therefore, there is an upper limit to the approach of increasing the measurement time. On the other hand, it is precisely under these rapid acceleration conditions, where the noise is dominated by angular random walk (ARW), that FL inertial sensors could have their greatest impact. This is because FL is predicted to reduce ARW, potentially by many orders of magnitude (an upper limit has been estimated to be ~10^6 (ref. 1). In contrast, the effects of FL on higher-order noise sources is less well understood.

To summarize, the benefit is that a measurement made at a particular measurement rate for a particular size gyro will be more precise. And, one can trade off this enhanced precision for faster measurements or for smaller gyros; i.e., faster, more precise measurements can be made, with smaller gyros. Therefore, the greatest benefits are likely in situations requiring rapid changes in attitude or position, or where knowledge of the environment is limited or obscured, for example, by dust. Such scenarios include entry, descent, and landing (EDL), surface operations with rovers, formation flying or automated rendezvous and docking, and missions to small bodies including sample return and kinetic impactor missions. Recently, the NASA Jet Propulsion Laboratory (JPL) researchers concluded that, for kinetic impactors, spacecraft attitude knowledge is the single biggest factor in determining impact success, and that even the best currently available IMUs resulted in a significant probability of mission failure.[2]

With sufficient advancement in Technology Readiness Level, FL IMUs could work in conjunction with terrain-relative navigation technologies such as NASA Langley Research Center's Doppler LIDAR and JPL's Lander Vision System to provide an overall solution for precision EDL, potentially even in conditions that obscure these other methods. Fast-light IMUs would also be markedly faster than these other technologies, providing enhanced compensation for last-minute motions; e.g., wind gusts that might occur during landing. The increased precision translates to reduced error ellipses enabling pinpoint landings for improved access to engineering needs and science targets.

Fast-light IMUs could therefore have cross-cutting benefits that span a range of applications from Flagship missions, such as Europa Lander and Mars Sample Return, to crewed missions to near-Earth asteroids, the moons and surface of Mars (DRM 6-9), and Flexible Lunar Explorers for the Moon, to New Frontier missions such as CAESAR, whose robotic arm would momentarily contact the surface of a comet, and international collaborations such as the Double Asteroid Redirection Test.

2. METHODOLOGY

2.1 State of the Art

There are two types of FL cavities that could be used in inertial sensors: passive (probed by an external laser) and active (the laser gain medium is intracavity). Recent work on active cavities[3] has estimated a scale-factor sensitivity enhancement as large as $S = 190$, but this value is inferred from spectra of the gain profile. Experiments at NASA Marshall Space Flight Center (MSFC) on passive FL cavities[4,5] on the other hand, have obtained values as large as $S = 363$ by taking the more direct approach of varying the optical path length and monitoring the change in the cavity mode frequencies. In addition, sensitivity enhancement of passive FL cavities operating in a closed-loop configuration has recently been demonstrated at MSFC,[6] enabling rapid measurements.

A sensitivity enhancement, by itself, is not sufficient to enhance precision, however. Precision is enhanced when the sensitivity increases without a concomitant increase in measurement uncertainty. Numerical calculations for passive cavities have shown that, under near-ideal (high-signal-to-noise and quantum-noise-limited) conditions, the increase in uncertainty is not as large as that in sensitivity, so an overall enhancement in precision can occur as a result of FL. An important and substantial advantage, however, may exist for active cavities. Recent work has predicted that the linewidth of active cavities is unaffected by FL,[7] which implies that the enhancement in precision in active cavities is larger than in corresponding passive cavities, being close to that of the enhancement in sensitivity itself.

A number of approaches to active FL gyros rely on the use of nonlinear optical processes generated by added pump beams,[3] which create a number of challenges such as difficulty of miniaturization, necessity for careful control of cavity and laser parameters via sophisticated control schemes, as well as added sensitivity to environmental effects. These nonlinear effects can be deleterious even when they are not used to generate the dispersion. In both passive and active FL cavities employing atomic vapors, for example, saturation and optical pumping can alter the resonance line shape, couple the counterpropagating beams, and limit the achievable intensity and signal to noise. Even when nonlinear effects are avoided entirely, reliance on discrete material transitions can have additional drawbacks. Transitions in atomic vapor FL media, for example, are highly temperature dependent, requiring state-of-the-art temperature stabilization techniques to minimize the resultant noise. More significantly, use of these transitions limits the wavelength of operation, which could inhibit wide adoption. RLG manufacturers are generally resistant to changing to a different operating wavelength, having spent many years perfecting their performance at helium-neon wavelengths. In addition, experiments to date have not matured enough to reveal the predicted increase in measurement precision, in either passive or active FL cavities, in large part because this observation itself requires fresh development of a high-quality RLG at a new wavelength, dictated by the discrete transitions of the FL medium.

A solution to these problems might be found in FL gyros based on coupled resonators.[8] These systems do not use a medium at all, and are therefore not constrained in wavelength nor do they suffer from the inherent problems described above. Typically, one of the resonators has net gain and the other has net loss. When the loss in one resonator is equal to the gain in the other, the system is characterized as 'PT-symmetric,' owing to its invariance under a reversal of parity (P) and time (T). Recently, investigators have proposed coupled-resonator PT-symmetric gyros[9] that would, in theory, display the same increase in sensitivity as active FL gyros based on atomic media, but are far simpler, and can be microfabricated onto integrated optical chips. The enhancement is maximized near a singularity known as an exceptional point where the system eigenvalues coalesce. In practice, however, PT-symmetric gyros have not shown any definitive boost in sensitivity because they rely on generating two modes for each counterpropagating gyro output direction. At small rotation rates, these two modes are not distinguishable, so no beat signal is obtained. Additionally, PT-symmetric gyros are not common path, and therefore do not possess the same level of common-mode noise rejection as typical RLGs or FL gyros based on atomic media.

2.2 New Approach

The approach taken has been to develop passive FL cavities and gyros in-house at MSFC, while leveraging Small Business Innovative Research (SBIR)/Small Business Technology Transfer (STTR) and Space Technology Mission Directorate programs to seed and mature a number of the most promising approaches for active FL gyros. The passive approach is less costly and complex to undertake, and preliminary results are thus easier to acquire. This approach has enabled MSFC to achieve a number of firsts in the field, some of which are described above in references 4 through 6 and reference 8. A direct demonstration of the increase in scale-factor sensitivity to rotation (rather than to length changes), as well as a definitive demonstration of the enhancement in precision, are still needed. The former is a relatively straightforward extension of experiments that MSFC has already performed[5,6] and can likely be accomplished with existing hardware. The latter goal may also be within reach (the most recent experiments at MSFC on closed-loop cavities attained a relative enhancement of 0.66 using only commercial off-the-shelf components), but will likely require the development of a more robust optical cavity with reduced noise, as well as a modification of the closed-loop, frequency-locking scheme.[6]

While the passive approach is promising for proof of concept, it seems unlikely that the ultimate FL gyro that is developed will be a passive one, for some of the reasons explained above. Therefore, an important part of the approach has been to leverage other NASA programs (such as SBIR/STTR) for external development of some of the more complex technologies required for active FL inertial sensors, in particular, to solve the challenges described above; i.e., to find approaches that are common path, are not limited in signal to noise, do not require frequency locking, permit operation at any wavelength, are not affected by environmental effects such as temperature and acceleration levels, and can be easily miniaturized or microfabricated.

3. CONCLUSIONS

Ultraprecise compact FL IMUs could reduce mission risk, cost, and propellant, providing cross-cutting benefits in a number of mission scenarios, in particular those requiring rapid accelerations or tight controls on attitude or position such as formation flying and automated docking, precision EDL, and missions to small bodies (kinetic impactors, sample return). The prospects of this technology have been discussed, as well as the advantages and disadvantages of different approaches, and the outstanding challenges to be addressed for its implementation.

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14. ABSTRACT

Prospects for the development of a new class of gyroscopes and accelerometers based on anomalous dispersion or 'fast-light' media are discussed. In recent experiments, fast light has been shown to dramatically increase the sensitivity of optical cavities to changes in optical path length. The boost in sensitivity may enable more rapid and precise inertial measurements, with smaller gyros, translating to greater spacecraft autonomy, provided the challenges presented herein can be addressed.

15. SUBJECT TERMS
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