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TIME-OF-FLIGHT-BASED RELATIVE DISPLACEMENT MEASUREMENT ON ULTRA-SMALL SPACE STRUCTURES FOR DEEP SPACE EXPLORATION

Abstract

Deep-space exploration missions generally require bespoke navigation solutions as they are out of range of the Global Navigation Satellite System (GNSS). As many recent mission concepts propose the use of multiple satellites operating together, e.g. a deep-space transfer vehicle and an independent lander / sampler, with emphasis on small satellites, there is new demand for simple relative navigation solutions that can be used for both long-distance relative navigation and proximity and docking scenarios. In one proposal, a "capsule" 5cm in diameter is proposed to deliver surface samples to a deep-space transfer vehicle (mothership) from a distance of 50 100km. In such scenarios, the expected optical and radar cross-sections are extremely small, making camera- and radar-based solutions unrealistic. Furthermore, since the battery resource is expected to be a few Wh and should operate for tens of hours, conventional transponders, including software-defined radio (SDR) solutions, are also power-prohibitive. Therefore, a new, extremely simple Radio-Frequency (RF) -based solution is needed.

In this paper, a novel RF Time-of-Flight (ToF) sensor is proposed, using an ultra-small RF beacon which can be turned off with external command. This method is extremely simple to implement, requiring only a switch and an envelope detector. Upon reception of the RF power (command) from the mothership, the capsule RF beacon halts its transmission. By switching the command signal at a known frequency, the beacon signal arrives with a phase delay proportional to the propagation delay between the capsule and the mothership. This concept is explored and experimentally tested with a prototype. The prototype also employs a novel Shape Memory Polymer (SMP) antenna to explore deployable high-gain antennas.

The prototype was fabricated using commercial off-the-shelf (COTS) components, consisting of a master circuit board (mothership) and a slave circuit board (capsule). The slave board consumes a little over 3W including synthesizers and all amplification stages. Using these boards with a set of SMP patch antennas, ranging experiments were conducted at varying distances: 1.50 m to 1.77 m, 3.00 m to 3.27 m, and 5.00 m to 5.27 m. The results show that ranging is possible with an error of approximately 1 m. Simulation results suggest that the cause of this error is multipath effect via surrounding metal fixtures, which will be absent in the operational environment. Future experiments will investigate ways to further reduce power consumption, as well as improve the measurement accuracy.