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Autonomous formation flying in the traffic

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Abstract: With the rapid growth of operational satellites and debris in congested areas, such as Low Earth Orbit, moving in the traffic is becoming key also due to new regulations potentially coming into play. This paper presents a selection of current guidelines that can play a major role in small satellite mission design and presents the Delfi-Twin mission, conceived to demonstrate Space Traffic Management capabilities. The mission s made by two small satellites which will operate as a formation using differential drag as control strategy. On-board orbit determination will be employed to speed-up the availability of high-accuracy ephemeris and improve their dissemination to other operators. Miniaturized commercial receivers have been evaluated in an emulated orbital scenario to assess the performances of future on-board orbit determination system, providing some insights on existing problems related to commercial receivers not designed for operating in space.

1. INTRODUCTION

With the increasing number of orbiting objects, the number conjunction has increased drastically and solutions to manage the space traffic are hardly needed. To cope with this problem, new guidelines are being discussed, such as the new European Space Law and the ESA Space Debris Mitigation Requirements, which mandate many new requirements on satellite operators, such as carrying out an avoidance maneuver within as little as 12 hours from the warning and assess a maneuver in less than 4 hours.

Such new capabilities require an on-call orbital dynamics team for any operator, even for very small teams, which could limit access to space. In an age where computing power, also in space, is booming, it is not a surprise many teams are considering the possibility of autonomous space traffic management: but would this become a revolutionary technology or simply increase the risk due to unpredictable maneuvers?

With the Delfi-Twin mission we plan to investigate the current Space Situational Awareness capabilities of ground networks to characterize the performances with a cooperating mission, used to provide accurate ground truth with a challenging small satellite formation. The mission includes two small satellites, smaller than a CubeSat, to challenge the detection capabilities and, at the same time, provide and distribute accurate ephemeris to other operators. The mission will start with the two satellites deployed while docked, providing a larger, and safely detectable mission. Once performances have been evaluated and the two satellites are commissioned, they will separate upon command providing a reference fragmentation event that could be followed live in space, validating existing models for fragmentation prediction. Ground radar, optical (by active light emission and reflection) and laser tracking of the satellites will be carried out to characterize the performances of existing assets and to also optimally combine measurements to demonstrate space situational awareness capabilities.

The mission will continue with a demonstration of formation flying with only differential drag control: this will allow to test the performances for along-track formations and debris avoidance maneuvers by using a deployable set of actuator-controlled spoilers that can significantly increase the satellite cross-section. This will be used for formation control with the goal of keeping an up to 100 km separation between the satellites and an emergency, debris-avoidance capability to perform rapid corrections. Propulsion systems have been purposedly discarded for this mission to evaluate the capabilities of differential drag specifically in view of its potential use under the upcoming regulations for carrying out recurrent maneuvers.

The satellites will be equipped with a dual-frequency Global Navigation Satellite System (GNSS) receiver for in-space precise orbit determination and to demonstrate atmospheric density measurements (at altitudes lower than 400 km) and precise calibration of the satellite drag coefficient. Thanks to the possibility of calculating the precise orbital elements on-board, the mission will be used to test autonomous strategies to avoid eventual debris while still under strict ground control. Predictability of the maneuvers is a key aspect, together with timely delivery of accurate orbital elements to other operators to quickly evaluate collision risk.

This paper will present first a selection of potential requirements for operators in Section 2. The Delfi-Twin mission will be briefly presented in Section 3, and in Section 4 the formation flying approach, together with the on-board GNSS receiver and orbit determination approach will be shown.

2. SPACE DEBRIS MITIGATION REQUIREMENTS

With the increasing number of orbiting objects, the number conjunction has increased drastically and solutions to manage the space traffic are hardly needed. To cope with this problem, new guidelines are being discussed, such as the ESA Space Debris Mitigation Requirements [1], which mandate many new requirements on satellite operators.

Few such requirements can be considered key for future missions, such as:

- 5.3.3.2.c: A spacecraft operating in near Earth orbit shall have a recurrent maneuver capability (…)
- 5.3.3.3.j: A spacecraft operating in near Earth orbit, after receiving a warning for a conjunction (…) shall perform a collision avoidance action (…) if the warning is received up to 12 hours before the conjunction and the spacecraft is operational (…)
- 5.3.3.3.g: The space and ground segments associated with spacecraft operating in near Earth orbits shall be designed to have ephemerides available for collision avoidance purposes in less than 1 day after orbital injection.

These requirements potentially can have a major impact on future mission designs, mandating on-board and ground systems to be employed. Many of these capabilities are already available on larger missions, especially thanks to orbital dynamics teams following the mission. But smaller missions or newer players often do not have this

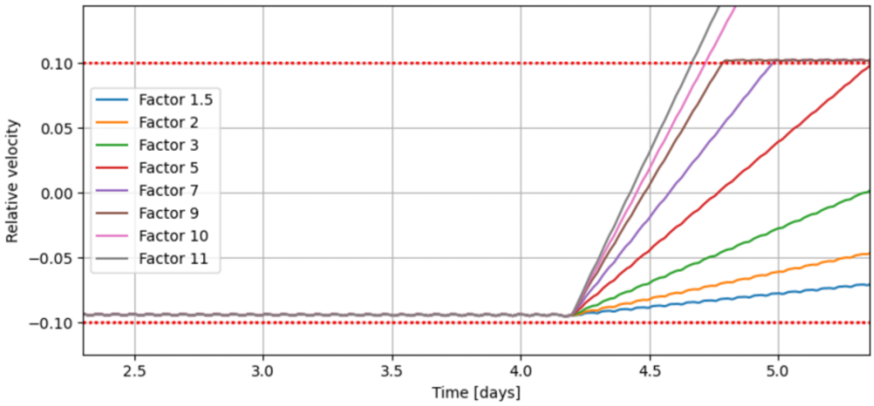


Figure 1: The effect of differential drag on the relative velocity (in cm/s) between the Delfi-Twin satellites as a function of the cross-section increase [3].

capability and, with this paper, we are analyzing achievable performances for a future on-board solution autonomous solution.

2.1 Can drag and autonomy help?

Collision avoidance is usually carried out with a propulsion system capable of providing a robust acceleration to avoid debris with short notice. This comes at the expense of fuel, shortening the operational life of the mission. Natural drag can come to the rescue in Low Earth Orbit (LEO) by allowing recurrent manoeuvres and saving fuel. By providing a large and temporary drag increase, large Δv (up to 10-20 cm/s within 12 hours) can be achieved, altering the along-track satellite position by up to 2 – 4 km, enough to safely reduce the collision risk in typical scenarios. This comes at a minimal orbital lifetime reduction and no increased power consumption.

But knowing precisely (or at least better than the typical 1 - 5 km uncertainty on debris position) where the satellite is can also drastically reduce the collision risk. The whole process should though be carried out quickly not to further impact the collision avoidance manoeuvre duration in case of notifications within 12 hours of the conjunction. GNSS data is very often used for this purpose, but processing is often carried out on the ground, requiring large data downlink and on-demand calculations.

What if precise orbit determination could be carried out in space, creating and distributing precise ephemeris directly? This is the approach that the Delfi-Twin mission will pursue, performing orbit determination directly in space and distributing ephemeris via an open radio channel to be received eventually by ground station networks.

3. THE DELFI-TWINS MISSION

The Delfi-Twins mission aims at launching two identical satellites in 2027 to demonstrate autonomous formation flying and collision avoidance using differential drag alone. This technique can be used to increase mission lifetime when employing propulsion or battling with limited (or depleted) fuel on-board.

The two satellites are based on the Delfi-PQ design [7], which operated successfully for 2 years in space: each satellite is 5 x 5 x 17 cm. Despite their very small size, the Delfi-

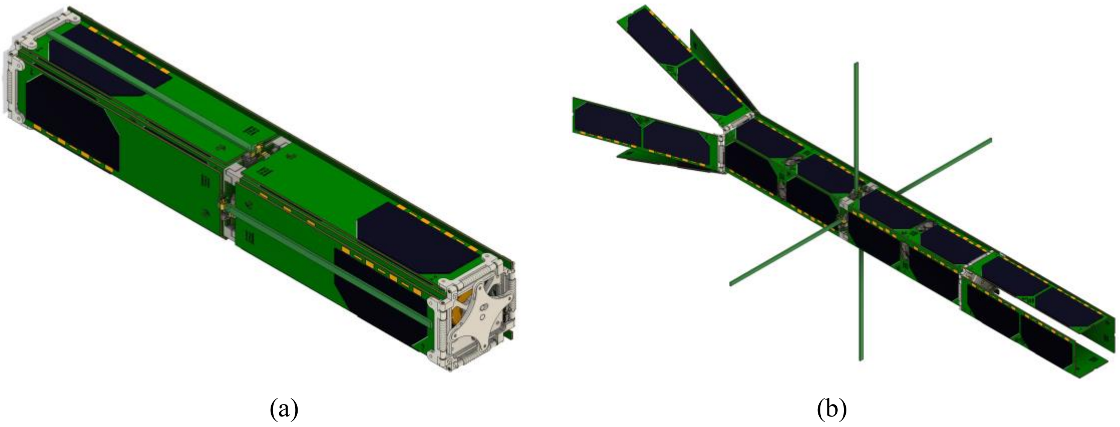

(a) (b)

Figure 2: The Delfi-Twin mission, shown in stowed configuration (a), before the antenna and drag-control appendages and after that (b).

Twins will have an available orbit average power of 2 W, enough to sustain multiple sub-systems.

The two satellites will be launched in docked configuration to limit the formation dispersion in rideshare launches which is caused by the rocket upper stage spin potentially causing small differences in orbital elements not correctable with differential drag. This also allows the satellites to operate docked throughout commissioning, to evaluate the performances of on-board GNSS receivers with a fixed physical separation: residuals can be evaluated and compared to each other to better assess orbit determination accuracy.

Once in orbit, deployable appendages to control drag and increase the available solar panels area will be deployed. Their angle with respect to the satellite body is controllable using a single motor, varying from fully deployed to a configuration with higher drag, also increasing passive attitude stability in the lower atmosphere. Magnetic attitude control, aided by an Earth horizon sensor, is employed to maintain the satellite cross-section stable, while passive stabilization limits the required control torques, also allowing to control the satellite at lower altitudes.

The mission is also equipped with a light-emitting beacon used to perform early satellite detection after deployment and refine existing orbital elements using ground optical Space Situational Awareness (SSA) networks. This will be used also upon satellite separation as it can be used to test fragmentation event detections by timing the satellite separation and following the satellites in the early phases from the ground. The on-board GNSS receiver will be used for validation of the ground measurements [5].

4. FORMATION FLYING WITH DIFFERENTIAL DRAG

After commissioning, the two Twins will separate using a spring system, providing a 10 cm/s relative Δv. This will allow for a safe separation that can later be controlled by varying the solar panel angles in two separate configurations. The separation attitude is a critical parameter to control as it can cause small eccentricity, right-ascension of the ascending node or inclination variations that could cause the satellites to periodically come too close and this would not be solvable using differential drag (see Figure 3 for more details). The Δv was also selected to provide weekly operations with a repetitive

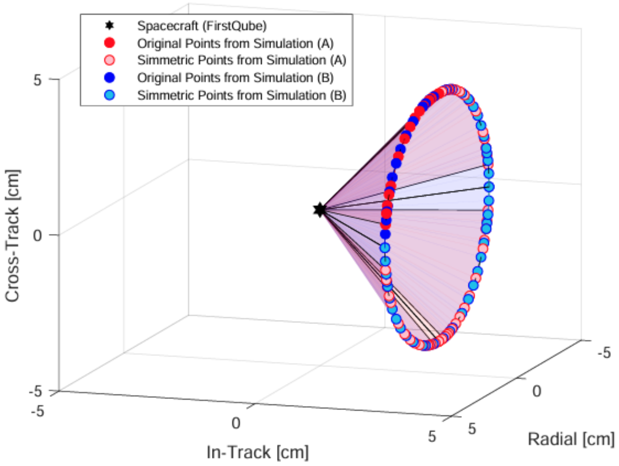


Figure 3: the set of points that defines the region of space beyond which satellite separation leads to a relative distance greater than 1000 m at the first close pass [4]. The region of space where deployment is considered safe has a conical shape with the axis aligned with the direction of motion and an half-aperture of 47 degrees.

pattern, bringing the satellites from few km up to approximately 100 km. This will allow to create conjunctions to test avoidance strategies in a controlled environment. Thanks to differential drag, maneuvers can be repeated multiple times over the expected mission lifetime of 2.5 years.

The mission also aims at performing such maneuvers in an autonomous way while still being predictable from the ground, to avoid risks due to space traffic. Dissemination of maneuvers plan and precise orbital elements will be implemented; to notify timely other operators but the team is targeting an on-board maneuver calculation with a ground approval process (before it is executed) to advance autonomy in space in a safe way.

4.1. On-board GNSS Receiver

Commercial miniaturized GNSS receivers from SkyTraq (S1216F8 and PX1122C) were used, with altitude and speed limits removed: tests were carried out using a SAFRAN Skydel emulator to prove the receivers can operate under space dynamics and provide a 3D solution. The receivers have been selected for their low power consumption (150 and

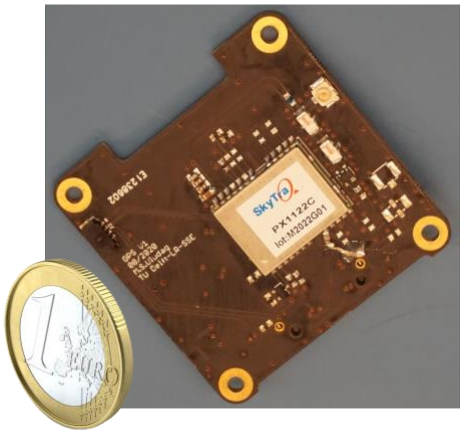


Figure 4: GNSS receiver RF board, shown in comparison with a 1 Euro coin for reference.

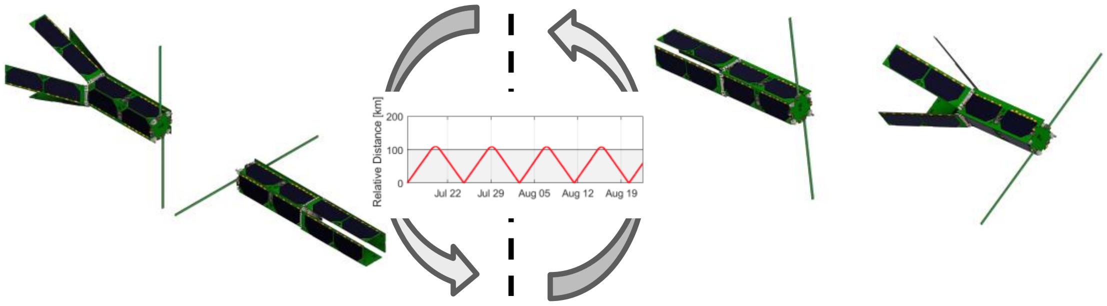


Figure 5: formation flying control by means of differential drag generated by the control appendages. Relative distance is controlled by alternating increased drag periods on one satellite (shown in the central plot where distance follows a non-linear increase or decrease) with reduced drag ones on both satellites (shown in the plot where relative distance follows a linear increase or decrease).

170 mW, respectively) and have been operated with a realistic signal-to-noise ratio with the emulator.

The GNSS module also includes an STM32 processor with external RAM and FLASH storage to perform orbit determination in space, this feature is still under development.

4.2. On-board Orbit Determination

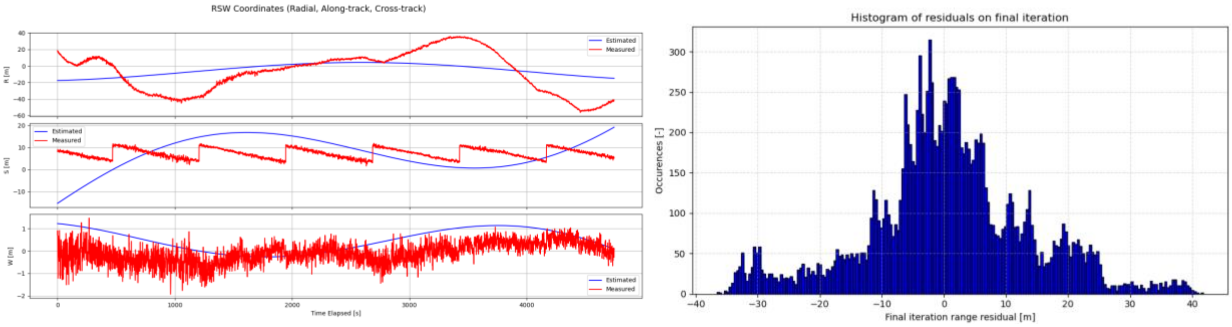
Besides the capability of modifying the orbit, it is also fundamental to know precisely the position and timely communicate it to other operators. This can, first of all, reduce the orbit covariance in the along-track direction from few km (typical value from TLEs) to few tens of meters. This can lower the uncertainty by two orders of magnitude, eventually reducing the need to maneuver or, at least, providing more accurate information.

Ground data processing first requires data download, further delaying the availability of ephemeris. On-board processing allows to deliver data quickly, but it limits the complexity of the processing algorithm. Due to the limited hardware available on small satellites, a limited amount of data can be used, such as single orbit with 30 s time step.

Currently orbit determination is performed on a computer, using the TU Delft Astrodynamics Toolbox (TUDat) for estimation [2]: the orbit is numerically propagated with a dynamic model including multiple perturbations, such as drag and spherical harmonics for the Earth gravity field plus the gravitational influence of the Sun and Moon. Ground truth is generated using TUDat and provided to the GNSS emulator and estimation performed on measurements. Only one orbit is used for estimation to simulate a realistic on-board orbit determination process, where a limited amount of measurement points can be used due to the limited memory available.

The mission has been simulated using a 525 km Sun Synchronous circular orbit with an inclination of 97.4 degrees with a launch date in January 2027: this has been selected based on the availability of commercial rideshare launches.

Considering commercial miniaturized GNSS receivers (with position errors of 5 – 10 m RMS [6]), this produces orbit estimations (under simulated conditions, using a Skydel GNSS Emulator) with residuals of 13.5 m RMS. Clear jumps in position can be seen, hinting at the limited capability of the receivers to deal with high dynamics. Residuals are



(a)

(b)

Figure 6: RSW residuals for measurements and orbit determination solution compared to ground truth (a) and measurement residuals distribution (b).

not completely gaussian, showing accuracy can be improved if the uncertainties are properly modelled.

5. CONCLUSION

This paper presented the Delfi-Twins mission which will operate as a demonstrator for Space Traffic Management capabilities by employing two small satellites flying first in dicked configuration and later separating and operating as a formation. The mission aims at meeting current space debris mitigation guidelines and demonstrate capabilities such as differential drag formation control and debris avoidance only using drag: this is an important capability that can significantly extend mission lifetime also for satellites employing a propulsion system.

The mission will moreover perform on-board orbit determination using a commercial GNSS receiver and this paper presents preliminary results of orbit determination accuracy based on emulator tests, achieving a RMS error of 13 m with respect to a ground truth orbit. Future work includes porting the current algorithm to be executed on embedded hardware.

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