Gemini: A Milestone towards Autonomous Formation Flying

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ABSTRACT

Against the background of a growing demand on controlled satellite formations, the Gemini technology mission is proposed on the basis of two micro-satellites. The primary mission objectives are the in-orbit demonstration and validation of laser metrology and GPS-based inter-satellite tracking as well as the autonomous orbit control of the Gemini space segment using a closed-loop formation keeping strategy. As derived from the mission objectives, the Gemini mission requirements are established together with a suitable payload concept, that allows for a flexible, high-performance, and low-cost technology demonstration of formation flying, required for a variety of missions envisaged within the next decade.

INTRODUCTION

In this context, we define the term spacecraft formation, in contrast to a constellation or a fleet, as a technology, that includes two or more spacecraft in a tightly controlled spatial configuration, whose operations are closely synchronized. Making use of the technology of spacecraft formations, new and exiting approaches to problems in the areas of remote sensing, communication, geodesy, atmospheric research, as well as astronomy and astrophysics are within reach. This comprises, for example, the forming of a single sensing system, whose size largely exceeds the barriers imposed by a single body, thus forming an intelligent sensor web, that comprises distributed spacecraft infrastructure. Based on this technology, new prospects are opened up especially in the area of interferometry, where demanding accuracy requirements are set up, or in the framework of missions with challenging needs for temporal and spatial simultaneity.

Flying two or more spacecraft in a precisely controlled formation presents, however, a number of complex challenges, such as that the spacecraft must have a sensor and control system enabling it to attain and maintain a precise relative position. Depending on the specific mission with its relative control requirements, the typical maneuver cycle for a maintenance of the formation may be too short for a ground-controlled formation and thus may require a fully autonomous on-board control algorithm. Furthermore, the system must enable the formation to attain a specified relative and absolute attitude, and, in general, the spacecraft must be able to communicate with each other.

In the run of the next decade, a series of missions has been proposed in the area of astronomy and astrophysics which are based on controlled satellite formations. This includes the X-ray telescope XEUS [1], made up of two satellites, the infrared interferometer DARWIN [2] with its main focus on the direct observation of extra-solar planets, and the laser antenna LISA [3] for the detection of gravity waves. The success of these missions crucially depends on the ability to control the distances between the individual satellites as well as their relative attitude in a highly precise and autonomous manner. Apart from mission specific applications, autonomous formation flying with its flexible use of distributed payloads on smaller platforms allows for a streamlined control segment as well as a reduced ground segment. Therefore, the technology of autonomous formation flying is also of high interest for Earth observation and remote sensing missions like SAR-Lupe [4], TerraSar [5], CartWheel and their commercial follow-ups.

Despite the fact, that a series of proposals for future formation flying missions with high demands on relative navigation accuracy and control is currently under discussion, the available knowledge and experience in the field of formation flying is severely restricted, if not lacking at all. Apart from the rendezvous and docking scenarios with manned stations or orbiters, the German-US Grace mission is among the first to establish a wide formation with 250 km in-track separation [6] and a high-precision inter-satellite tracking, based on a radiometric K-band link at 5 µm accuracy. Since the GRACE relative position control requirement is about 20 km, the formation control can well be performed by the mission control center, based on the use of the GRACE ground segment. As orbit control requirements increase, however, formation keeping can no longer be achieved by the control center, but necessarily has to be performed autonomously on-board the spacecraft. Typical orbit control requirements for past and future missions with their dependence on the spatial separation of the formation are depicted in Fig. 1.

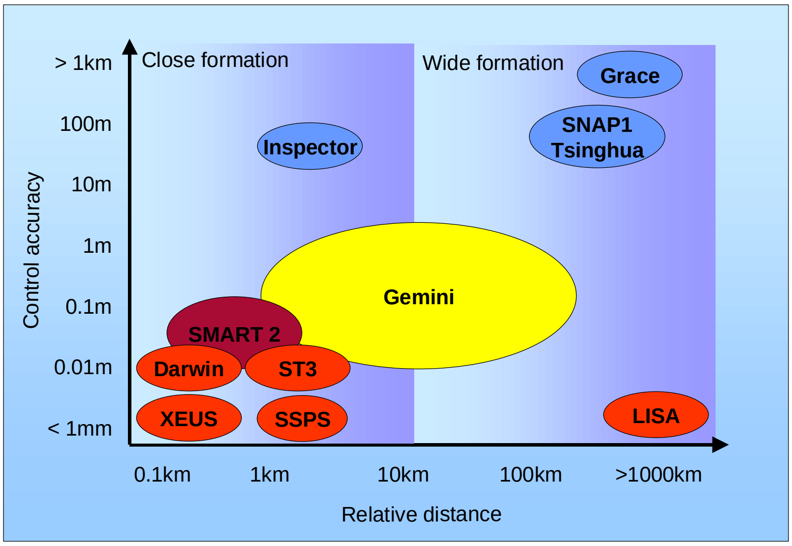

Fig.1 Formation Flying Control Accuracy versus distance for selected missions

It is evident, that there is a lack of experience from present-day controlled formation flying missions to the high-accuracy control demands for XEUS (1 mm) or LISA (1 nm), that can not even be overcome with pre-cursor missions, such as SMART 2. The Gemini technology mission therefore intends to bridge the gap between the limited knowledge in nowadays formation flying experience and the challenging needs of future formation flying missions.

THE GEMINI MISSION

Mission Objectives

Gemini (GPS-based Orbit Estimation and Laser Metrology for Intersatellite Navigation) is a technology demonstration mission, proposed by DLR's German Space Operations Center (GSOC), Astrium GmbH, and Vectronic Aerospace GmbH aiming to gain formation flying experience for the planned ESA projects in the upcoming decade.

The major Gemini mission objective is the controlled establishment of a satellite formation in a low-Earth orbit. To that end, advanced in-orbit technologies will be demonstrated based on laser metrology, as well as innovative GPS-based approaches to relative navigation. As part of its technological objectives, the Gemini formation control will entirely be based on an autonomous orbit control approach. Secondary mission objectives concern the separation concept from the launcher, the drift stop and the development of a controlled formation acquisition strategy. As a technology demonstration mission, emphasis is given to an independent verification of the relative distance by means of a laser radar sensor.

To allow a formation flying demonstration for a wide range of applications, the technologies for the control of the relative distance cover both the regime of close and wide formations ranging from several hundreds of meters up to 100 km. In contrast to the relaxed orbit control requirements of nowadays formations, Gemini aims at a relative position keeping of several cm to several meters, that is expected to be of significance for many of the upcoming formation flying missions and, in addition, paves the way for even more advanced requirements, such as for SMART 2. To achieve that level of control accuracy, the Gemini sensors have to provide relative position measurements in the range of millimeters or better, that may not be achievable solely using a spaceborne GPS receiver.

Mission Scenario

The Gemini mission scenario considers two micro-satellites of about 80-100 kg each, that are based on the Miniflex satellite concept [7]. Being equipped with a laser interferometer, a pulse laser radar and a GPS receiver, the absolute position accuracy can be determined at the meter level, while the laser interferometer provides range rate measurements, which can be mapped to a range measurement accuracy at the 10 µm-level. As a prerequisite for the autonomous formation control, the satellites will exchange position-related measurements through an inter-satellite communication link, thus reducing the costs for the ground station complement. As complement to the payload sensors, a low-thrust actuator will provide the necessary velocity increments for the formation keeping cycle. Fig. 2 depicts the mission scenario adopted within Gemini.

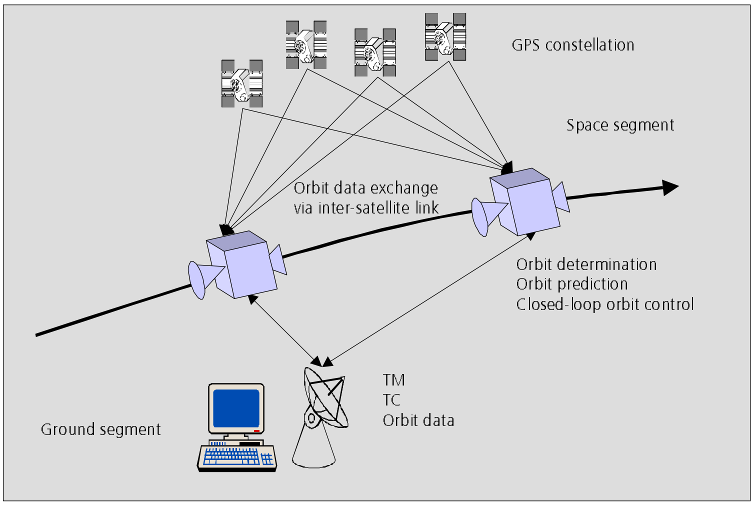

Fig. 2 Gemini Mission Concept

Making use of a piggyback launch onboard the Russian Rockot, the Indian PSLV, or the European Ariane 4, the current scenario considers the two spacecraft to be injected into a circular orbit at 500-700 km. To streamline the operations phase, a nominal missions operations phase of 6 month is currently considered as sufficient to demonstrate the formation acquisition and formation keeping phases. The mission operations will be conducted by DLR's German Space Operations Center making extensive use of low-cost operations systems and advanced autonomy concepts. A reduction of the ground station complement support is furthermore enabled due to the use of the Gemini inter-satellite communication link.

Formation Flying Concept

Following the separation of the spacecraft from the launcher, the state vectors of both satellites will first be determined using conventional radiometric angle tracking data in a ground-based orbit determination scenario. After the GPS receivers have been switched on, the GPS position fixes determined on-board are transmitted through telemetry to the ground and an orbit determination of the two spacecraft can be achieved at the meter level. Within that phase, the checkout and verification of the inter-satellite communication link and the onboard navigation algorithm will be conducted in a monitoring mode, to ensure proper operations of the formation flying control system. Depending on the launcher separation mechanism, the formation acquisition phase will stop the resulting drift of the satellites by the on-board thruster system of both satellites based on ground control commands, similarly as described in [6]. Once the formation acquisition phase has been completed, the initial formation configuration will have been achieved with a typical separation distance of 100 km.

Once the formation has been established, the autonomous formation control concept handles both narrow formation configurations of 1 km or less as well as wide configurations of up to 100 km. In the latter regime, the on-board orbit determination is based on single raw GPS pseudo-range measurements or derived GPS position fixes. Here, a relative position measurement accuracy at the meter-level is expected with an associated relative orbit control accuracy of better than 10 m. At distances of down to one kilometer, the data exchanged through the inter-satellite link will comprise GPS carrier-phase measurements. This allows to determine the relative spacecraft positions at the centimeter to decimeter level and significantly benefits from the cancellation of common error sources in the GPS carrier phase measurements. At even smaller separations, the orbit control will essentially rely on a laser interferometer, augmented with GPS differential carrier phase measurements. The laser interferometer then provides highly precise range rates, corresponding to a ranging accuracy of about 10 µm and allows for a formation orbit control at the cm-level.

To allow an independent verification of the GPS and laser-metrology measurements, an onboard pulsed-laser radar is part of the Gemini payload. Within the mission operations phase, the different formation flying scenarios are demonstrated, that depend on relative spacecraft distance, the controlling requirements, and the adopted relative navigation algorithm. Within each scenario, an autonomous keeping of the formation within the specified control bounds is performed to demonstrate the high level of automation achievable in formation flying.

Spacecraft Bus

Based on the Miniflex satellite concept, a design of the Gemini spacecraft has been developed, that assumes identical spacecraft for redundancy purposes as well as for a cost-efficient implementation. The spacecraft structure is of cubic geometry with a characteristic axis length of 60 cm. Electrical power is provided by three solar panels attached to the structure during launch, two of them being released and unfolded after separation from the launcher. The spacecraft bus itself is build up of three different compartments: the payload segment, the electronics segment and the service segment, as depicted in Fig. 3.

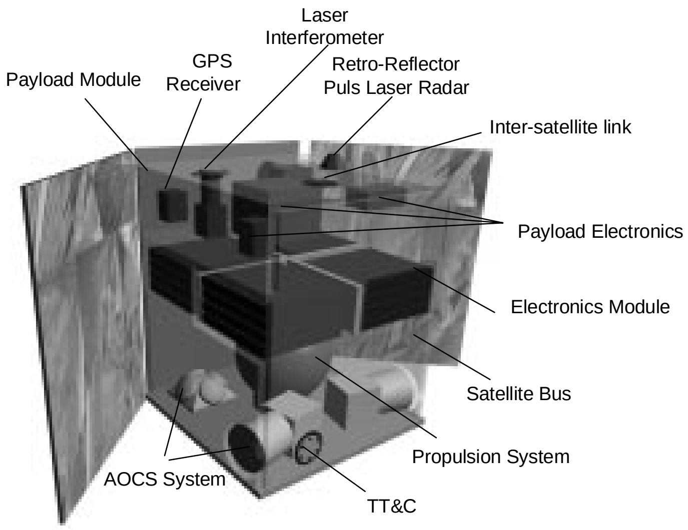

Fig. 3 Gemini Spacecraft Design

The main characteristics of the Gemini spacecraft bus as well as its subsystems are summarized in Tab. 1. It is noted, that within the Gemini mission, the specific formation flying objective causes the GPS receiver as well as the reaction control system (RCS) to be part of the payload segment, and not of the service segment, as would be the case for conventional missions.

BENEFITS OF A FORMATION FLYING DEMONSTRATION MISSION

Current plans for upcoming missions, that require controlled formation flying, suffer from a significant lack of knowledge and experience in the field of formation flying in general. As considers the sensors required for precise relative navigation, the technology of laser metrology has not been conducted or demonstrated in space and little experience is available in the field of differential GPS applications.

Concerning today's status of formation flying, only few experiences have been made so far. While a formation flying experiment of the SNAP1/Tsinghua [8] satellites failed, since the SNAP1 spacecraft ran out of fuel (W. Sun, priv. comm.), demonstrations in the framework of the Enhanced Formation Flying [9] of Landsat 7, EO-1, and SAC-C are currently under way [10]. However, the targeted control accuracies are by no means sufficient for the demanding missions of the future.

Hence, the demonstration of autonomous formation flying, as suggested by the Gemini mission is of fundamental importance, since it demonstrates the implementation of a high degree of autonomy, required for those missions and allows a verification of the achievable controlling accuracies in the cm-range. In view of the upcoming ESA missions,

Tab. 1 Summary of Gemini System and Subsystem Characteristics

System/Subsystem	Characteristics	System/Subsystem	Characteristics
Spacecraft		**OBDH**	
Volume	60*60*80 cm³	CPU	Processor 1750
Mass	100 kg	Mass storage	10 Gbit
Power	70 W on average	**Power**	
Payload		Solar array	2 m^2, GaAs
Volume	60*60*30 cm³	Battery	NiCd / Li-Ion
Mass	30 kg	**AOCS**	
Power	40 W	Attitude	three-axis stabilized
Communications		Sensors	1 Sun & 2 star sensors, 1 IMU
TT&C	S-Band	Actuators	3 reaction wheels
TC	4 kbps	Thruster	12 cold gas thrusters
TM housekeeping	32 kbps	Thrust level	< 40 mN
TM payload	1 Mbps	Thrust capacity	40 m/s

the test of mission critical components of the SMART 2 mission, such as laser metrology, may be demonstrated as well as a direct verification of the relative orbit control for the XEUS mission. In general, autonomous onboard navigation is neither a state-of-the-art technology in the field of absolute orbit control nor for formation control, but forms an essential contribution to future Earth observation and science missions.

CONCLUSIONS

The Gemini mission concept for the demonstration of autonomous formation flying based on laser metrology sensors and relative GPS concepts is presented. To that end, Gemini mission objectives are introduced, its mission design is described and the navigation concepts for the different strategies of formation acquisition and formation control are presented. Based on the schedule of proposed technology and demonstrator programs like SMART 2, the Gemini precursor demonstration mission should be ready for launch in 2004. Making extensive use of the experience of the contributing organizations and companies, especially in the field of autonomous navigation, satellite technology, and micro-satellite components, this schedule appears to be feasible though it certainly represents a considerable challenge. The Gemini mission allows to build-up competence in the field of relative navigation and laser metrology, that represents a prerequisite for a competitive position in upcoming scientific ESA missions and, moreover, paves the way towards future commercial Earth observation missions which require autonomous formation flying.

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