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MUSTANG: A Technology Demonstrator for Formation Flying and Distributed Systems Technologies in Space

Peter C. E. Roberts, Tom S. Bowling and Stephen E. Hobbs
Space Research Centre, Cranfield University, Beds MK43 0AL

Abstract

Future astronomical, surveillance and communications concepts are expected to depend heavily upon distributed systems – many satellites flying in formation to form synthesized detector arrays many times the size of each individual spacecraft. Various concepts for these systems are already under development at establishments around the globe. The MUSTANG project is a UK programme funded by the British National Space Centre (BNSC) to demonstrate distributed systems using two nano-spacecraft in a low Earth orbit. This will include the demonstration of a variety of formation flying techniques as well as demonstrating various enabling technologies that will facilitate such distributed systems. The use of many small spacecraft in distributed systems greatly increases the potential for the production of large amounts of space debris. Passive end-of-life de-orbit technologies will also be demonstrated to address this problem.

Introduction

Stated simply, large receivers can be synthesized using just a few small sections of that same receiver distributed over the area of the receiver. The trick is to maintain the sections of the receiver in the right place and to the required accuracy. To realise such distributed systems, various technologies are clearly required. These technologies are predominantly to do with relative position sensing and actuation, and absolute attitude sensing and actuation. However, the nature of these distributed systems also requires many small or nano-spacecraft to carry the receiver sections. Therefore, nano-satellite related technologies, such as COTS micro-systems technology (MST), are also required.

Using many identical spacecraft has advantages and disadvantages. Clearly having large production runs will greatly reduce the cost of each spacecraft. Redundancy at the formation flying system level is also gained - the loss of a single, or even several, satellites not causing total mission failure. This increased redundancy in turn allows each spacecraft to have fewer redundant systems itself. In addition it allows the use of COTS subsystem technologies with both lower cost but also lower reliability than fully space qualified subsystems.

Disadvantages concern the sheer number of spacecraft, which poses a debris problem when each individual spacecraft fails. This necessitates a concerted debris mitigation and end-of-life de-orbit program.

MUSTANG, which stands for Multi-University Space Technology Advanced Nano-satellite Group, is a university led collaboration with the UK space industry, which is to address the above issues by demonstrating distributed systems technologies and formation flying in space. Cranfield University's Space Research Centre and the University of Southampton jointly lead the project with industrial support provided by Astrium UK. Funding for the program has been provided by the BNSC. As such the programme expands on existing academic collaboration with industry, and promotes student interest and involvement in the space industry.

The preliminary aim of the collaboration is the MUSTANG-2 mission due to be launched in the 2004 time frame. This mission consists of a pair of nano-spacecraft (each with a mass of less than 10 kg) that will demonstrate a variety of formation flying techniques and formations that are representative of larger formations. The majority of the spacecraft subsystems will be based upon technologies designed and built within the UK. The two spacecraft will carry cameras for ranging and imaging, as well as various experimental payloads. These payloads will include MST solid-state gyroscopes and accelerometers to establish their viability for use in the space environment. Additional miniature experimental payloads will also be flown which may include microSAR, and electric thruster demonstration payloads.

To mitigate debris production, each spacecraft will also carry an end-of-life, drag-enhancement, de-orbit device capable of causing satellite re-entry within two months of the deployment of the device.

MUSTANG-2 Overview

MUSTANG-2 relies on a launch of opportunity as an auxiliary payload for orbital deployment due to its very small mass and budgetary constraints. This has led to a structural design that is very stiff so that the spacecraft can withstand the launch loads and vibrations on all likely launch platforms.

A circular low Earth orbit is desired. This simplifies maintaining the relative positions for formation flying and minimises the ΔV requirements. For power and thermal calculations, a 90° inclination, true polar orbit at 600 km altitude, which is typical for many Earth observation payloads, has been assumed as shown in figure 1.

The two spacecraft are launched in a stacked configuration as shown in figure 2 with their own launch adapter. The stacked configuration allows separation from the launch vehicle to occur without the two spacecraft separating from each other. This in turn allows the spacecraft to be thoroughly checked out, over a period of weeks in orbit, before the formation-flying phase of the mission begins. Stacking the two spacecraft also means only one auxiliary launch slot will be occupied. The stack has its own launch adapter for two reasons. Firstly, the launch vehicle is unknown at this time so some kind of an adapter will clearly be needed. Secondly, typical micro-satellite positions on launch vehicles (such as the ASAP micro-position of Ariane 5) are designed for payloads around 100 kg, whereas the two MUSTANG-2 spacecraft have a mass of only 20 kg. Separation loads will therefore exceed the nominal shock design load of the satellites unless a custom adapter and separation mechanism are used.

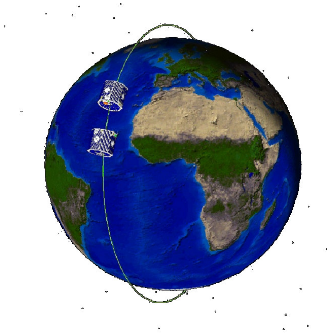


Figure 1 – The MUSTANG-2 spacecraft in true polar orbit. The spacecraft are orientated along the orbit path as shown.

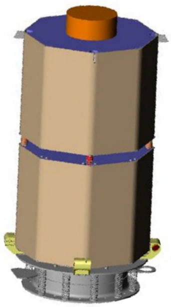


Figure 2 – The launch configuration or the two MUSTANG-2 spacecraft including the launch adapter.

Once the two spacecraft are separated from the launch vehicle and have been checked out, they will separate from one another maintaining the same relative attitude as they had in the launch stack. This allows attitude and relative position sensors to be functional before and immediately after the separation. The formation flying phases of the mission will then begin.

The operations schedule is shown in figure 3. The nominal operational lifetime of the mission is one year. Following the separation of the two spacecraft from one another, two formation-flying phases take place, each lasting around 5 months. These are discussed in the following section. At the end of the operational life, the de-orbit devices on each spacecraft will be deployed to remove them from the orbital environment as quickly as possible.

Launch Separation Deploy de-orbit device

~ 2 weeks	~ 5 months	~ 1 month	~ 5 months	
Checkout phase	Formation Flying Short-Baseline (~100m)	Increase separation to ~30km	Formation Flying Long-Baseline (~30km)	De-Orbit

Figure 3 – MUSTANG-2 Operations Schedule.

Formation flying

The first of the two formation flying phases will be the most demanding. Initially a leader-follower formation will be established with a baseline of 100 m. The aim is to maintain this baseline to an accuracy of ± 1 cm. The largest perturbation to the relative motion of the satellites is the J2 Earth oblateness term. A more detailed analysis of the leader-follower formation modelling for MUSTANG-2 has been carried out at Cranfield University and can be found in reference [1].

Following the successful completion of the leader-follower formation, alternative formations representative of a larger group of spacecraft will be demonstrated. This will include formations such as that which would be required for aperture synthesis type missions, the spacecraft forming and maintaining a plane of any orientation whilst using the minimum amount of fuel. Once the success requirements for the short-baseline constellations have been met, the spacecraft will separate further using a stepping manoeuvre to a baseline of 30 km. At this baseline more general constellation maintenance will take place with a position accuracy requirement greatly reduced to that which can be provided by simple code-based GPS.

A COTS cold gas thruster system using butane is the most likely candidate for the translational control system. This has the benefit of storing the fuel in a liquid state minimising the tank pressure and therefore the tank mass. It should be possible to avoid the use of thruster heaters, as the small losses in thruster performance are not critical. Polyflex, based in Gloucestershire, is the most likely supplier of the thruster system.

A variety of technologies will be demonstrated for relative position sensing. These include code-based GPS, DGPS and carrier-phase-based DGPS, laser ranging, radio ranging (pseudo GPS), and photogrammetry.

- Code-based GPS will be used for the long-baseline formation-flying phase.
- Code-based differential GPS (DGPS) will be used for initial alignment purposes for some of the other ranging methods.
- Carrier-phase DGPS, or real-time kinematic GPS, is one COTS solution to the relative position sensing problem.
- Laser ranging is fairly self-explanatory – in collaboration with Imperial College the MUSTANG team have been developing a suitable laser ranging experiment that will provide sufficient position and range rate accuracy for the leader follower formation.
- Radio ranging will use transponders to determine the range and range rate of the two spacecraft.
- Photogrammetry involves determining the separation vector of the spacecraft by processing images from the on-board camera. Substantial work at Cranfield University has already been carried out in this field [2],[3],[4].

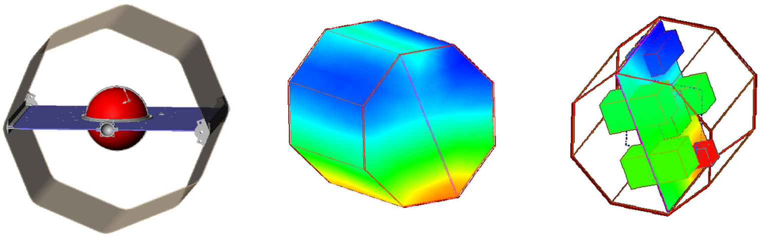
The accuracy and potential problems involved with some of these systems is under study.

Spacecraft Design

The spacecraft subsystems have been designed using UK technology where this is possible. The following gives a brief overview of the main subsystems.

Structure / Thermal

The carbon-fibre filament wound spacecraft structures are under study by Astrium UK. These have an octagonal cross-section and provide the majority of the structural stiffness for the spacecraft. Inserted into, and hanging off, the filament wound tube is a carbon-fibre vertical shelf that carries most of the spacecraft subsystems as in figure 4(a). The open ends of the tube are then closed using non-structural thin panels that carry solar cells.



(a) (b) (c)

Figure 4 – (a) Main structural design and (b) & (c) thermal analysis.

Thermal design is fairly conventional for polar spacecraft, a combination of insulation and paints providing the correct thermal balance for the spacecraft subsystems. Thermal analysis is being carried out using IDEAS TMG (example results are shown in figures 4(b) and 4(c)).

Power

The spacecraft carry body mounted, GaAs, double junction, solar arrays. These provide a peak power of around 27 W at just over 6 V. Power storage will use AEA Technology lithium ion batteries. These together with a small shunt regulator and power-conditioning unit provide an average of 15 W to the other spacecraft subsystems. Figure 5 shows how solar cells are placed wherever possible on the surface of the spacecraft.

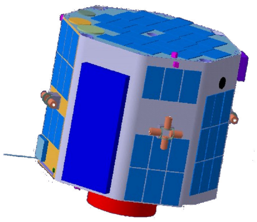


Figure 5 – MUSTANG-2 external arrangement.

Attitude Control System

The attitude control system has the usual complement of sensors and actuators. The University of Southampton are currently designing a three-axis set of reaction wheels which, along with a set of magnetorquers for wheel desaturation, provide three-axis control for the spacecraft. Attitude sensors include five sun sensors, an Earth sensor, and rate gyros.

Communications and On Board Data Handling

An S-band patch antenna provides the downlink and uplink capabilities for the two spacecraft to a 2 m antenna on the ground. One candidate for the ground station is the S-band dish at the Rutherford Appleton Laboratory. This link provides for a downlink capability of around 1 Mbit per second shared between the two spacecraft.

There is also an inter-satellite communications link between the two satellites to facilitate the formation flying control and also as a back up for the main downlink. In the case of failure of the downlink system on one of the spacecraft, there is sufficient bandwidth to transmit experimental data to the second spacecraft and then to the ground during its communications pass.

OBDH for MUSTANG is based around the I2C bus by Philips. This bus allows many systems to be easily integrated.

Assembly, Integration and Test

AIT is to be carried out at Cranfield University and the University of Southampton. Subsystems are to be mounted on each side of the vertical shelf in parallel with the integration of the solar cells to the octagonal tube. Once the spacecraft are ready for their final integration the shelf is then slotted into the runners on the inside of the tube and bolted into place as shown in figure 6. Brackets are then fitted to the end of the tube to support the end faces which are screwed into place.

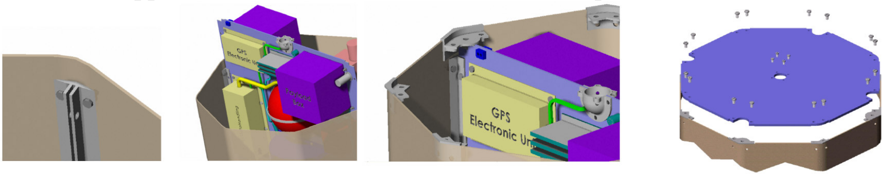


Figure 6 – Integration of the MUSTANG-2 spacecraft.

The testing philosophy is to begin with an electrically functional "flat-sat" breadboard model to test the electrical interfaces as the system is built and to test hardware in the loop as it becomes available. Two structural models will also be built to vibration test the two spacecraft in their stacked configuration, and for fit checks. A proto-flight model will also be made that will be tested to qualification vibration levels before being refurbished for flight. Finally, the second flight spacecraft will be made.

Additional experimental payloads

The two spacecraft will carry additional experimental payloads. These include the following.

MicroSAR

The MicroSAR experiment involves a miniature SAR tile that fits onto one facet of the MUSTANG-2 structure. The tiles are largely self-contained and need only be supplied with a trickle charge as they have their own batteries. With a single tile, the SAR can be used in several modes including acting as a simple altimeter and also as an X-band communications transmitter. It is hoped that two tiles will be flown, one on each spacecraft, to test some of the principles involved with synthetic aperture generation. The MicroSAR tiles are being design and built by Astrium UK at Portsmouth.

FEEP thruster experiment

Demonstrating FEEP (Field Emission Electric Propulsion) thrusters in space has yet to be achieved. One proposed experiment is to fly a single FEEP thruster with a miniaturised control electronics box, to demonstrate the use of FEEP in the space environment. Substantial work has been done, in the area of control box miniaturisation and the use of FEEP for nano-satellite missions, at Cranfield University [5] along with Centrospazio in Italy.

Micro-colloid thruster experiment

The University of Southampton has substantial experience in the development of electric thrusters. Current work involves the development of micro-colloid thrusters. These represent another possible candidate for an experimental payload.

End-of-Life De-Orbit

Inoperative spacecraft in low Earth orbit can expect to continue orbiting for several years to decades depending on their orbital altitude. If the population of spacecraft in LEO continues to grow then the problems involved with space debris will continue to grow along with this. Distributed space systems can only greatly increase this problem unless active measures are taken to remove spacecraft from orbit once they cease to operate. The fact that it is mostly inoperative spacecraft that need to be removed makes the method of removal a difficult one.

Cranfield University has carried out substantial research over the past few years into various de-orbit device concepts [6][7][8]. As attitude control capability cannot be assumed for inoperative satellites, thruster and tether related strategies cannot be serious candidates unless the attitude can first be stabilised using another system. Research has therefore focussed on autonomous, passive, dynamically stable, drag-enhancement devices for LEO. These will either cause the spacecraft to de-orbit on their own, or will stabilise the spacecraft so that other strategies can be employed.

Substantially increasing the area-to-drag ratio of a satellite by deploying a large sail dramatically reduces the time to de-orbit of the satellite. There is an argument which states that, as the area-time product of the spacecraft remains unchanged by the deployment of a sail, and therefore the probability of impacts with other spacecraft remains unchanged, that drag-enhancement devices should not be considered. However, such devices will cause the spacecraft pass through the populated orbits very quickly and, as in general the deployment of a large area of metalised kapton film will make the spacecraft appear very brightly on NORAD radar, any threat will be clearly visible. Also most of the area of the de-orbiting spacecraft, which will itself be hit by debris, will be the sail, in which case puncturing of the sail and no fragmentation will occur. In contrast, a spacecraft that is allowed to linger for long periods in low Earth orbit will be hit directly by the same amount of debris and is likely to be fragmented further.

Simulations show that the time to de-orbit for the MUSTANG-2 spacecraft without a drag-enhancement device are greater 2 years from a 600 km orbit. A 10 m^2 drag-device will reduce this time to less than 2 months. Such a device is expected to weigh a few hundred grams and be deployed using either simple steel tapes or shape memory alloys. Work on the deployment mechanism for the sail is being carried out in collaboration with Cambridge University. The autonomous nature of the device arises from the need for the device to be deployed once the spacecraft become inoperative. For MUSTANG-2 it is expected that the de-orbit devices will be triggered remotely once payload operations have been completed. An impression of the MUSTANG-2 spacecraft with the de-orbit device deployed is shown in figure 7.

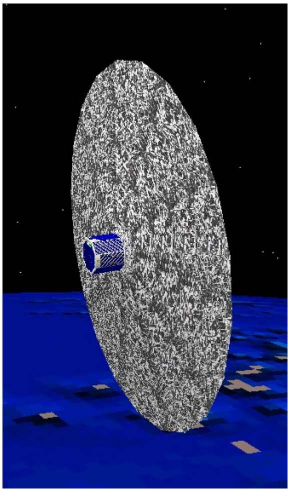


Figure 7 – The MUSTANG-2 spacecraft with the de-orbit device deployed.

Discussion

The MUSTANG-2 spacecraft are expected to be launched in the 2004 time frame. They will demonstrate distributed systems technologies that can be applied to forthcoming dispersed antenna and interferometry missions. These technologies specifically include formation flying and miniaturised systems. It will also carry several experimental payloads. An end-of-life de-orbit capability will be demonstrated. Nearly all the technologies involved in the MUSTANG-2 spacecraft have been developed and built within the UK space industry. MUSTANG-2 will therefore improve and broaden the UK's technology base in the critical and growing area of distributed space systems. The programme also encourages industrial relations with academia, and provides extensive encouragement to students by offering them the opportunity to work on a live project.

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