Sensor Webs of Agile, Small Satellite Constellations and Unmanned Aerial Vehicles with Satellite-to-Air Communication Links

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Abstract

This paper reviews the progress in model-based systems engineering tools developed to design satellite constellations, satellite formations, satellite agile attitude control and satellite communication with unmanned aerial vehicles (UAVs). The aim is to leverage advances in the Cubesats, constellations, UAVs and autonomy to make faster and more responsive measurements of the Earth. A Sensor Web of satellites and UAVs connected by sat-to-air communication links will enable images to be captured by avoiding clouds as much as possible, as well as collection of images from multiple vantage points allowing for better BRDF correction and image calibration. Such a mission will be planned using an integrated toolset for satellite and UAV mission design, and its utility verified using a simple Observing System Simulation Experiment.

Introduction

Distributed Space Missions (DSMs) are being recognized as important solutions to increase measurement samples over space and time[1]. DSMs can be considered homogeneous or heterogeneous combinations of monolithic spacecraft. They include homogenous constellations like the Global Positioning System or heterogeneous ad-hoc flyers like the A-Train, autonomous formation flying clusters such as PRISMA, fractionated spacecraft such as the System F6 Program and cellularized systems such as the DARPA Phoenix Program. Formation flight, as required in clusters, fractionation or cellularization, entails active control of the individual spacecraft in order to maintain relative distances, orientations and geometry[2]. Since DSM architectures are defined by monolithic architecture variables and variables associated with the distributed framework, it leads to a large number of design variables. The number increases further in heterogeneous cases. DSMs are also expected to increase mission flexibility, scalability, evolvability and robustness as well as to minimize costs and risks associated with launch and operations. Thus, DSM design is a complex problem with many design variables, multiple objectives for performance, cost and emergent (often unexpected) behavior.

Continued effort for creating and maintaining an interoperable environment for a diverse set of sensors (land, marine, air, space) using software and internet is also underway in NASA Sensor Webs[3]. The goal is to allow sensors to operate in a semi-automated, collaborative manner for scientific investigation, disaster management, resource management and environmental intelligence. Given the increasingly accurate attitude control systems emerging in the commercial market, small spacecraft now have the ability to slew and point within few minutes of notice. The scheduling of pointing operations of narrow field-of-view (FOV) sensors over mission lifetime to maximize global coverage and revisit statistics, has already been shown in simulation, thereby making already-capable small satellites more intelligent. If narrow FOV sensors, on a small satellite constellation, are commanded (using robust algorithms) to slew their sensor dynamically, they would be able to cover the global landmass in a coordinated manner, much faster and minimizing spatial resolution distortions.

Past literature[4], [5] has also shown the applicability of small satellite formations in approximating bi-directional reflectivity (BRDF) better than current state-of-art single spacecraft, globally. BRDF represents variations in surface reflectance as a function of measurement and illumination angles at any time instant, and is used to correct any satellite image with known acquisition angle. However, for the purpose of image calibration, BRDF retrieval using satellite formations is hindered by cloud cover and difficulty in controlling formation tracks such that the time and solar conditions match those of the original image acquisition as closely as possible. Unmanned Aerial Vehicles (UAVs) can mitigate this problem by flying to regions where satellite images have recently been taken and capture the BRDF at those locations. As of 2016, NASA's UAV Traffic Management (UTM) project [4] has begun to demonstrate beyond visual line of sight operations (BVLOS) of UAVs for a variety of applications including package delivery and agriculture/railroad inspection, and real-time image calibration will be a strong application to the Earth sciences.

This paper summarizes currently ongoing research on designing constellations or formations of multiple satellites for various Earth Science missions and designing a robust UTM that can operate UAVs in the national airspace safely and efficiently. It explores the idea of connecting the space-based assets with the UTM system, in the form of a dynamic Sensor Web, and proposes a case study whereby such a system would be useful for Earth Science measurements. While the utility has not been simulated in this paper for conciseness, the tools required for a simulation that would help plan such a mission have been described. The tools proposed are modular in nature, as per the rules of model based systems engineering or MBSE [6], therefore can be altered for different mission objectives, hardware availability or resource constraints.

Sensor Webs

To achieve an all-embracing understanding of the emergence and evolution of Earth Science processes and physical phenomenon requires the collection and assimilation of enormous amounts of data, using complementary measurements in space and time. Spatial measurements from multiple vantage points – space, air, ground and water – help resolve measurement and model uncertainties. The term 'Sensor Web'[3] was coined 20 years ago and they have been researched within NASA and ESTO for more than 15 years- https://sensorweb.nasa.gov/. Their main objective is to create an interoperable environment for a diverse set of satellite, airborne and ground sensors via the use of software and the Internet. Such a capability can be used to better understand intrinsically dynamic, complex, and interactive Earth-science processes and delivered globally visa Web 2.0 tools. Open access tools such as Google Earth can then be used to create superposition of datasets that can be used for visualization and calibration.

NASA's Sensor Webs project piloted in several disaster-related applications such as early flood warnings in Namibia (2010-11), observation of fires in California and Australia (2008-09) and volcano monitoring in Iceland (2010). The sensors can be an amorphous network of spatially distributed sensor platforms that wirelessly communicate with each other. While all the major publications list space and ground assets as pods, the enormous uprising on UAV and balloon operations in the recent past shows that they can be easily included as pods in a Sensor Web, thereby increasing the diversity of sensors and improving accessibility to remote sites in a faster and cheaper manner.

Constellations

NASA Goddard Space Flight Center is developing an open source, open access tool called Tradespace Analysis Tool for Constellations (TAT-C) for program managers and scientists to initiate constellation mission design[7], [8]. The tool will allow users to explore the tradespace between various performance, cost and risk metrics (as a function of their science mission) and select Pareto optimal architectures that meet their requirements. Previous literature[8] has listed the main input and output parameters for an imaging constellation mission design, based on interviews within NASA centers and collaborators. It describes the structure, functionality and information flow between the Executive Driver, Orbits and Coverage, Data Reduction and Metric Computation modules. The Executive Driver controls the end-to-end run of TAT-C by calling different modules as and when required. It also uses physical rules to streamline the tradespace of design variables so that a full factorial set of architectures do not have to be simulated. After Metric computation module has written out all the results files, the user may visualize the trades using TAT-C's user interface. Two use cases have been shown as representative examples of the utility of TAT-C generated trades, and results have been preliminarily validated against AGI's Systems Tool Kit. The use cases are based on NASA's Landsat and new Cubesat radiometer missions. The entire software is programmed in Python and C++, and does not need the purchase of any licenses.

Agile Satellites and Constellations

Cubesats are increasing in size (27U, ~40 kg in development) with increasing capabilities to host multi-spectral imager payloads[9] and NASA has recognized their value in Earth Science[10]. Given the precise attitude control systems emerging in the commercial market, Cubesats now have the ability to slew and capture images within short notice. An ESTO-funded project at NASA Ames Research Center has recently proposed a modular framework that combines orbital mechanics, attitude control and scheduling optimization to plan the time-varying orientation of agile Cubesats in a constellation such that they maximize the number of observed images and observation time, within the constraints of Cubesat hardware specifications. The attitude control strategy combines bang bang and PD control, with constraints such as power consumption, response time, and stability factored into the optimality computations and a possible extension to PID control to account for disturbances. Schedule optimization is performed using dynamic programming with two levels of heuristics, verified and improved upon using mixed integer linear programming.

The framework is generalizable over small spacecraft, sensor specifications, imaging objectives and regions of interest, however demonstrated using multiple 20 kg satellites in Low Earth Orbit for two case studies – rapid imaging of Landsat's land and coastal images and extended imaging of global, warm water coral reefs. For example, Figure 1 shows the difference in the number of observed images over a day with (left) and without (right) the proposed framework. The proposed algorithm captures up to 161% more Landsat images than nadir-pointing sensors with the same field of view, on a 2-satellite constellation over a 12-hour simulation. Linear programming was able to verify that optimality of the solution for single satellites was within 10% and find up to 5% more optimal solutions. The optimality gap for constellations was found to be 22% at worst, but the schedules were found at nearly four orders of magnitude better computational speed. The algorithm can integrate cloud cover predictions, ground downlink windows or any other spatial, temporal or angular constraints into the orbital module and be integrated into planning tools for agile constellations (e.g. TAT-C).

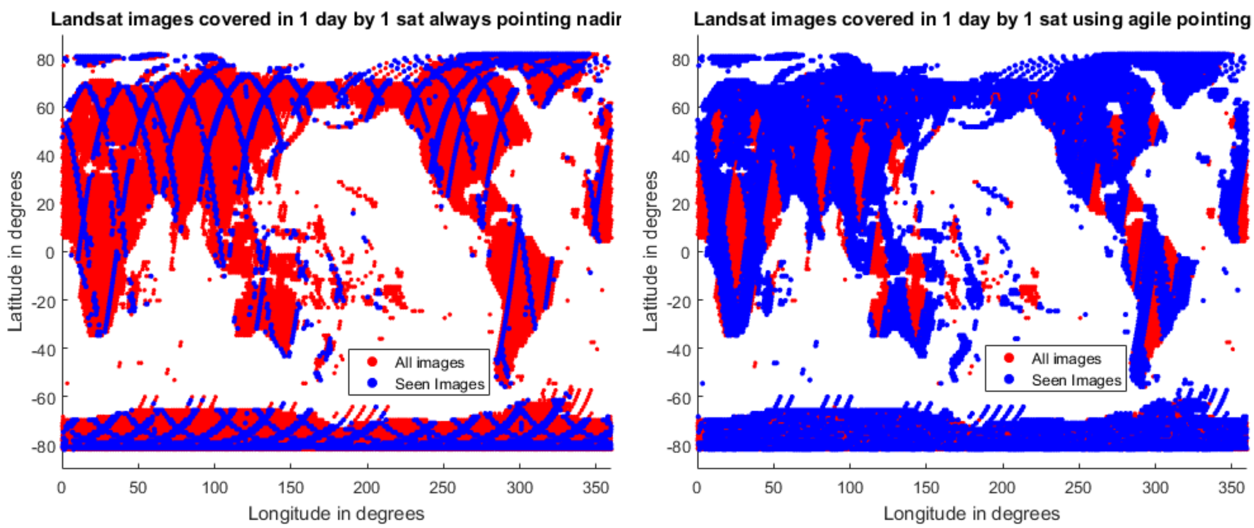

Figure 1: Coverage (blue) of Landsat's WRS-2 land and sea images (red) using a nadir pointing OLI instrument (left) vs. an agile slewing equivalent (right)

The proposed framework can also run onboard the satellite for autonomous scheduling, if the satellites can propagate their states accurately for a short time horizon and communicate their states with all other satellites within the same horizon with or without relay (both technologies are current under development for small spacecraft). This will allow satellite clusters to make decisions in flight without ground-in-the-loop, based on image observation requests and their states, and enable more autonomous remote sensing.

Formations

We have confirmed the applicability of using small satellite formation flight for multi-angular earth observation to retrieve global, narrow band, narrow field-of-view albedo[4] and more generally, BRDF and some dependent products. BRDF of an optically thick body is its reflectance as a function of illumination geometry and viewing geometry, and carries information about the anisotropy of the surface[11]. BRDF, as a ratio of infinitesimals, is a derivative with instantaneous values of reflected radiance and solar illumination. While it can never be measured directly, real measurements can involve non-zero intervals of above parameters. The CAR is known to be the heritage NASA instrument for highest accuracy BRDF estimation, and albedo is the hemispherical integration of BRDF over all reflectance angles.

The methodology employed to assess the optimal formation flight architectures and validate their BRDF or albedo estimation capabilities couples MBSE with observing system simulations. A tradespace of architectures can be analyzed by varying the design variables in the MBSE model, and assessing their effect on data assimilation and science products, against a known reference. Albedo errors are calculated against bi-directional reflectance data obtained from NASA airborne campaigns made by the Cloud Absorption Radiometer (CAR) for the seven major surface types, binned using MODIS' land cover map – water, forest, cropland, grassland, snow, desert and cities. A full tradespace of architectures for formations with three to eight satellites, maintainable orbits and imaging modes (collective payload pointing strategies) have been assessed. The maximum possible albedo error, purely based on angular sampling, of 12% for monoliths is outperformed by a five-satellite formation in any slotted arrangement and an eight satellite formation can bring that error down four fold to 3%. More than 70% ground spot overlap between the satellites is possible with 0.5° of pointing accuracy, 2 km of GPS accuracy and commands uplinked once a day. The formations can be maintained at less than 1 m/s of monthly ΔV per satellite.

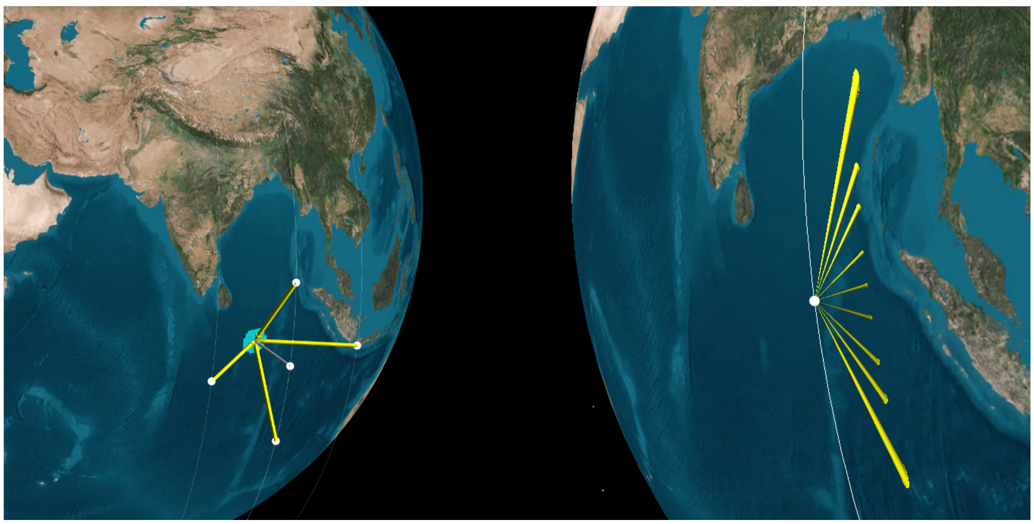

Figure 2: A formation of five satellites (left) in orbits of same inclination and altitude observing the same ground spot at different angles vs. a single satellite (right) with nine sensors observing difference spots at different angles.

The same formations have been compared to each other and multi-sensor single spacecraft, in terms of estimation error of BRDF and its other dependent products such as light use efficiency (LUE), and vegetation index (NDVI)[5]. Performance is benchmarked with respect to data from previous airborne campaigns (NASA's Cloud Absorption Radiometer), and tower measurements (AMSPEC II), and assuming known BRDF models. Simulations show that a formation of six small satellites produces lesser average error (21.82%) than larger single spacecraft (23.2%), purely in terms of angular sampling benefits. The average monolithic albedo error of 3.6% is outperformed by a formation of 3 satellites (1.86%), when arranged optimally and by a formation of 7 to 8 satellites when arranged in any way. An 8-satellite formation reduces albedo errors to 0.67% and LUE errors from 89.77% (monolithic) to 78.69%. The average NDVI for an 8 satellite, nominally maintained formation is better than the monolithic 0.038.

Aircraft Surveillance using Constellations

Suitably equipped global and local air traffic can be tracked and the tracking information may then be used for control from ground-based stations, by receiving the Automatic Dependent Surveillance-Broadcast (ADS-B) signal. The ADS-B signals are currently tracked by ground-based receivers but not over remote oceans or sparsely populated regions such as Alaska or the Pacific Ocean. Worldwide coverage of ADS-B signals from airplanes will not improve air traffic control significantly[12], but also lay the first building block of a satellite-to-air surveillance system that can enable Sensor Webs of different platforms.

Better still would be the integration of unmanned aerial systems (UAS), including balloons, into the Sensor Webs. The Federal Aviation Administration (FAA) forecasts seven million small unmanned aircraft systems (UAS) [13] to be operational by 2020, of which 2.6 million will be commercial. NASA postulates the demand for low-altitude UAS to rise for a variety of applications including infrastructure monitoring, precision agriculture, search and rescue, and delivery of goods. The NASA UAS Traffic Management (UTM) project is a systemic research approach to prototype technologies for a traffic management system that could develop airspace integration requirements for enabling safe, efficient low-altitude operations. Research results will be transferred to the FAA for further testing. However, a recent study[14] has found that ADS-B is feasible only for UAS-to-UAS or UAS-to-ground surveillance only at very low power and short distances, given the traffic numbers assumed, beyond which it will adversely affect manned aviation surveillance and itself. Therefore, the communication and surveillance solution for UAS integration into the national airspace and Earth Science Sensor Webs should be a mix of technologies including but not limited to cell network coverage (LTE with a possible dedicated band) and LEO and GEO satellite assisted networks.

Sensor Web Case Study

Our proposed case study introduces an Earth Science case for satellite-to-air communication links between satellites, both fixed pointed and agile slewing, and UAVs. A Sensor Web can take well-calibrated multi-angular images of surface areas that have the risk of being obfuscated with clouds. Agile constellations have the capability to point and take images in directions that are minimally covered by clouds. Global multi-angular imaging can be enabled by formation flight and the agile capabilities of satellites. Advances in onboard processing within satellites will allow intelligent decisions to be made autonomously and advances in inter-satellite communication will allow such decisions to be made by coordinating all satellites. This will not only allow enable faster reaction times to measure Earth science processes, but also determine and request calibration or correction targets quickly.

UAVs are capable of local multi-angular imaging, which can then be used for correction of the partially cloud covered images, observed by satellites. Sites for vicarious image calibration can be chosen based on suitability for calibration given by surface type generalization, ease of UAV access given by battery endurance and command/control capability, and predicted ground trajectories of the satellite taking the images given by traditional orbit determination methods. The UAV(s) is expected to fly to the selected sites, establish communication links with the satellite, thereby determine a more exact location of image acquisition based on spacecraft/aircraft onboard processing and begin its BRDF measurement routine. To approximate BRDF, the UAV will fly around the target ground spot in circles at various altitudes and collect reflectivity values as a function of measurement angles with respect to the Sun, just as the CAR instrument. This concept of using UAVs for calibration can also be used in conjunction with current state-of-art flagship missions.

To test the above concept in simulation, the constellation design software described earlier can be used, after the development of a UAV planning module plug-in. One or more UAVs can be tasked with a specific remote sensing task and the resultant flights will be evaluated based on value addition to the mission. The tasks and locations will be enumerated based on what is to be measured and the flight path of the other complimentary assets in the Sensor web (satellites and balloons), to prevent the explosion of the variable tradespace. Mission Planner is a Windows-based, open source software tool - http://ardupilot.org/planner/docs/mission-planner-overview.html, which is used by NASA's UTM project as a configuration utility or as a dynamic control supplement for any type of UAV. We will use Mission Planner to simulate the dynamics of a UAV based on a database of known types of UAVs, primarily categorized as small size, multi-rotor, short-range UAVs and heavy, fixed wing UAVs. This characterization is important because the latter is far more dependent on the weather than the former and variables such as wind speed, as obtained from weather forecasts, become an important input into the simulator. Mission planner will simulate the output of the mission, given a particular UAV and set of waypoints, as constrained by the targets to be measured and hardware or mission constraints. We will modify the open source software to output the resource utilization of the UAV such as power/energy consumed and compute probability of success of meeting the case study's requirements, based on Mission Planner's outputs. Commercially available UAVs and batteries will be assumed for all computations.

The utility of the proposed satellite-UAV joint measurement making capability can be validated with the help of Observing System Simulation Experiments or OSSEs. OSSEs have been traditionally used to quantify the impact of observations from future observation systems such as satellite instruments or ground-based networks on data products such as weather forecasts, by mimicking the process of data assimilation to validate science return for proposed instruments[15]. OSSEs can be simplified and used as a tool for mission design because they allow scientists to choose between different architectures of measurement (in our case, different assets for measurement) using a tightly coupled evaluation model[16]. Our motivation for using hybrid air-space sensor webs can be validated using a detailed OSSE, developed or modified as a function of Earth Science use cases.

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