Evaluating Virtual Satellite Mission Opportunities

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Systems sharing unused capacity are mostly developed in information technology

- SETI,
- Uber
- Lyft
- Energy Grids,
- AirBnB
Virtual Satellite Missions (VSM)

- Opportunistic space missions
- Aggregation of spare capacity of federated spacecraft into new “virtual” mission
- Introducing the notion of “mission as-a-service”
Possible 2 Spacecraft VSM Scenario

S1 and S2 spacecraft carrying VSM through VSM Operations Center (ViSMOC)
# VSM Benefits and Disadvantages

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>➤ Low capital barrier of access to space (no fixed costs)</td>
<td>➤ Absence of total control over mission parameters</td>
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<td>➤ No risk associated with spacecraft development and launch</td>
<td>➤ Non-viability of long term VSMs</td>
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<td>➤ Cheap data acquisition</td>
<td>➤ Introducing new risks for spacecraft</td>
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<tr>
<td>➤ Increased value creation</td>
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<tr>
<td>➤ Increased flexibility</td>
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Approach

Class diagram of objects within the model

Simplified flowchart of the Scheduler.

- Task
  - Resource
  - DueDate
  - Area
  - Priority
  - AccessIntervals

- STKInterface

- Scheduler
  - S
  - T

- Spacecraft
  - Name
  - OrbitalParameters
  - R
  - IdleWindows
Resource Allocation in VSM through Operations Scheduling

- VSMs can benefit only from the spare capacity, hence in the scheduling there is additional time constraint.

- VSMs are multi-satellite missions, hence the operations scheduler needs to generate a multi-satellite schedule.

Scheduler sought is an instance of the job-shop scheduling class [Zalzala & Fleming, 1997]
Objective: maximize the cumulative priority of the tasks scheduled

**Legend**
- Blue: Satellite idle window
- Green: Task access window
- Red: Wrong allocations

**Right**
- 12:05 PM - 12:28 PM: Task 1
- 12:35 PM - 12:56 PM: Task 2

**Wrong**
- 12:40 PM - 2:41 PM: Task 1
- 4:22 PM - 6:33 PM: Task 1

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Model Workflow

Flowchart shows the simplified workflow of the system

Is there saved data?

- YES: Initialize Main Entities
  - Initialize Spacecraft
  - Initialize Tasks

- NO: Generate STK Scenario
  - Add Study S/C to STK
    - Generate Tasks
    - Add Target Areas
    - Initialize AccessIntervals

Run Scheduling
  - Save Generated Data
Case Study

- Earth Resources and Weather spacecraft were taken as ones having wide variance of resource types. **Total number** of spacecraft **51**.

- Area targets were taken in **equal distribution** all around the world.

- Tasks were **equally distributed** among targets and resource types. **Total number** of tasks **765**.

- Planning horizon 1 October 12:00 p.m. – 10 October 12:00 p.m. local time
There are different combinations of different spacecraft giving the same efficiency

The top efficiency of the system is 83.22%
Evaluating Viability and Feasibility of VSMs

- Reference monolithic missions TERRA, SAC-C, AQUA, SAC-D are the most capable ones within the subgroup considered.

- VSMs substituting those missions were created depending on the reference missions’ resources.

- A Full factorial tradespace exploration of all possible VSMs was conducted with cost and value objectives.
Cost and Value Functions

- Cost of one observation with duration $\Delta t$ of spacecraft with lifetime cost ($CM$) and design life ($DL$)
  \[ C = \frac{CM}{DL} \times \Delta t \]

- Value of the VSM compared with monolithic reference mission in case of $\Delta T$ time error
  \[ V = \frac{N_{VSM}}{N} \times e^{-r\Delta T} \]
  - $r$ is the discount rate
  - $N$ is the monolithic mission resource number
  - $N_{VSM}$ is the VSM resource number
Lessons Learnt from the Experiments

- VSMs for **TERRA, AQUA, SAC-D** were proven to be **viable and feasible**
- VSMs for **SAC-C** were proven to be
  - **partially feasible**, due to resource singularity
  - **non-viable**, as the mission itself is cheaper for the capacity it possesses.
- There are **no unified VSM solutions** for all the cases.
- VSMs can introduce **resource redundancies**
- Small groups of more capable spacecraft dominate over less capable big groups spacecraft
Pareto Frontier Examples (1/2)

Cost and Value Tradeoff for the Mission TERRA Over Ithaca

Cost and Value Tradeoff for the Mission TERRA Over Nairobi

IRS P6 + GOSAT + OCEANSAT 2 redundancy of resources
Pareto Frontier Examples (2/2)

Cost and Value Tradeoff for the Mission TERRA Over Sydney

Cost and Value Tradeoff for the Mission SAC-C Over Ithaca

- SCD + GOSAT + OCEANSAT 2
- SCD 2 + AQUA + SPOT
- SCD 2 + AQUA + JASON 2
Conclusions

This research

- Introduces the notion of “mission as-a-service”
- Provides **methodology** for
  - **Scheduling** observation tasks on a complex, resource sharing spacecraft system with uncertain topology
  - **Estimating the efficiency** of that system and providing alternative VSM designs
- **Compares** VSM architectures with monolithic ones in terms of cost and value and **finds viable VSM alternatives** for monolithic missions
Thank you!
Backup Slides
Space Networks and Distributed Systems

- Heterogeneous Spacecraft Networks (HSN) [Faber et. al. 2014]
- Federated Satellite Systems (FSS) [Golkar & Lluch 2015] - a resource exchange market in space, similar to cloud computing on Earth
Optimization Problem

X: order in tasks. $x_{ij} = 1$, if $i$ is completed before $j$, 0 otherwise.

Y: shows which idle time window of which s/c does the task fit in. $y_{sk}^i = 1$, if the task with index $i$ occupies the idle window with indices $s$ and $k$, 0 otherwise.

W: shows which access time was allocated in the window. $w_{sh}^i = 1$, if the task with index $i$ is finished within the access window with indices $s$ and $h$. 
Optimization Problem

\[
\sum_{i=1}^{N} p_i \left( \sum_{j=1}^{N} x_{ij} \right) \quad (1)
\]

Where \( p_i \) is the priority of \( i \)-th task, subject to for each task \( i \):

\[
\sum_{j \neq i} x_{ij} \leq 1 \quad (2)
\]

\[
\sum_{j \neq i} x_{ij} - \sum_{s,k} y_{sk}^i = 0 \quad (3)
\]

\[
\sum_{s,k} y_{sk}^i AWS_{sk} - \sum_{s,h} w_{sh}^i AS_{sh}^i \leq 0 \quad (4)
\]

\[
\sum_{s,h} w_{sh}^i AE_{sh}^i - \sum_{s,h} y_{sk}^i AWE_{sk} \leq 0 \quad (5)
\]

\[
\left( \sum_{s,h} w_{sh}^i AE_{sh}^i \right) \sum_{j \neq i} x_{ij} - \sum_{j \neq i} x_{ij} \left( \sum_{s,h} w_{sh}^j AE_{sh}^j \right) \leq 0 \quad (6)
\]

Where \((AWS_{sk}, AWE_{sk})\) is the idle interval with index \( k \) of the spacecraft with index \( s \), \((AS_{sh}^i, AE_{sh}^i)\) is the access interval with index \( h \) for solving the task with index \( i \) on the spacecraft with index \( s \).