Automated Swarm Architectures for Planetary Moon Impactor Missions

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Motivation

Impactor missions provide valuable opportunities to explore the interior of small bodies. Impactor missions have been demonstrated on comets (Figure 1) and have been planned for asteroid studies and planetary moons in the future. In these missions, a carrier spacecraft releases a deadweight called the "Impactor" which collides at high-speeds with the target body exposing the interior in the vicinity of the impact site. Prepositioned "Observer" spacecraft(s) study the impact site on the target body. Having multiple spacecrafts perform these actions in a swarm broadens the scope, increases science return but also heightens mission complexity.

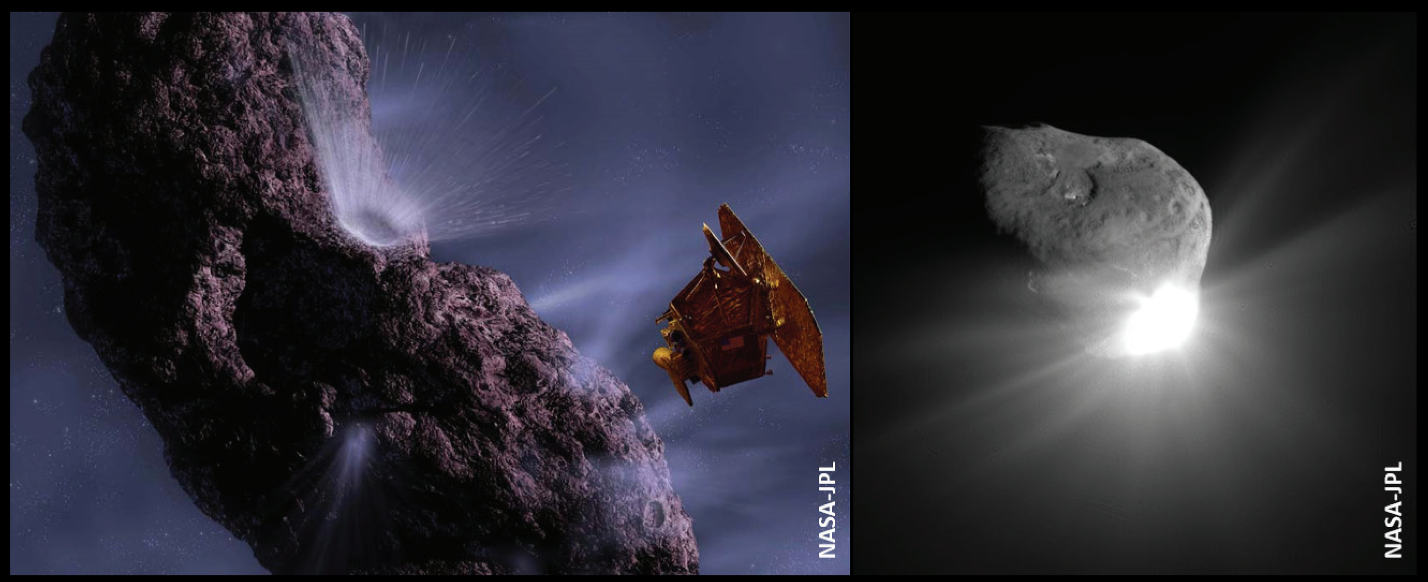

Figure 1: Deep Impact mission to the comet Tempel 1 showing the spacecraft (left), and the comet during impact (right).

Objectives

1.0 To present an automated design architecture for spacecraft swarm impactor missions.

2.0 To demonstrate the architectures with a simulated case study of an impactor swarm design to Deimos using Martian co-orbits.

IDEAS Architecture

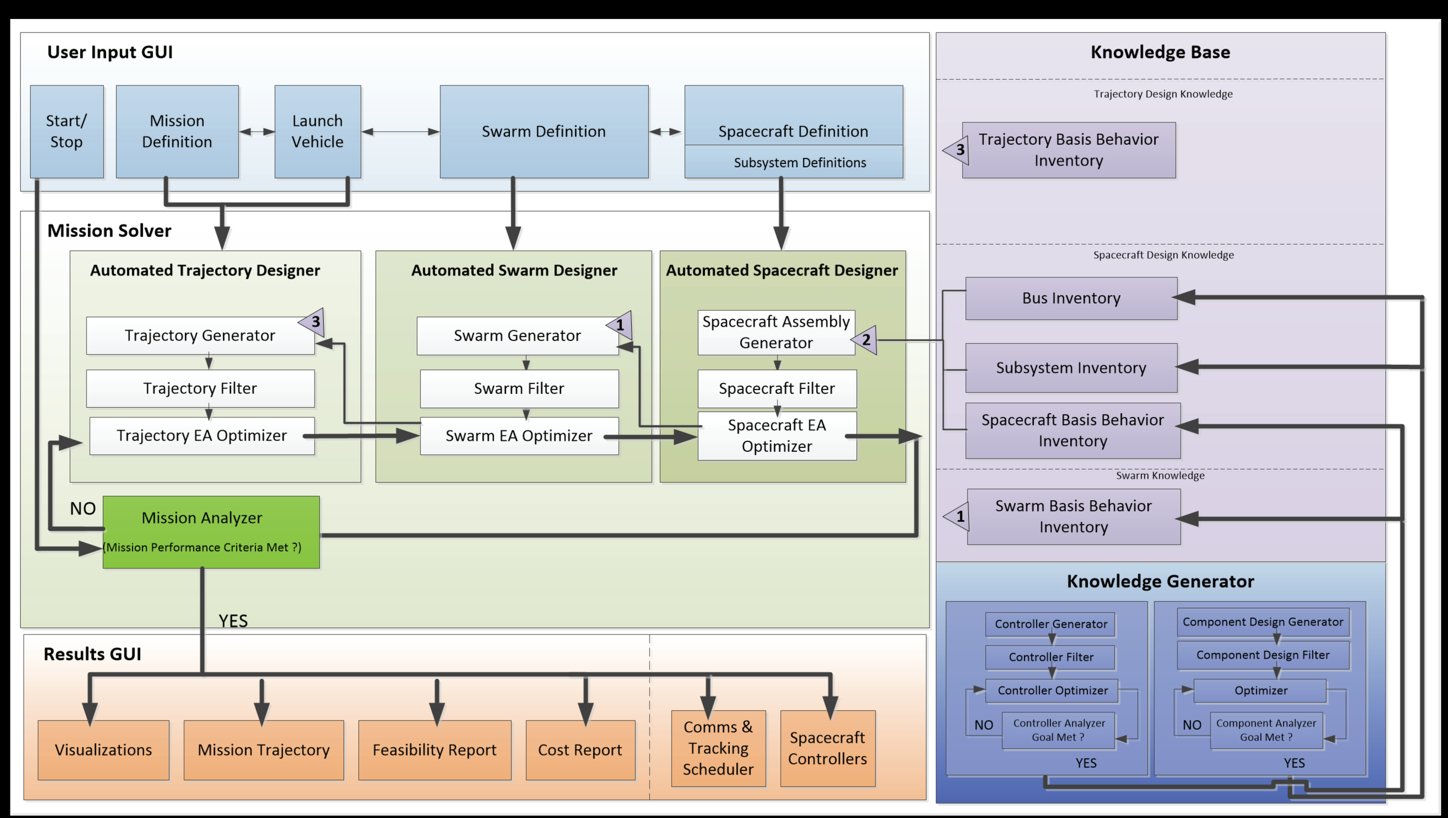

Figure 2: Software architecture of IDEAS showing its three principal automated design modules.

The Integrated Design Engineering and Automation of Swarms (IDEAS) Framework is an automated end-to-end swarm mission design software. IDEAS uses evolutionary algorithms to optimize the designs of trajectories, swarm operations, and the seed spacecraft as shown in Figure 2. In this work, we present a case study where an impactor swarm mission is designed using the Automated Swarm Designer module of IDEAS.

Design Objective

To design a swarm mission to a planetary moon where an "Impactor" strikes at a target region on the moon. Multiple "Observer" spacecraft are required to image a Region of Interest (RoI) spread around the impact site subject to spatial and temporal coverage requirements around the RoI. All spacecraft need to be deployed on resonant co-orbits around the central planet.

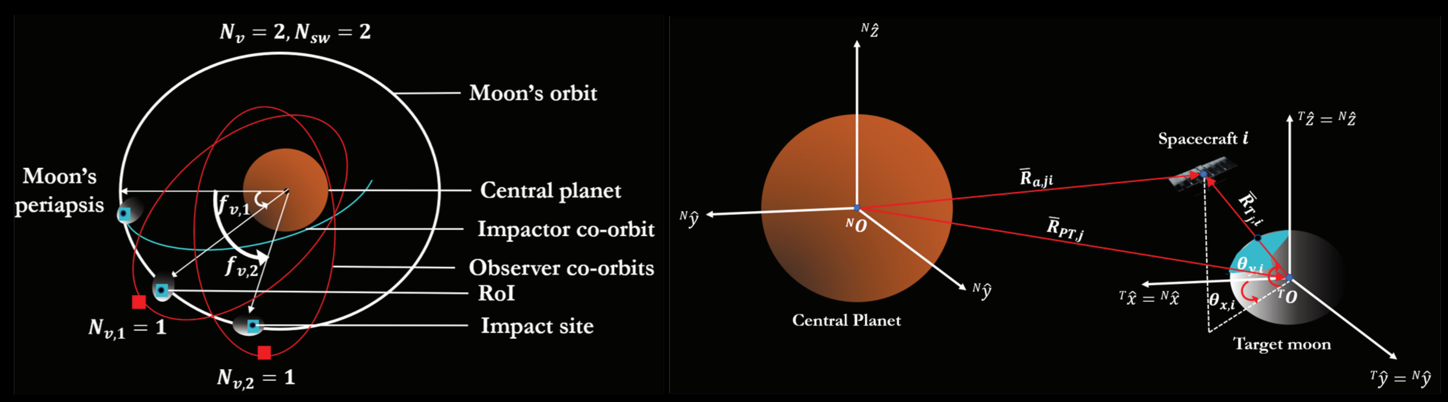

Figure 3: Design space of the impactor swarm mission, showing the swarm configuration (left), and geometrical encounter parameters (right).

Optimzation Problem

The swarm design optimization problem, which minimizes the number of "Observer" spacecraft, to meet the coverage requirements is presented below. The corresponding swarm design gene is presented in Figure 4.

$$\min J_{Sw} = N_{Obs}$$
$$\text{Subject to: } P_{RoI} \geq P_{Req}$$
$$T_{RoI} \geq T_{Req}$$
$$\text{Collisions} = \text{False}$$

Parameter	# moon encounters	True anomaly of the moon			Spacecraft azimuth at encounter			Spacecraft elevation at encounter		
Variable	N_v	$f_{v,1}$	…	f_{v,N_v}	$\theta_{x,1}$	…	$\theta_{x,N_{Sw}}$	$\theta_{y,1}$	…	$\theta_{y,N_{Sw}}$
Range	Integer $[1, N_{1,max}]$	Real $[0, 360]$ deg			Real $[0, 360]$ deg			Real $[-90, 90]$ deg		

Figure 4: Swarm design gene showing the design variables of optimization.

Case Study: Deimos Impactor Swarm

Table 1 presents the input parameters of the swarm design optimization problem. The optimization problem is solved using a Genetic Algorithm (GA) optimizer. The results of 5 GA trials are presented in Figure 5. A swarm with 1 "Impactor" and 4 "Observer" spacecraft is selected as a desirable solution as shown in Figure 6.

Table 1: Mission parameters for the RoI swarm mission.

Parameter	Value
Impact site location	(45, 45) deg
RoI angular spread	15 deg
RoI observation time requirement, T_{Req}	20 mins
RoI coverage requirement, P_{Req}	90 %
Desired resolution	1 m

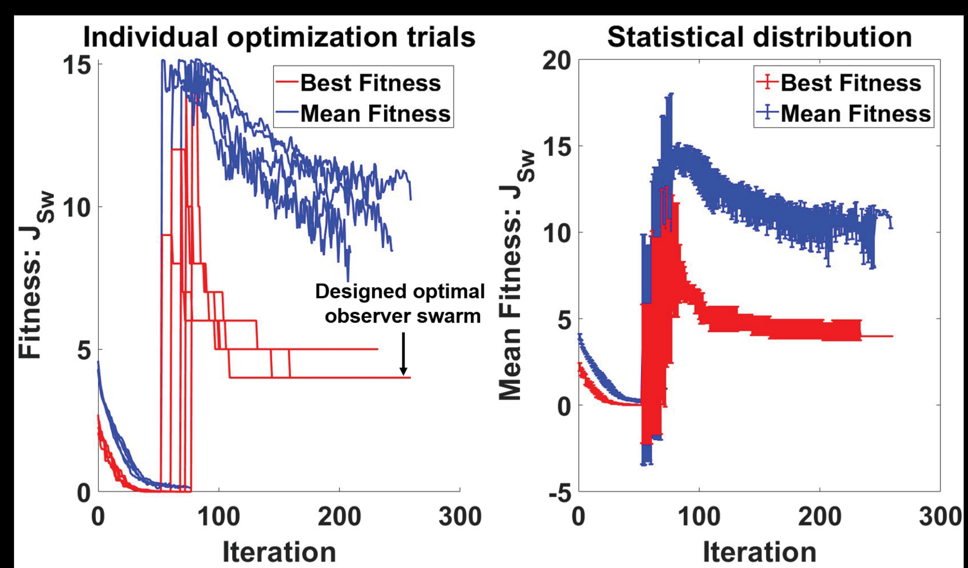

Figure 5: Results of 5 GA optimization trials showing the convergence to the selected optimal swarm size.

Swarm Performance

The candidate optimal solution with a minimum swarm size consists of 1 "Impactor" spacecraft and 4 "Observer" spacecraft. All spacecraft in the swarm enter into a 4:9 resonant Martian orbit with Deimos (shown in Figure 6), which has an estimated worst-case velocity change of 2.52 km/s if aerobraking at Mars is used. Following the impact, the "Observer" spacecraft, serially observe the impacted RoI. The simulated operations of the "Impactor" along with an "Observer" spacecraft in the swarm are presented in Figure 7. The "Impactor" spacecraft strikes the surface of Deimos with a relative terminal velocity of 0.67 km/s. The serial visits of the "Observer" spacecraft are noted to cumulatively observe the complete impacted RoI for a total period of 20.8 mins (shown in Figure 8), thus meeting the designed coverage requirements.

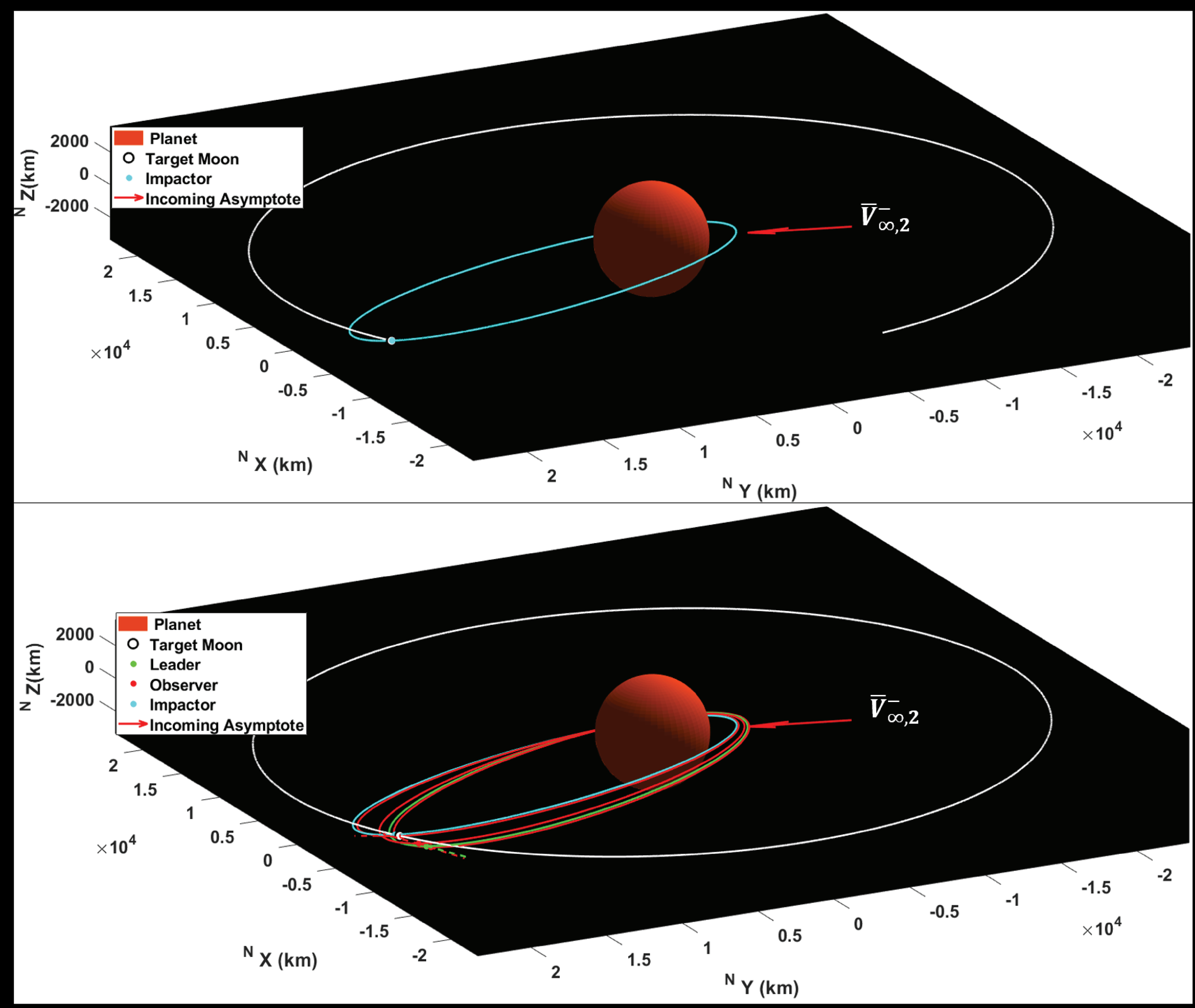

Figure 6: Martian trajectories of the 'Impactor' (top), and the spacecraft swarm (bottom).

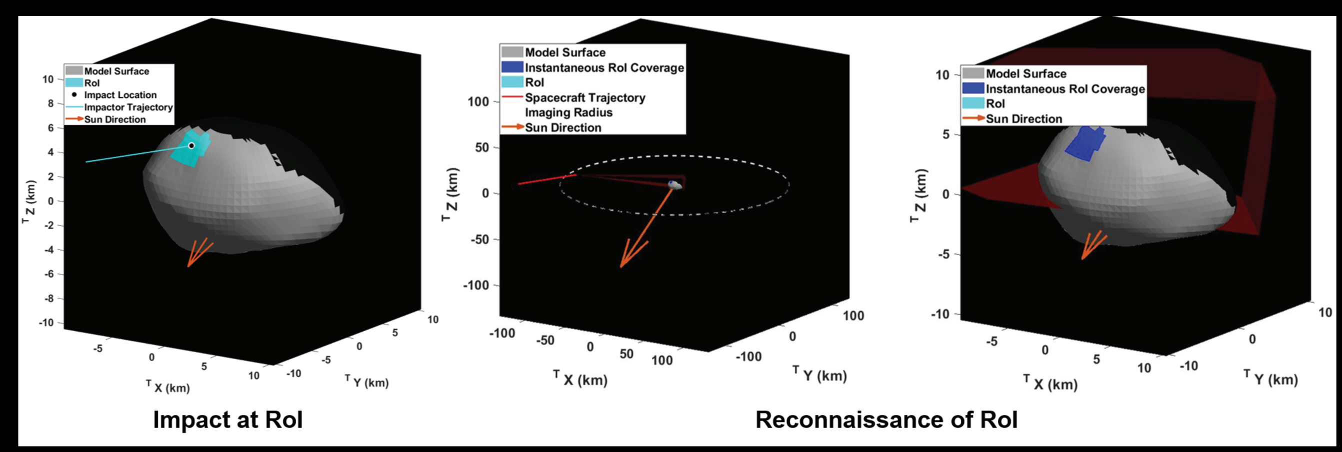

Figure 7: Simulated operations of the 'Impactor' spacecraft and an 'Observer' spacecraft during its encounter with Deimos

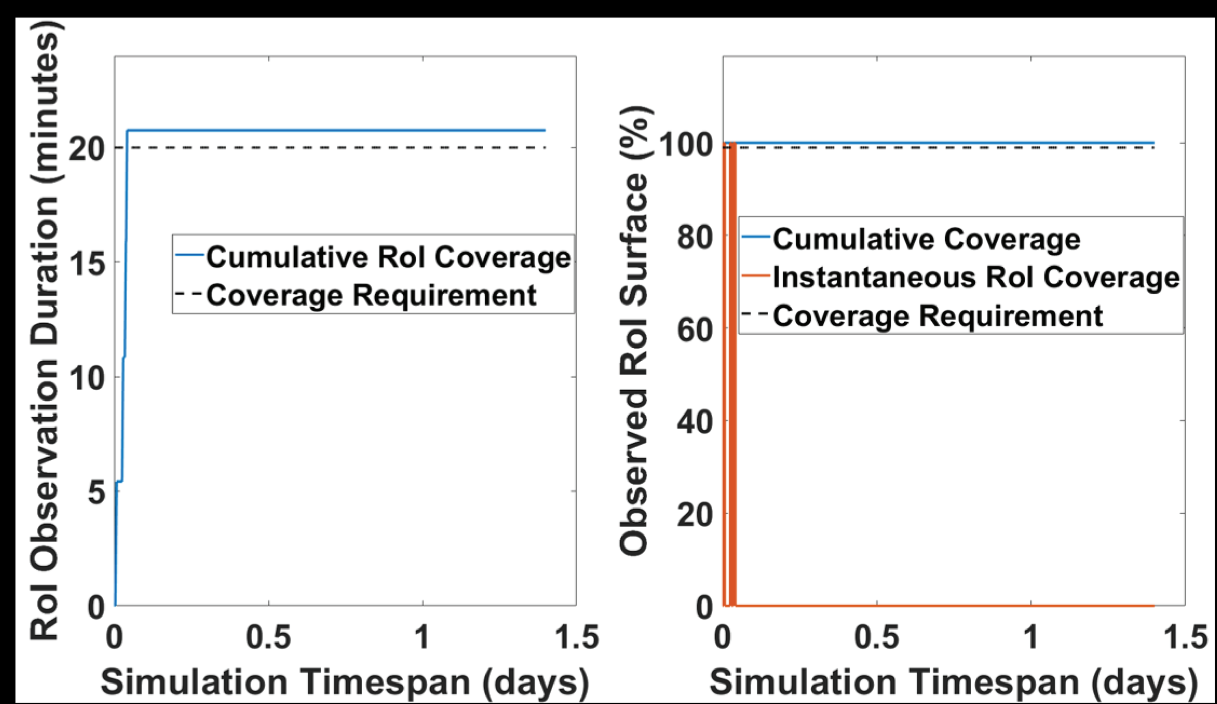

Figure 8: Temporal (right) and spatial (left) coverage performance of the 'Observer' spacecraft.