20th Annual AIAA/USU Conference on Small Satellites

Frank J. Redd Student Scholarship Competition

Controlling Swarms of Bandit Inspector Spacecraft

by

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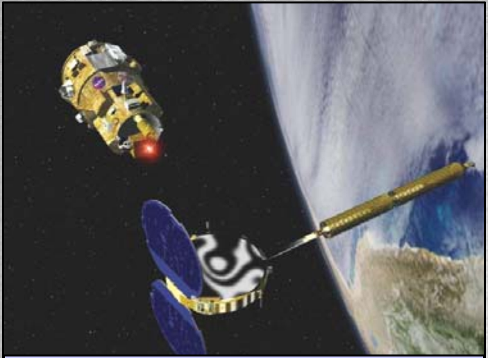
Outline

- **Introduction:** On-orbit servicing and the Bandit system
- **Control:** Behavior-based methods, Bandit control strategy, and convergence.
- **Results:** Effects of disturbances & model error, building complex missions.
- **Conclusions & Future Work**

Introduction: On-Orbit Servicing

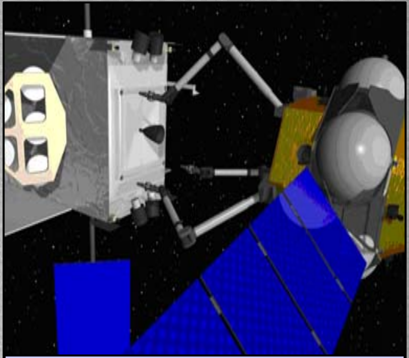
XSS-10: 31 kg, 2003

XSS-11: 100 kg, 2005

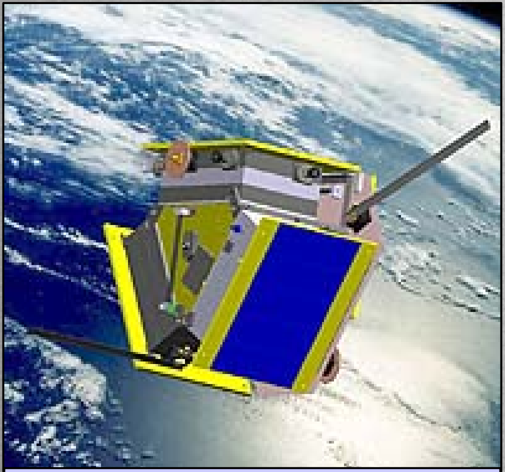


DART: 360 kg, 2005

Orbital Express: 700 kg, 2006



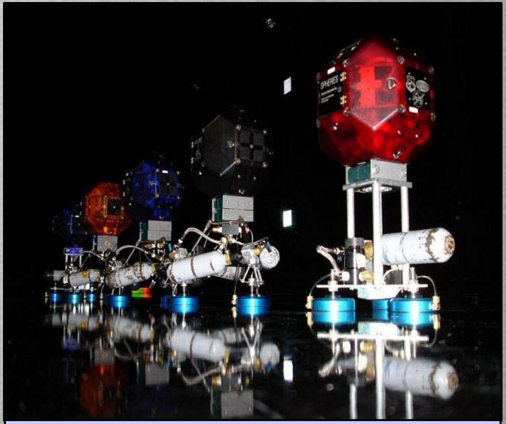
SUMO: 400kg (?), 2008



SNAP-1: 6.5 kg, 2000

SPRINT AERCam: 16 kg, 1997

MINI AERCam: 5 kg

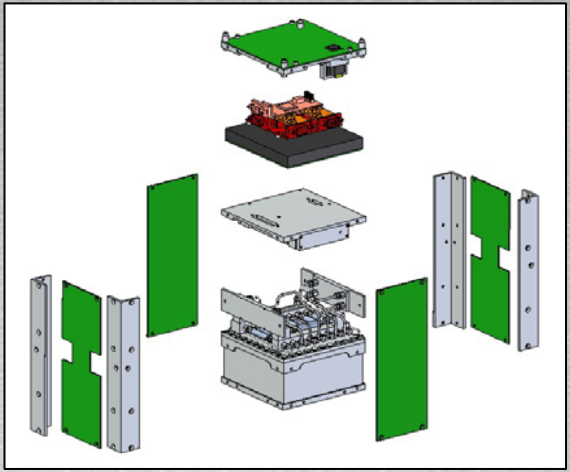


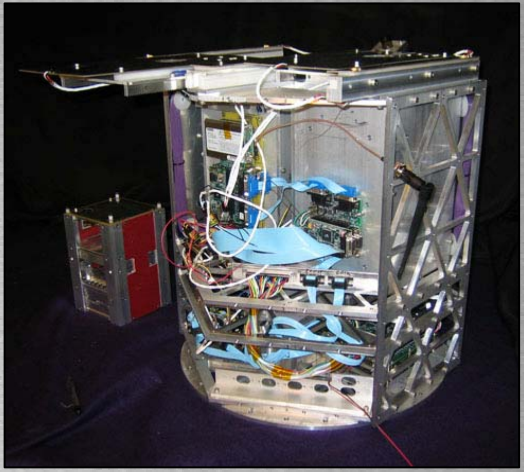
SPHERES: 4 kg, 2006

Introduction: The Bandit System

The Concept

- Autonomous
- Deployed & Redockable
- Expendable





The Consequences

- Limited Individual Capabilities
- Extended Swarm Capabilities

The Problem

- **Control**

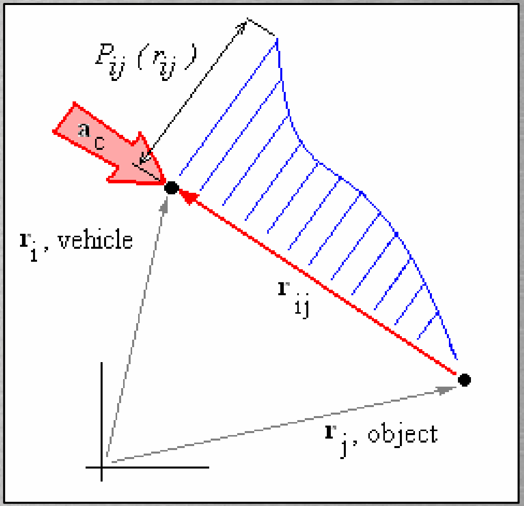
Control: Behavior-Based Methods

Complex team behaviors emerge from simple individual behaviors

- *Good*: robustness, communication and computational costs
- *Bad*: system analysis and predictability

Potential Function Control

- Define potentials based on inter-object distances.
- Define a control that descends the potential gradient.
- System seeks potential minima.



Bandit Applications

- Adapt the method to a constrained, impulsive actuator

Control: Strategy

- Define a desired velocity field, $\mathbf{v}_d$

  defined for all **r,** *leads to* $\mathbf{r}_d$

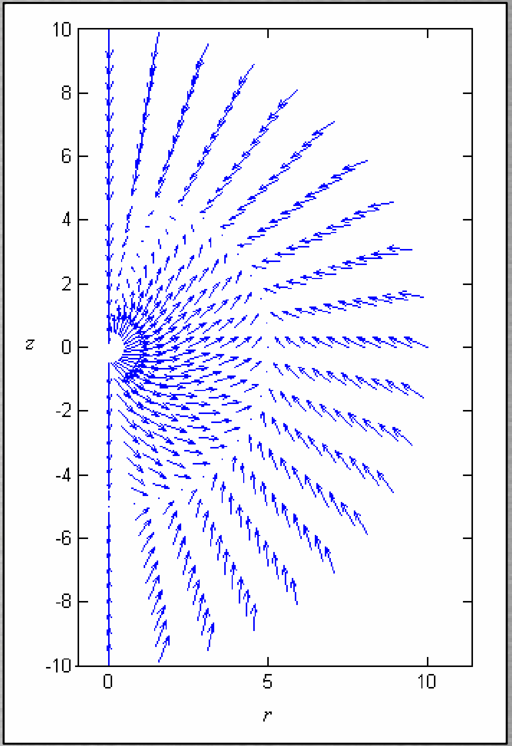
- Define a potential, P, based on velocity error

  Ex.: $$P = k\left(\mathbf{v} - \mathbf{v}_d\right)^T\left(\mathbf{v} - \mathbf{v}_d\right)$$

- Sum the potentials for each vehicle, $\Phi = \sum P$

- At time step, calculate the change in Φ from the independent firing of each thruster, $\Delta\Phi_k$.

- If $\Delta\Phi_k + \sigma < 0$, fire thruster k.



Example Velocity Field

Control: Velocity Convergence

Consider $\Phi = k_\omega \boldsymbol{\omega}_e{}^T \boldsymbol{\omega}_e + k_T \mathbf{v}_e{}^T \mathbf{v}_e$

Then the criteria to fire a thruster becomes:

$$2\left[k_T \mathbf{v}_e{}^T \quad k_\omega \boldsymbol{\omega}_e{}^T\right] \begin{bmatrix} \Delta\mathbf{v} \\ \Delta\boldsymbol{\omega} \end{bmatrix} + k_T \left|\Delta\mathbf{v}\right|^2 + k_\omega \left|\Delta\boldsymbol{\omega}\right|^2 + \sigma \le 0$$

With knowledge of the thrust matrix this can be reduced to:

$$\frac{k_T \left|\Delta\mathbf{v}\right|^2 + k_\omega \left|\Delta\boldsymbol{\omega}\right|^2 + \sigma}{2\alpha} \le \left| k_T \mathbf{v}_e{}^T \quad k_\omega \boldsymbol{\omega}_e{}^T \right|$$

Control: Position Convergence

Assuming $\mathbf{v}_d \pm \mathbf{v}_e$ has been attained, the convergence requirement is given by: $\left(\mathbf{v}_d + \mathbf{v}_e\right)^T \left(\mathbf{r}_d - \mathbf{r}\right) > 0$

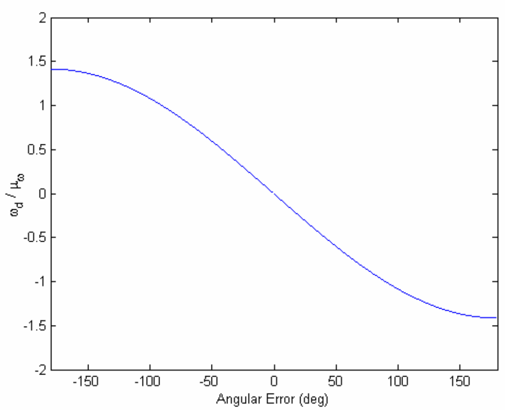
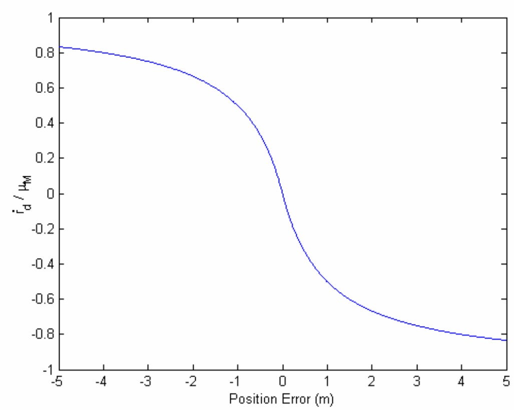
Then, with the worst case $\mathbf{v}_e$, this becomes:

$$\mathbf{v}_d^{\,T} \mathbf{r}_e > \frac{k_T \left|\Delta \mathbf{v}\right|^2 + k_\omega \left|\Delta \boldsymbol{\omega}\right|^2 + \sigma}{\alpha k_T} \left|\mathbf{r}_e\right|$$

Similarly for rotation:

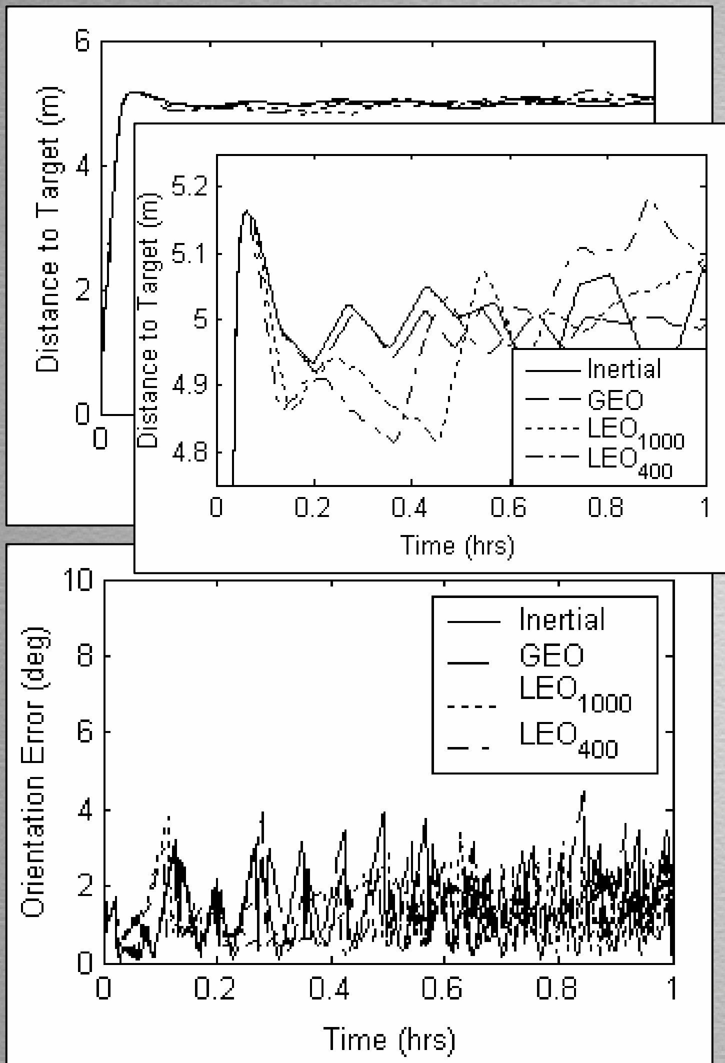
$$\boldsymbol{\omega}_d^{\,T} \left(\frac{\hat{\mathbf{n}} \times \hat{\mathbf{r}}}{\left|\hat{\mathbf{n}} \times \hat{\mathbf{r}}\right|} \right) > \frac{k_T \left|\Delta \mathbf{v}\right|^2 + k_\omega \left|\Delta \boldsymbol{\omega}\right|^2 + \sigma}{2 \alpha k_\omega}$$

Control: Potentials

Rotation: Target Pointing	*Translation: Distance Keeping*	*Translation: Inter-Vehicle*
$P_\omega = k_\omega \boldsymbol{\omega}_e{}^T \boldsymbol{\omega}_e$ $\boldsymbol{\omega}_d = \left(\mu_\omega \sqrt{1-\hat{\mathbf{n}}\cdot\hat{\mathbf{r}}}\right)\frac{\hat{\mathbf{n}}\times\hat{\mathbf{r}}}{\lvert\hat{\mathbf{n}}\times\hat{\mathbf{r}}\rvert}$	$P_H = k_H \mathbf{v}_{e,H}{}^T \mathbf{v}_{e,H}$ $\mathbf{v}_d = \frac{\mu_H}{1+\lvert\mathbf{r}_e\rvert}\mathbf{r}_e \quad \mathbf{r}_e = \left(\frac{r_d}{\lvert\mathbf{r}\rvert}-1\right)\mathbf{r}$	$P_I = \sum_m \frac{k_{I,lm}}{\lvert\mathbf{r}_{lm}\rvert}\mathbf{v}_{e,lm}{}^T \mathbf{v}_{e,lm}$ $\mathbf{v}_{d,lm} = \frac{\mu_{I,lm}}{\lvert\mathbf{r}_{lm}\rvert}\mathbf{r}_{lm}$
		

Parameters to Select	*Parameters to Compute*
μ_H , μ_ω , $\mu_{I,lm}$, $r_{e,ss}$, $\theta_{e,ss}$, $k_{I,lm}$	k_T , k_ω , σ

Results: Effects of Disturbances



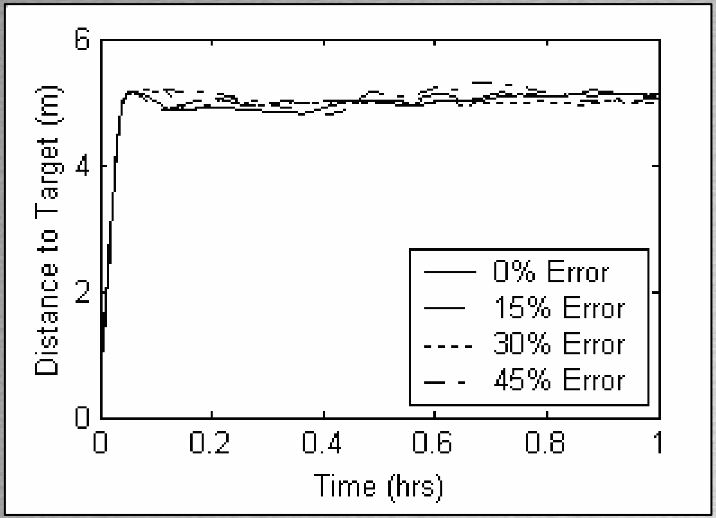
Orbit	$\Delta \mathbf{v}$ *(m/s)*	$\frac{\int_{t_o}^{t_f} \lvert \mathbf{r}_e \rvert dt}{t_f - t_o}$ *(cm)*	$\frac{\int_{t_o}^{t_f} \theta_e dt}{t_f - t_o}$ *(deg)*
Inertial	0.1373	12.14	1.34
GEO	0.1368	10.67	1.46
LEO_{1000}	0.1643	14.84	1.31
LEO_{400}	0.1940	16.70	1.34

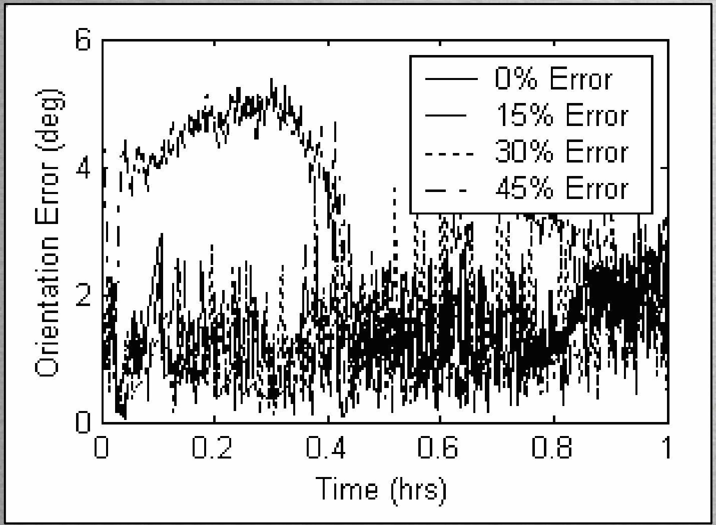
Maintains performance in a wide range of orbit conditions.

Selected Steady State Errors:

0.25 m & 15^o

Results: Effects of Model Error @ 400 km





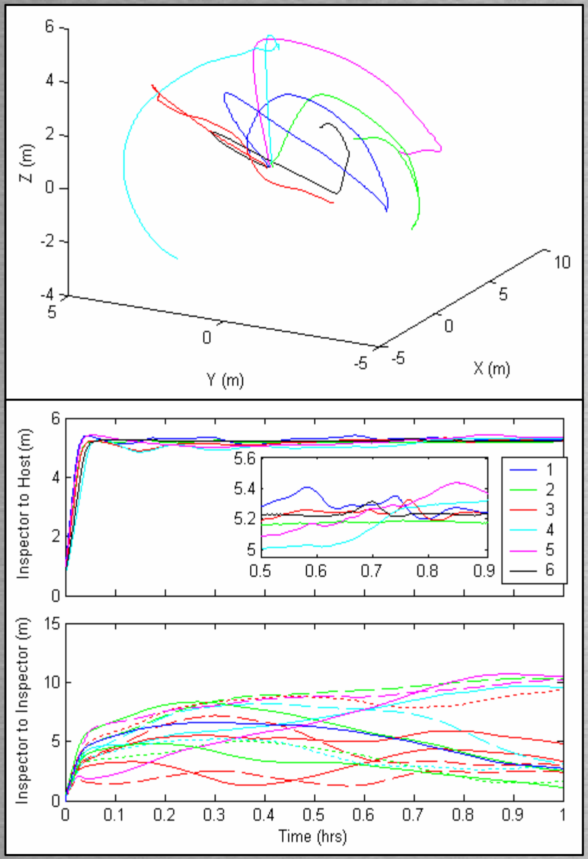
Calibration Error	$\Delta \mathbf{v}$ *(m/s)*	$\frac{\int_{t_o}^{t_f} \lvert \mathbf{r}_e \rvert dt}{t_f - t_o}$ *(cm)*	$\frac{\int_{t_o}^{t_f} \theta_e dt}{t_f - t_o}$ *(deg)*
0 %	0.1940	16.70	1.34
15 %	0.2325	14.68	1.27
30 %	0.1843	10.99	1.43
45 %	4.4575	20.81	3.22

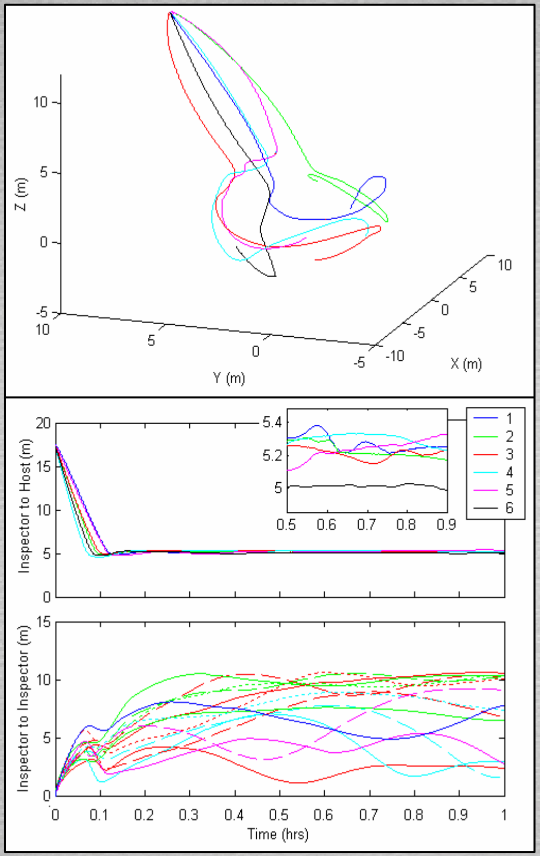
Largely insensitive to calibration error.

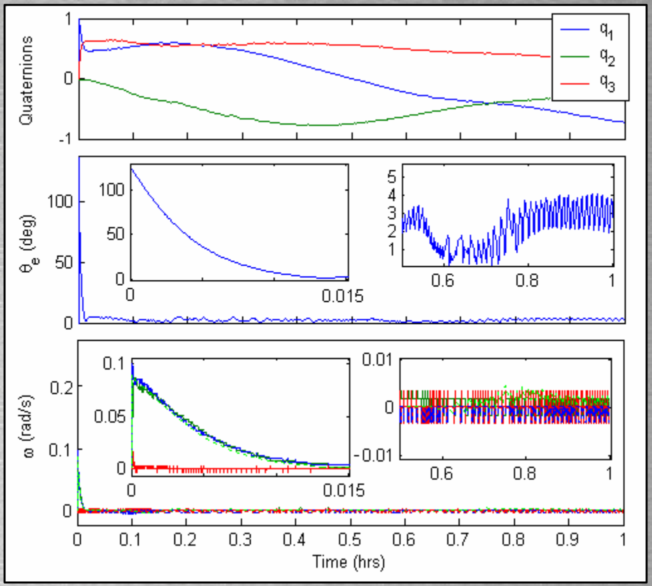
Selected Steady State Errors:

0.25 m & 15°

Results: Multi-Vehicle Maneuvers @ 1000 km







Representative Attitude History

Deployment

0.2823 m/s

Rendezvous

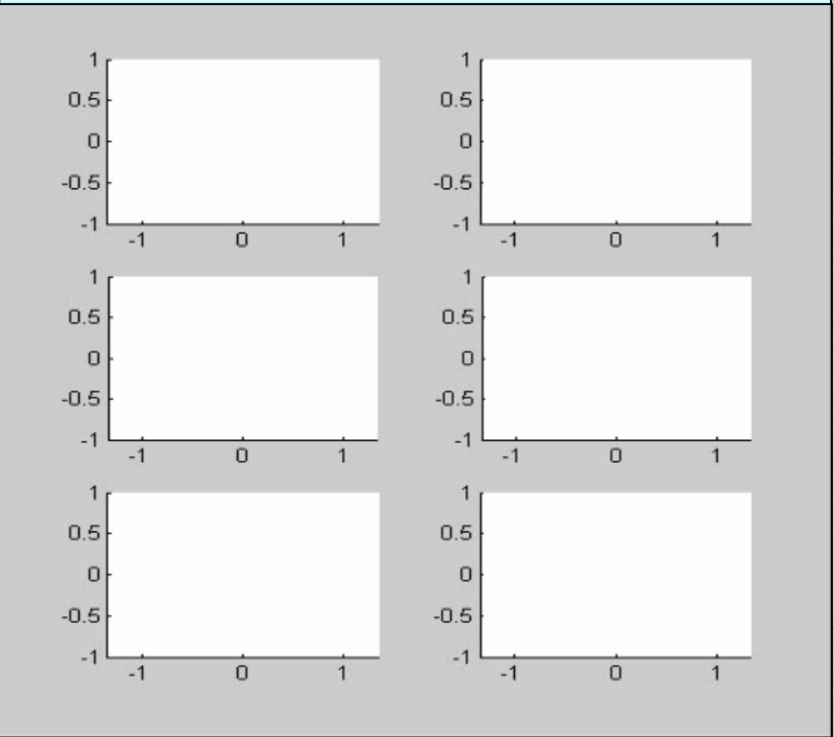
0.3294 m/s

Selected Steady State Errors:

0.50 m & 10^o

Results: Reconnaissance @ 400km

Bandit Camera Views



1. Deploy from and inspect host

2. Rendezvous with a target 100 m away

3. Return to the host

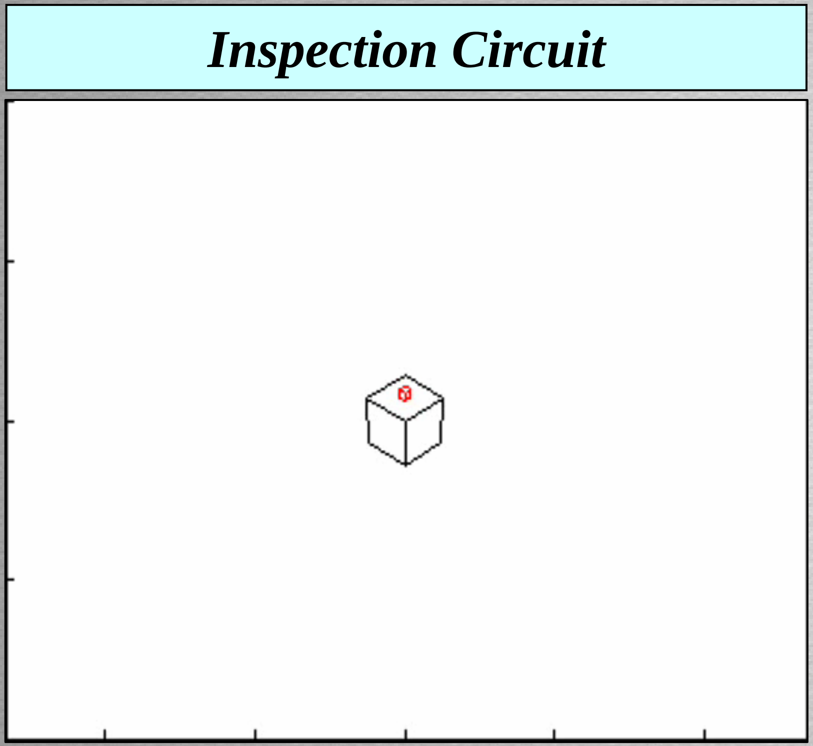
4. Dock

Vehicle	*Propellant Use (m/s)*				
	Deploy	*Rend.*	*Return*	*Dock*	*Total*
1	0.3745	0.8380	0.7385	0.3865	2.3375
2	0.3780	0.8830	0.7535	0.3423	2.3568
3	0.3413	0.7075	0.8455	0.3518	2.2461
4	0.3633	0.6492	0.8700	0.2945	2.1770
5	0.3558	0.7735	0.8560	0.2270	2.2131
6	0.3895	0.8357	0.6780	0.2465	2.1497
Avg.	0.3671	0.7812	0.7903	0.3081	**2.2466**

Selected Steady State Errors:

0.25 m & 15^o

Results: Way-Point Inspection Circuit @ 400 km



- A way-point potential to directs the vehicle to a desired position.
- Way-point progresses between six pre-defined imaging locations.
- Way-point potential replaced with the docking potential after the sixth way-point is reached.
- Consumes 1.5470 m/s of propellant in just 0.56 hrs!

Conclusions

The Highs:

- Provides desirable, predictable performance from limited resources.
- Immense flexibility / scalability.
- Simple to implement and tune.
- Robust to external disturbances and model errors.

The Lows:

- Sub-optimal propellant consumption.
- No analytical risk assessment for collision.

Future Work

- Further investigate robustness to disturbances, model inaccuracies, and sensor error.
- Extend capabilities through the development of new potentials.
- Implement in hardware and conduct real world experiments.

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