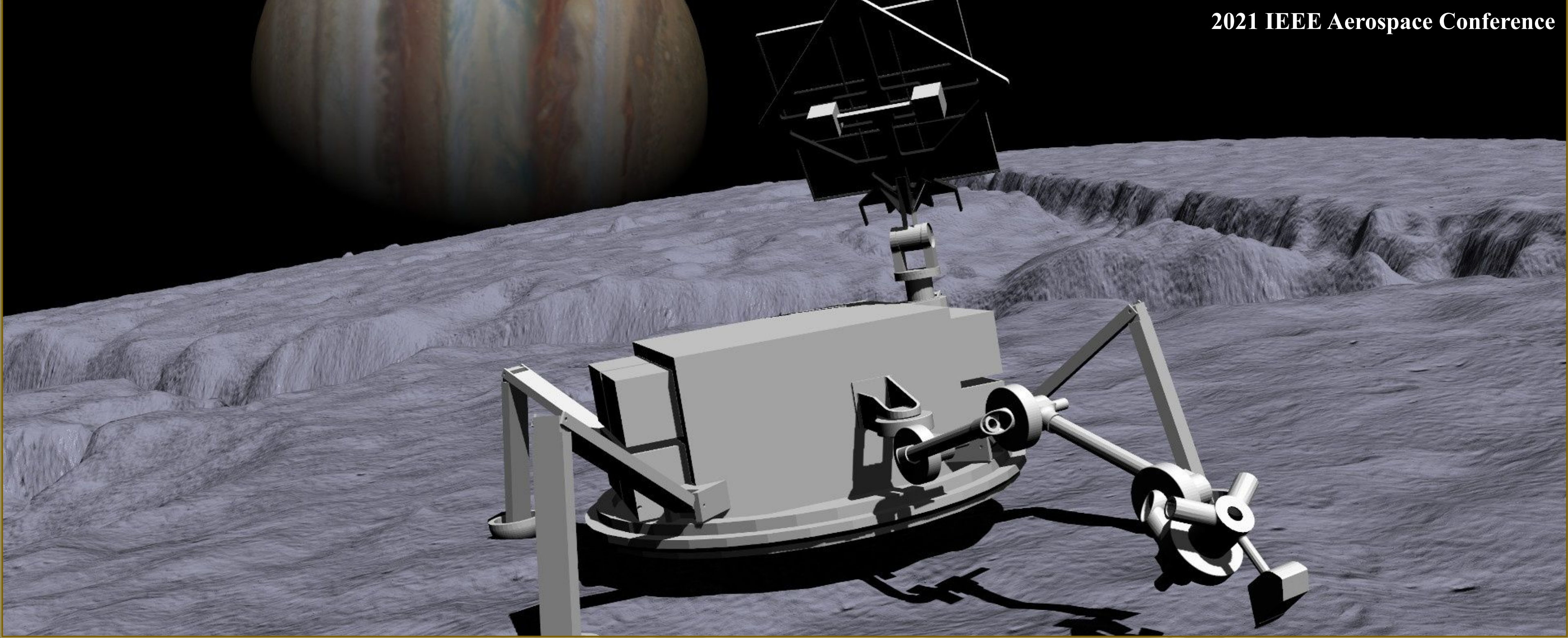


2021 IEEE Aerospace Conference

OceanWATERS Lander Robotic Arm Operation

Damiana Catanoso[1], Anjan Chakrabarty[2], Jason Fugate[2], Ussama Naal[2], Terence M. Welsh[3], Laurence J. Edwards[4]

[1]Universities Space Research Association, [2]KBR, [3]Logyx LLC, [4]NASA Ames Research Center

PRESENTATION OUTLINE

- The OceanWATERS simulation testbed
- Europa Lander system
- Robotic arm description
- Modes of operation
- Power consumption
- Arm-terrain interaction
- Conclusions and future work

BACKGROUND AND MOTIVATION

Outer solar system moons (Europa, Enceladus, Titan) have subsurface oceans

Past and present life may be found

Surface exploration missions

- Ground communication delays due to long distance
- Short life span of electronics due to highly radioactive environment

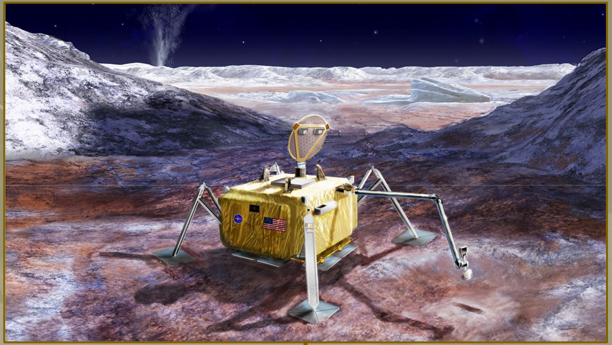
Need for high level of autonomy

Need for development and testing of new autonomy technologies enabling increased science operations productivity in presence of sub-system failures

THE OCEANWATERS SIMULATION TESTBED

Ames Research Center

Jet Propulsion Laboratory
California Institute of Technology



[8]

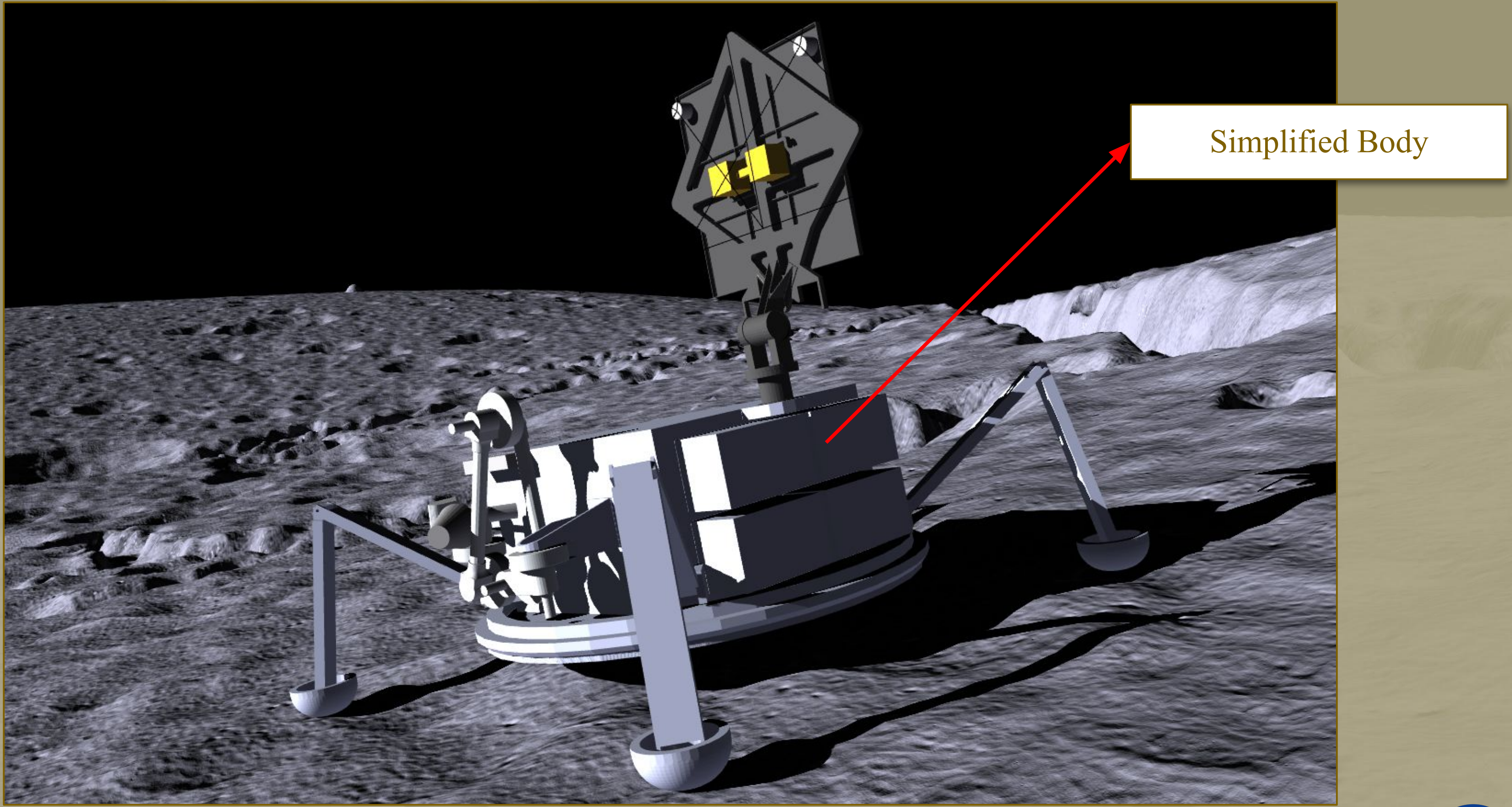
Physical testbed for validation

Europa Lander reference mission

Ocean Worlds **A**utonomy **T**estbed for **E**xploration **R**esearch and **S**imulation
OceanWATERS

- Lander model in simulation environment
- Test autonomous operations in presence of sub-system failures
- Based on the Robot Operating System (ROS) and Gazebo
- Open source on GitHub

EUROPA LANDER SYSTEM DESCRIPTION



OceanWATERS Lander Robotic Arm Operation

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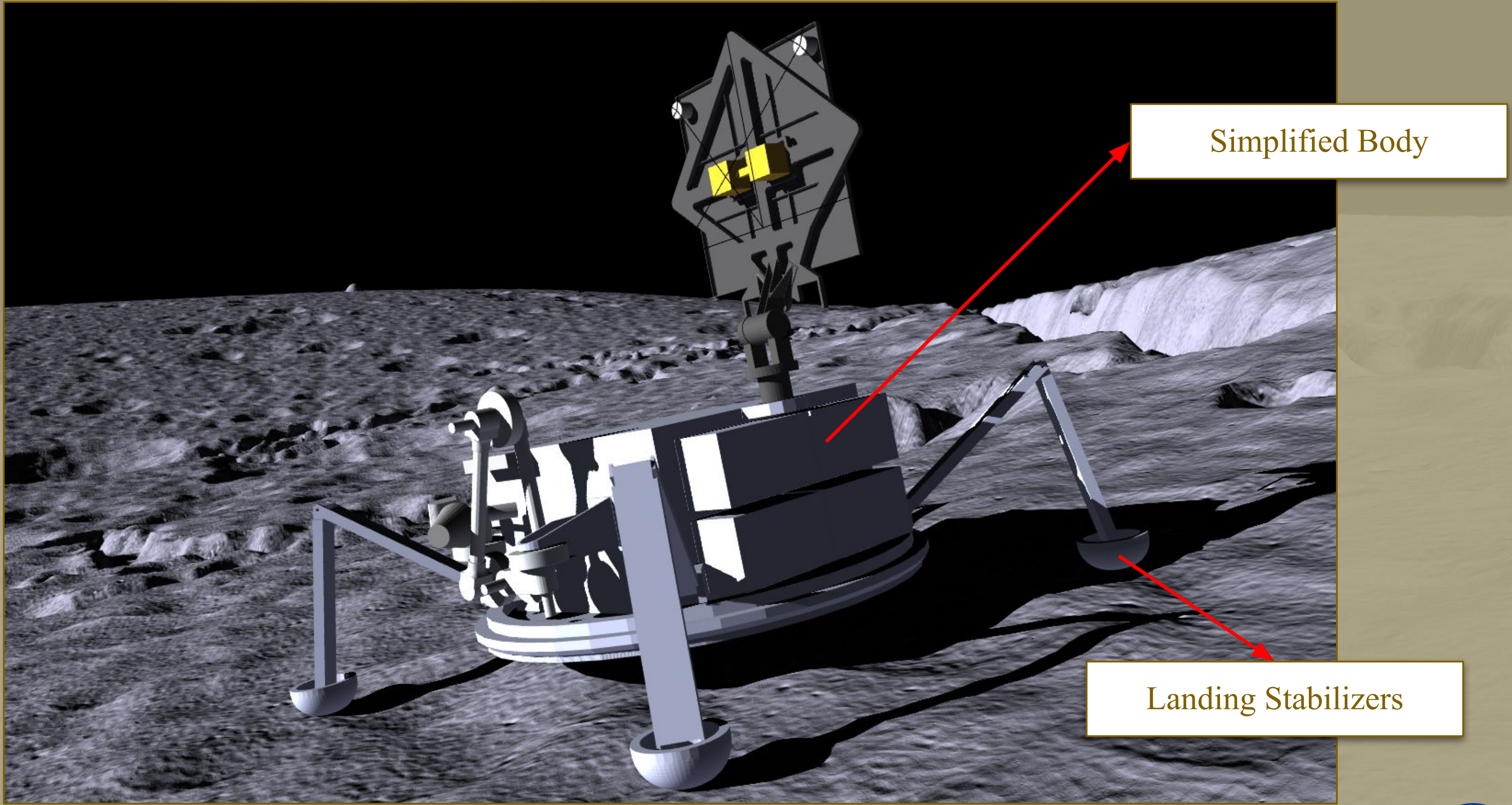
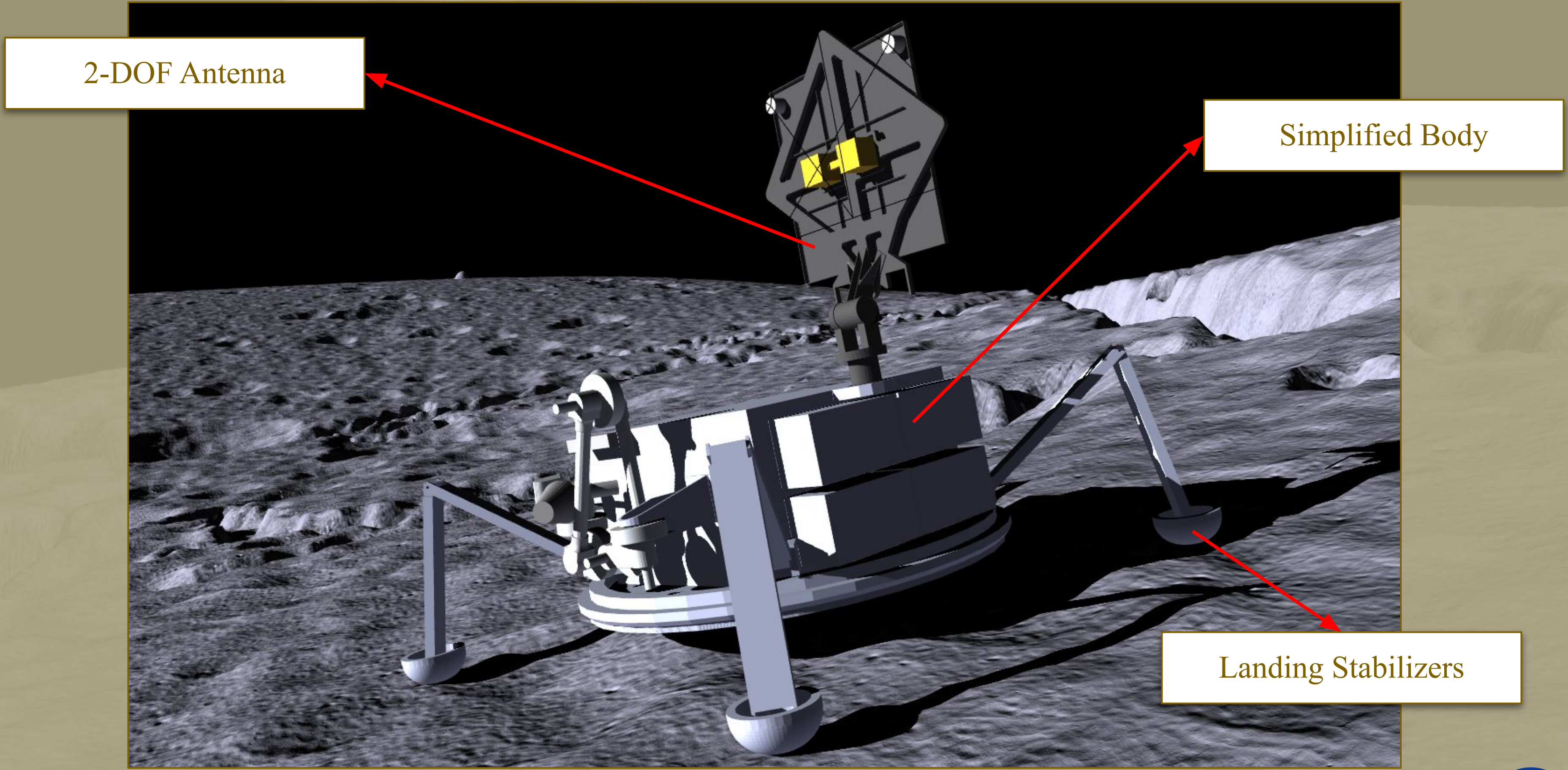


EUROPA LANDER SYSTEM DESCRIPTION



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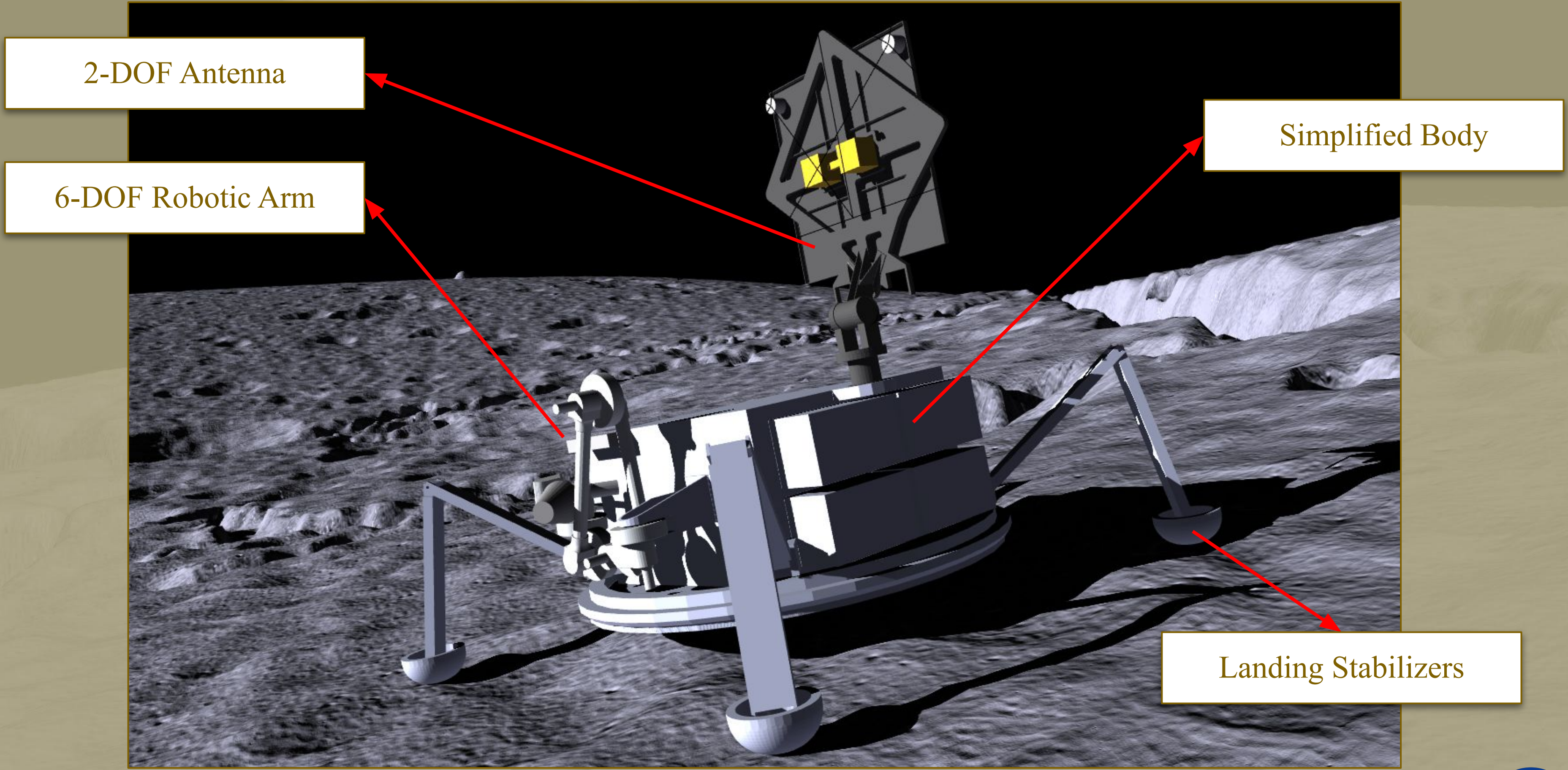
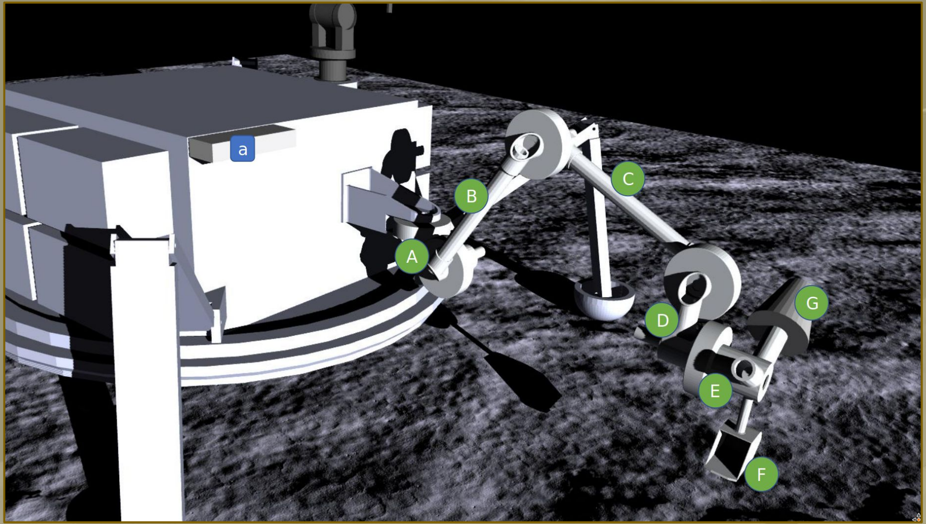
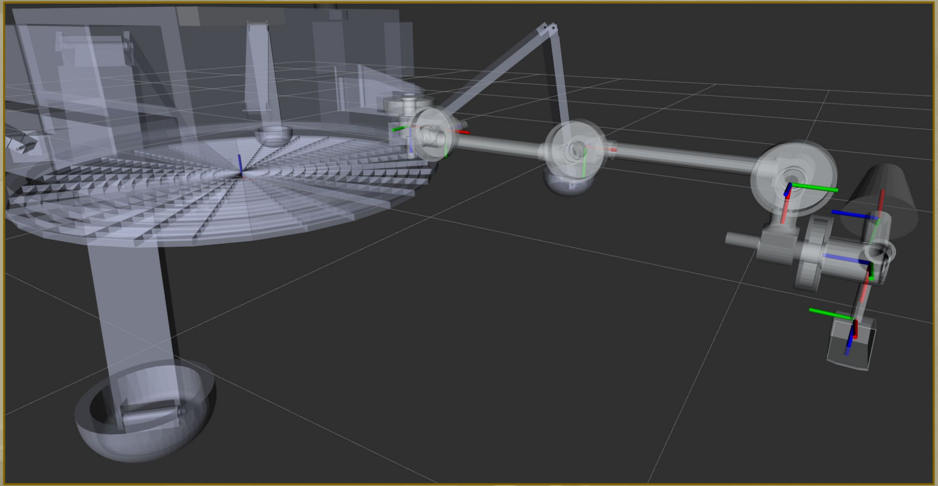


THE ARM



Base_link and the robotic arm link frames



Robotic arm links:
A) Shoulder link, B) Proximal link,
C) Distal link, D) Wrist link,
E) Hand link, F) Scoop link,
G) Grinder link,
a) Sample transfer dock

MOTION PLANNING AND EXECUTION

ROS Service:

- define motion planning problem through Python API
- Set final and intermediate goal states in joint or Cartesian space

.py files

MoveIt motion planner:

- solves the planning problem
- Outputs a "plan" to get to each goal state.
- Each plan is a joint space position/velocity/acceleration trajectory that the arm should follow to get to each goal state

plans

Fake controller:

- Interpolates trajectory position points
- Records interpolated trajectory in a .csv file

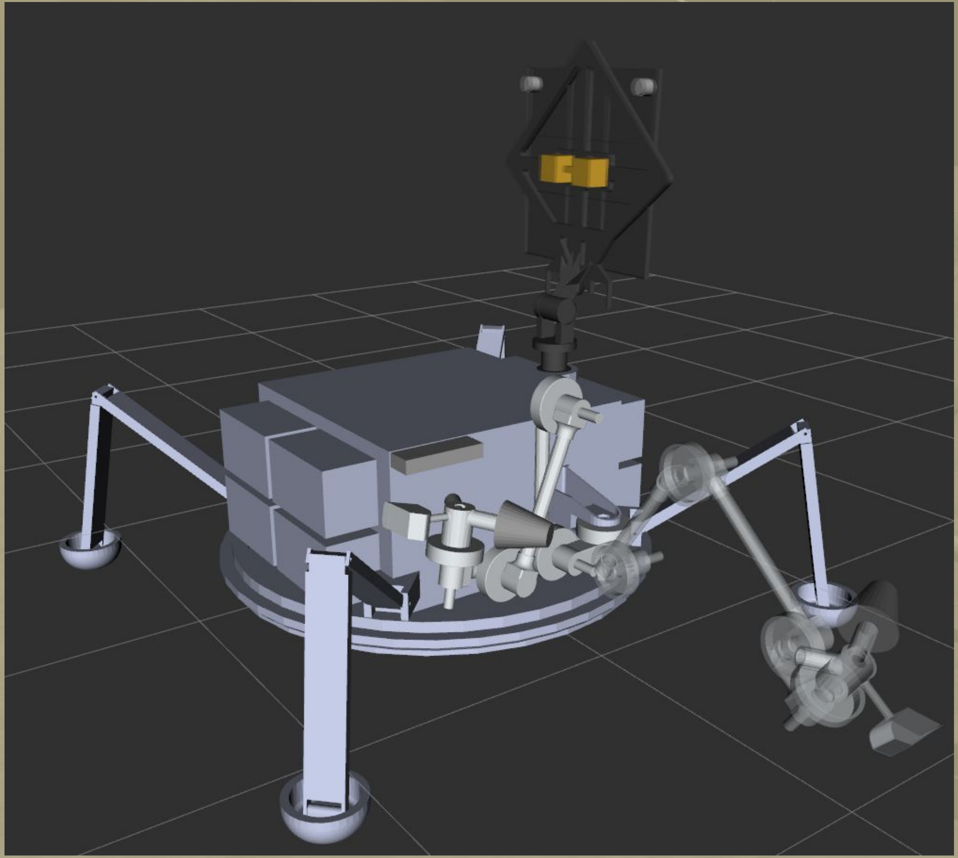
.csv file

Publish Trajectory:

- ROS service
- Reads .csv file and publishes desired joint states on a specific topic for the controllers to activate it

MOTION PLANNING AND EXECUTION

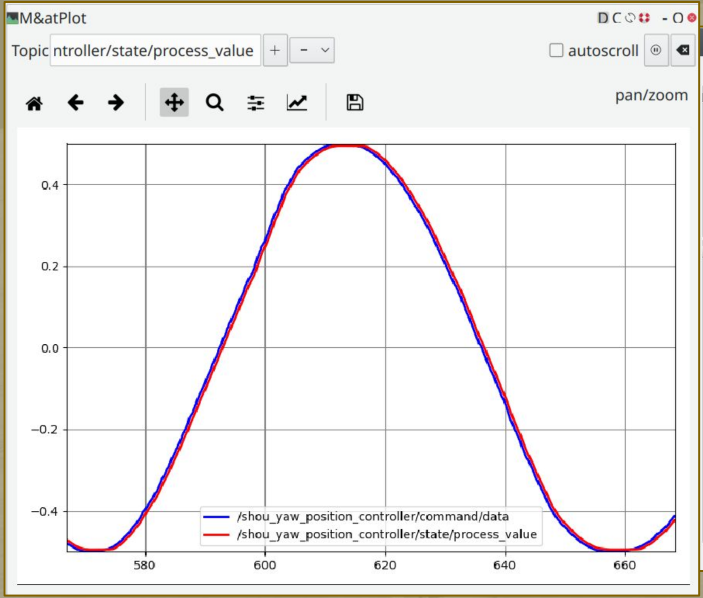
Rviz: “ghost” arm for planning VS real arm (solid arm):

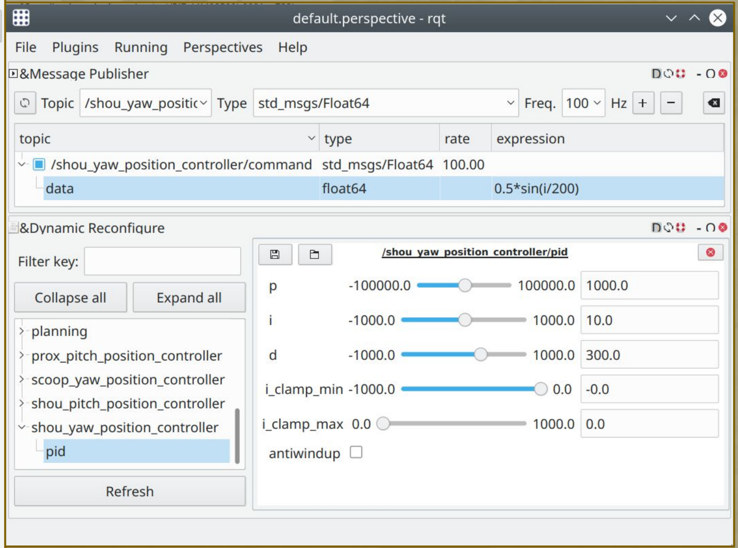


JOINT CONTROLLERS

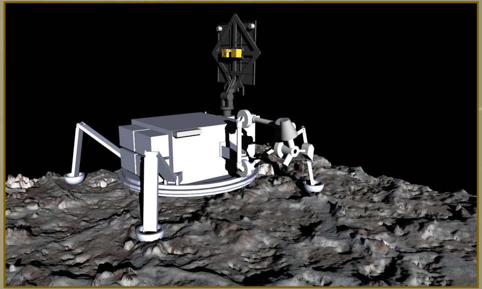
- Proportional Integral Derivative (PID) controllers for all joints

- Tuning using rqt plugins:
  - Dynamic reconfigure
  - Message publisher
  - Plotting tool



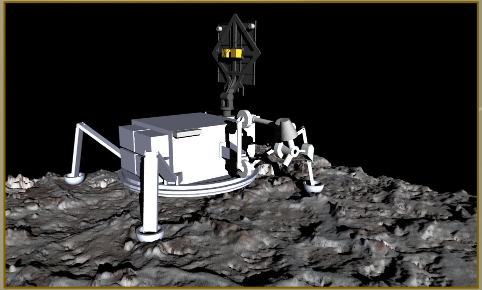


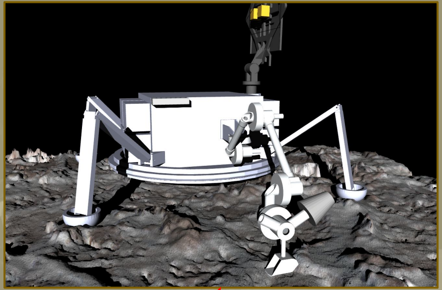
MODES OF OPERATION



Name	Planned movement
Unstow	Unstow arm
Guarded_move	Perform a guarded move
Grind	create a Trench grinding solid ice
Dig_circular	Collect sample with circular motion
Dig_linear	Collect sample with rasping motion
Deliver_sample	Sample delivery and discard
Stow	Stow arm

MODES OF OPERATION





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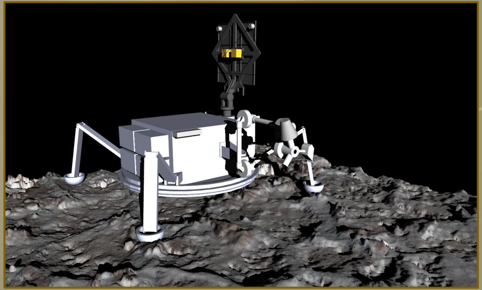

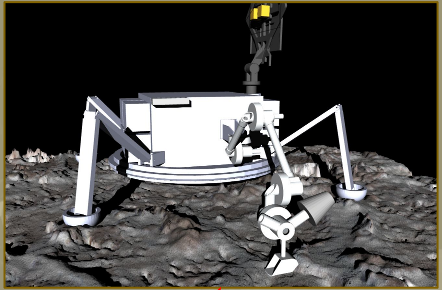

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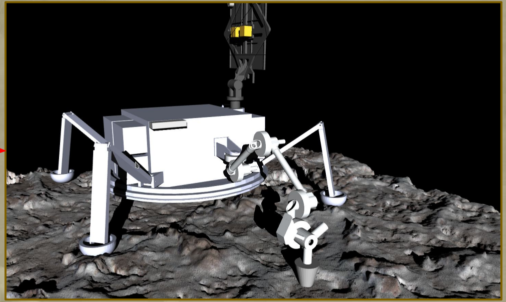

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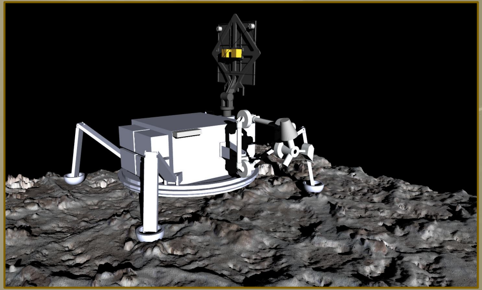

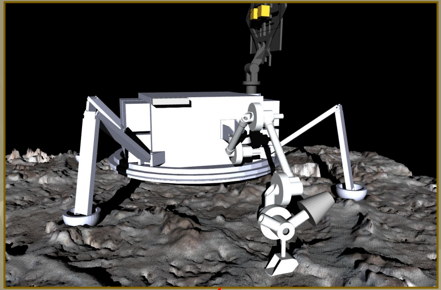

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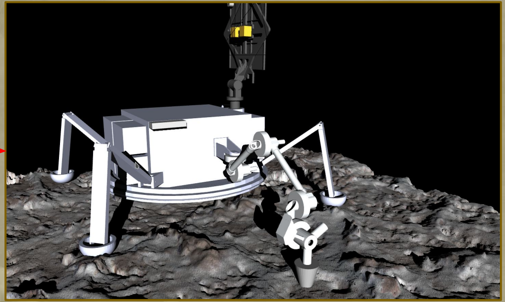

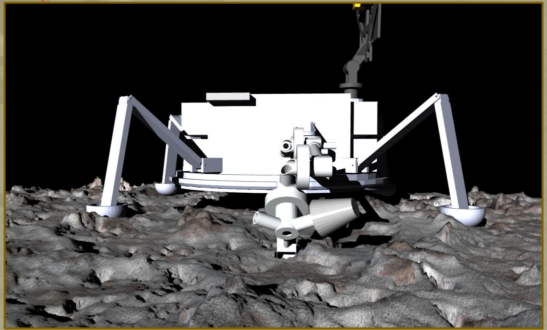

OceanWATERS Lander Robotic Arm Operation

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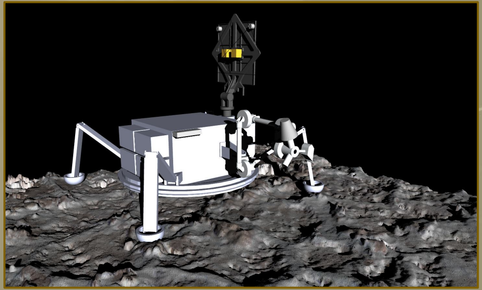

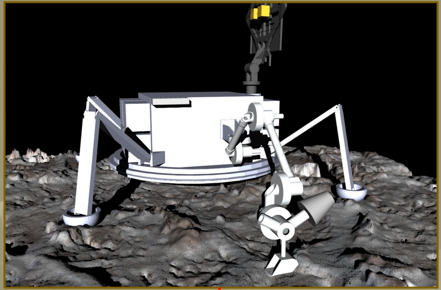

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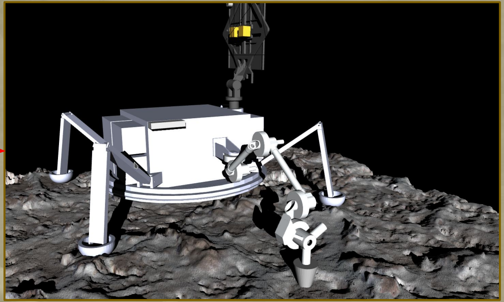

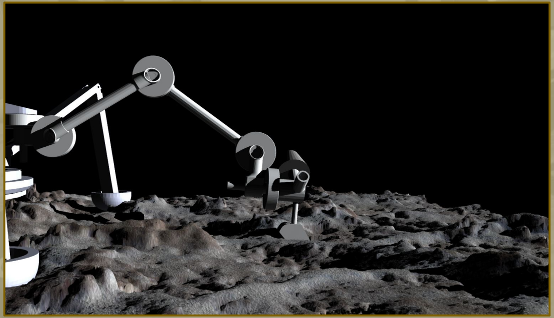

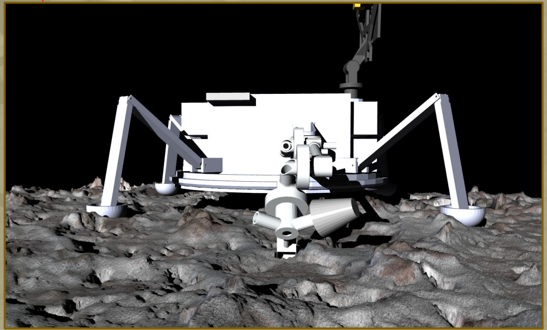

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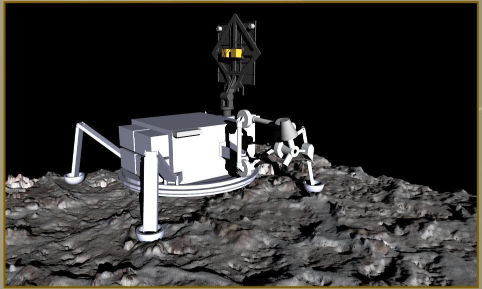

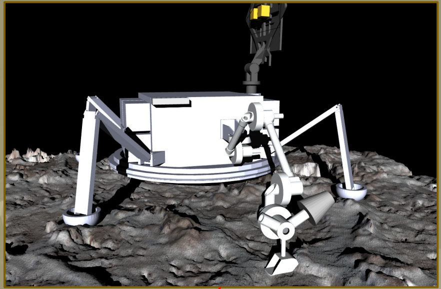

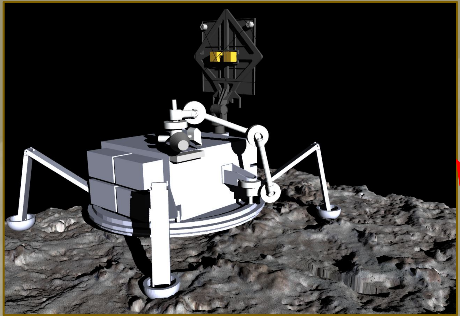

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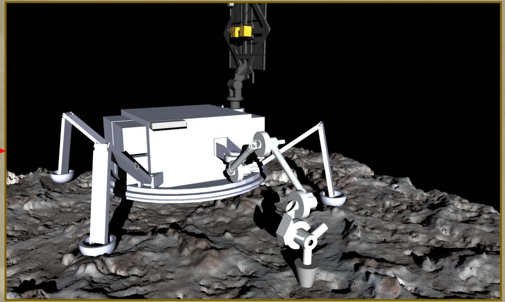
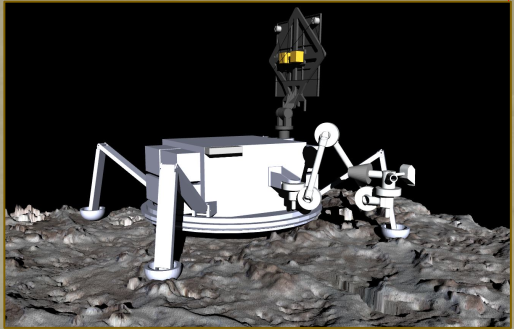
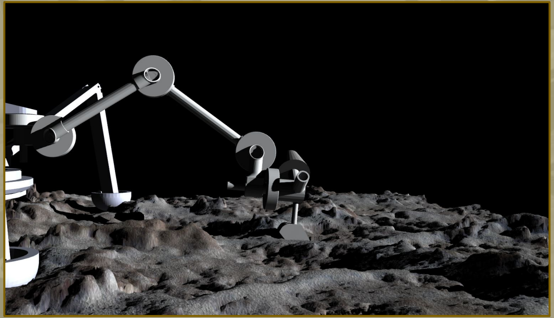
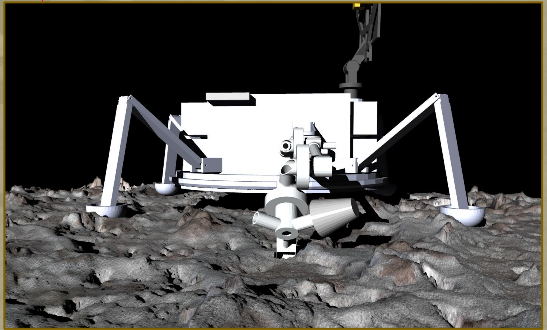


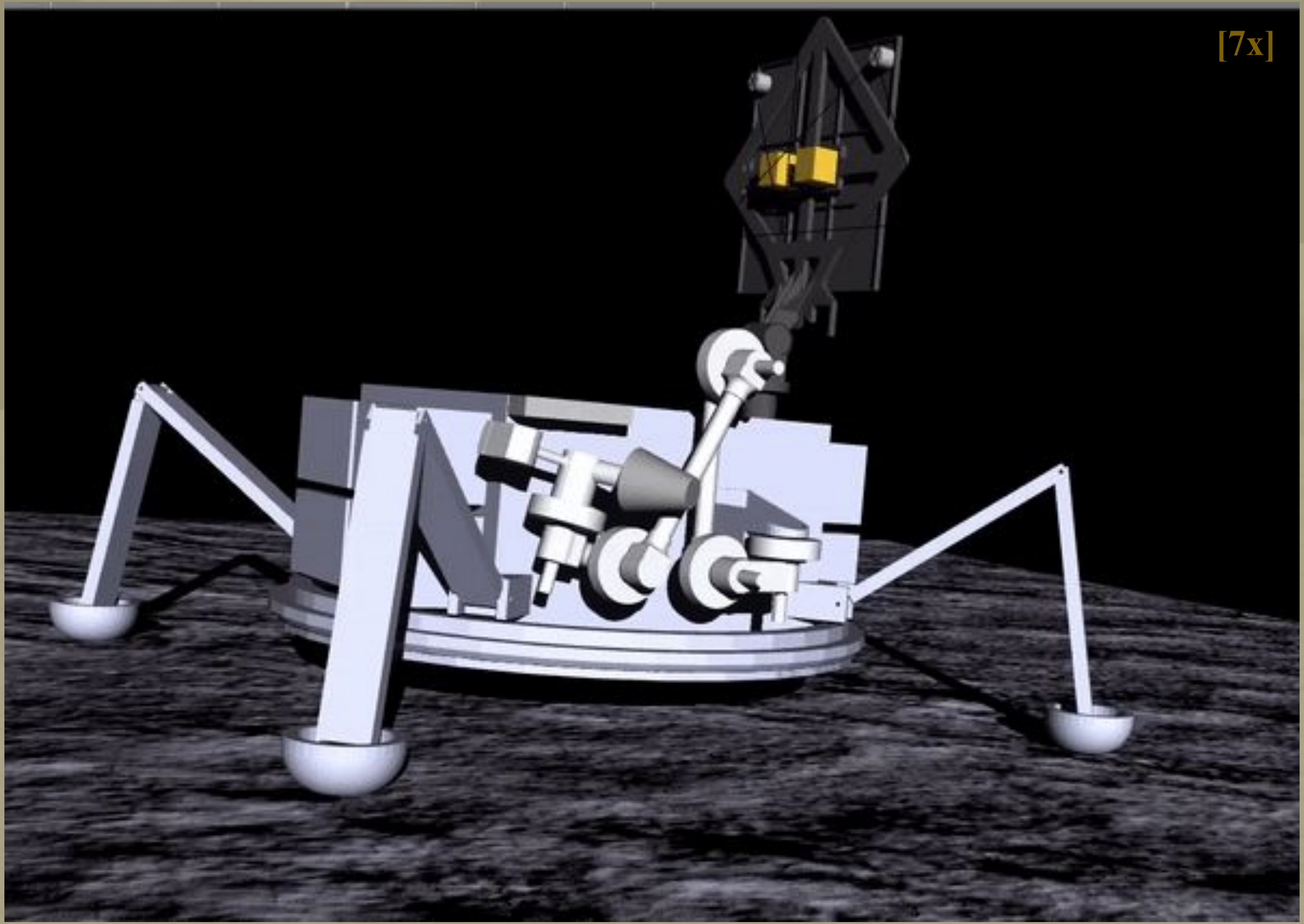






OceanWATERS Lander Robotic Arm Operation

REFERENCE MISSION 1



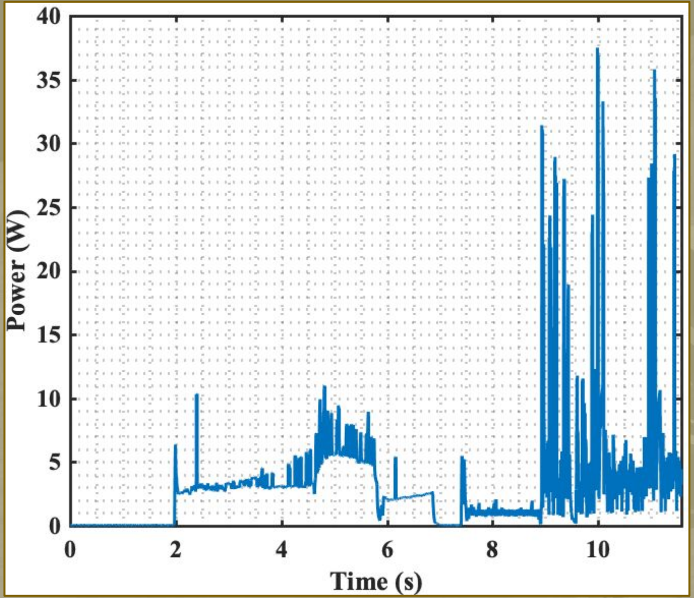
OceanWATERS Lander Robotic Arm Operation

POWER CONSUMPTION

Energy consumption estimation for each operation mode needed for:

- Design: evaluate overall power requirements
- Operation: decision making based on remaining battery level

Power required for guarded_move:



Estimate power for each joint from instantaneous torque and angular speed:

$$P(k)_i = \tau_i(k)\dot{\theta}_i(k)$$

Calculate total consumed power, sum $P(k)_i$

Estimate energy for a maneuver (t_f-t_0) long

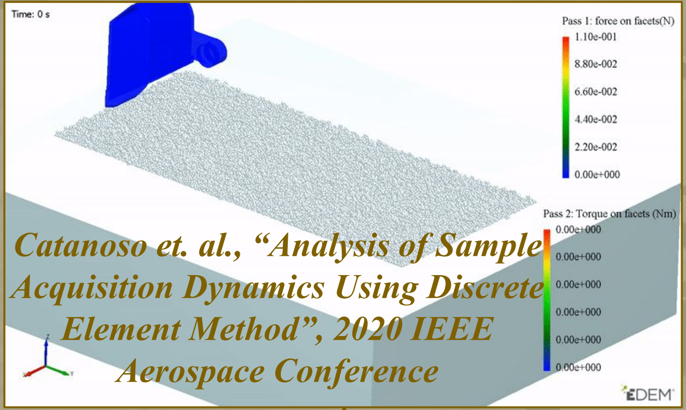
$$E = \sum_{t_0}^{t_f} P(k)dt_k$$

ARM-TERRAIN INTERACTION

Run simulations in EDEM [19] commercial software, varying set of parameters

Embed data in lookup table

- **Terrain types: ice, snow, sand**
- **Sample collection:**
  - Circular-linear-circular
  - Multiple passes
  - Increasing depth between passes



Catanoso et. al., "Analysis of Sample Acquisition Dynamics Using Discrete Element Method", 2020 IEEE Aerospace Conference

Include it in Gazebo through dedicated plugin

Include in OceanWATERS open source DEM solution

User runs customized simulations on demand

Embed data in lookup table

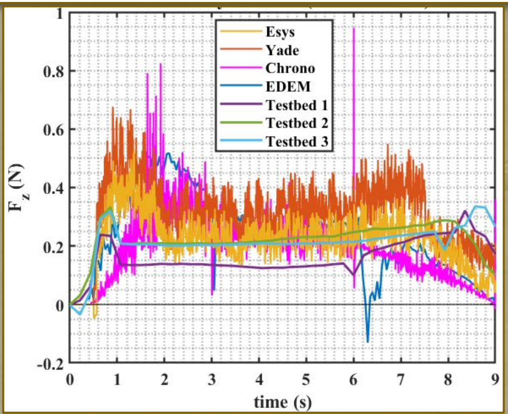
Parallel DEM-Gazebo simulation

Analysis of Sample Acquisition Dynamics Using Discrete Element Method

ARM TERRAIN INTERACTION

Open source DEM software candidates:

- ESyS-Particle [17]
- PROJECT CHRONO [18]
- Yade [16]



Parameters, weights and total score for comparison, evaluation and selection of most suitable open source DEM software for integration in OceanWATERS:

Parameter name	EDEM	YADE	ESyS-Particle	Chrono	Weight
Scripting wrappers	1	1	1	0	0.65
C++ API	0	1	1	1	0
Limit in number of particles	0	0	0	0	0
Particle bonding	1	1	1	0	1
Polyhedral particle shape	0	1	0	1	0.5
Multi-sphere particle	1	1	1	0	0.8
Parallel computations	1	1	1	1	0
Super-computer suitable	0	0	1	1	0.4
Clear documentation	1	1	0.5	1	0.6
Active community	1	0.8	0.6	0.7	0.75
GPU capable	1	1	0	0.5	0.5
Fx normalized Score Compared to EDEM	1	0	1	0.56	0.9
Fy normalized Score Compared to EDEM	1	0.36	0	1	0.2
Fz normalized Score Compared to EDEM	1	0	0.68	1	0.7
Fx normalized Score Compared to Testbed	0.68	1	0	0.23	0.45
Fy normalized Score Compared to Testbed	1	0	0.25	0.92	0.05
Fz normalized Score Compared to Testbed	0	0.42	1	0.77	0.15
Total	0.84	0.68	0.67	052	N/A

Highest score: Yade

CONCLUSION

- OceanWATERS: a ocean worlds simulation testbed to test performance of autonomy algorithms under injected faults for surface exploration missions, based on Robot Operating System, open source on GitHub
- Europa Lander chosen as reference mission. Simplified lander model has: body, antenna, landing stabilizers, stereo camera, 6-DOF robotic arm with two end effectors: scoop, grinder
- Arm motion is planned and executed using ROS Services and the MoveIt planner
- Modes of operation are: unstow, guarded move, grind, dig circular, dig linear, deliver/discard sample, stow
- Power consumed by joints motors during operation is estimated
- Yade has been selected as open source DEM to determine dynamic feedback from terrain to scoop

FUTURE WORK

- Transition from a single-joint position controller to a collective trajectory (position+velocity) controller in OceanWATERS' Release 7
- Development of fault injection/system state interrogation facility
- Implementation of Yade-Gazebo co-simulation plugin

REFERENCES

[1] "Oceanwaters on github," last accessed 15 January 2021. [Online]. Available: https://github.com/nasa/ow_simulator/

[2] L. Fluckiger and C. Neukom, "A new simulation framework for autonomy in robotic missions," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3. IEEE, 2002, pp. 3030–3035.

[3] L. Edwards, M. Sims, C. Kunz, D. Lees, and J. Bowman, "Photo-realistic terrain modeling and visualization for mars exploration rover science operations," in *2005 IEEE International Conference on Systems, Man and Cybernetics*, vol. 2. IEEE, 2005, pp. 1389–1395.

[4] M. Ai-Chang, J. Bresina, L. Charest, A. Chase, J.-J. Hsu, A. Jonsson, B. Kanefsky, P. Morris, K. Rajan, J. Yglesias *et al.*, "Mapgen: mixed-initiative planning and scheduling for the mars exploration rover mission," *IEEE Intelligent Systems*, vol. 19, no. 1, pp. 8–12, 2004.

[5] M. Allan, U. Wong, P. M. Furlong, A. Rogg, S. McMichael, T. Welsh, I. Chen, S. Peters, B. Gerkey, M. Quigley *et al.*, "Planetary rover simulation for lunar exploration missions," in *2019 IEEE Aerospace Conference*. IEEE, 2019, pp. 1–19.

[6] D. R. Andrews, A. Colaprete, J. Quinn, D. Chavers, and M. Picard, "Introducing the resource prospector (rp) mission," in *AIAA SPACE 2014 Conference and Exposition*, 2014, p. 4378.

[7] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: an open-source robot operating system," in *ICRA workshop on open source software*, vol. 3, no. 3.2. Kobe, Japan, 2009, p. 5.

[8] K. Hand, A. Murray, J. Garvin, W. Brinckerhoff, B. Christner, K. Edgett, B. Ehlmann, C. German, A. Hayes, T. Hoehler *et al.*, "Europa lander study 2016 report: Europa lander mission," *NASA Jet Propuls. Lab., La Cañada Flintridge, CA, USA, Tech. Rep. JPL D-97667*, 2017.

[9] O. M. Umurhan, M. B. Allan, L. J. Edwards, A. Tardy, T. M. Welsh, and U. Wong, "High resolution digital elevation models of the devil's golf course: a possible terrestrial analog of europa's surface," *AGUFM*, vol. 2019, pp. P53C–3468, 2019.

[10] C. Acton, N. Bachman, B. Semenov, and E. Wright, "Spice tools supporting planetary remote sensing," 2016.

[11] D. Catanoso, T. Stucky, J. Case, and A. Rogg, "Analysis of sample acquisition dynamics using discrete element method," in *2020 IEEE Aerospace Conference*. IEEE, 2020, pp. 1–11.

[12] R. Arvidson, R. Bonitz, M. Robinson, J. Carsten, R. Volpe, A. Trebi-Ollennu, M. Mellon, P. Chu, K. Davis, J. Wilson *et al.*, "Results from the mars phoenix lander robotic arm experiment," *Journal of Geophysical Research: Planets*, vol. 114, no. E1, 2009.

[13] S. Chitta, I. Sucan, and S. Cousins, "Moveit![ros topics]," *IEEE Robotics & Automation Magazine*, vol. 19, no. 1, pp. 18–19, 2012.

[14] S. M. LaValle, *Planning algorithms*. Cambridge university press, 2006.

[15] T. Foote, "tf: The transform library," in *Technologies for Practical Robot Applications (TePRA), 2013 IEEE International Conference on*, ser. Open-Source Software workshop, April 2013, pp. 1–6.

[16] J. Kozicki and F. V. Donze, "Yade-open dem: An open-source software using a discrete element method to simulate granular material," *Engineering Computations*, 2009.

[17] D. Weatherley, "Esys-particle v2. 0 user's guide," 2009.

[18] A. Tasora, R. Serban, H. Mazhar, A. Pazouki, D. Melanz, J. Fleischmann, M. Taylor, H. Sugiyama, and D. Negrut, "Chrono: An open source multi-physics dynamics engine," in *International Conference on High Performance Computing in Science and Engineering*. Springer, 2015, pp. 19–49.

[19] "Edem simulation," last accessed 16 October 2020. [Online]. Available: https://www.edemsimulation.com/

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Universities Space Research Association

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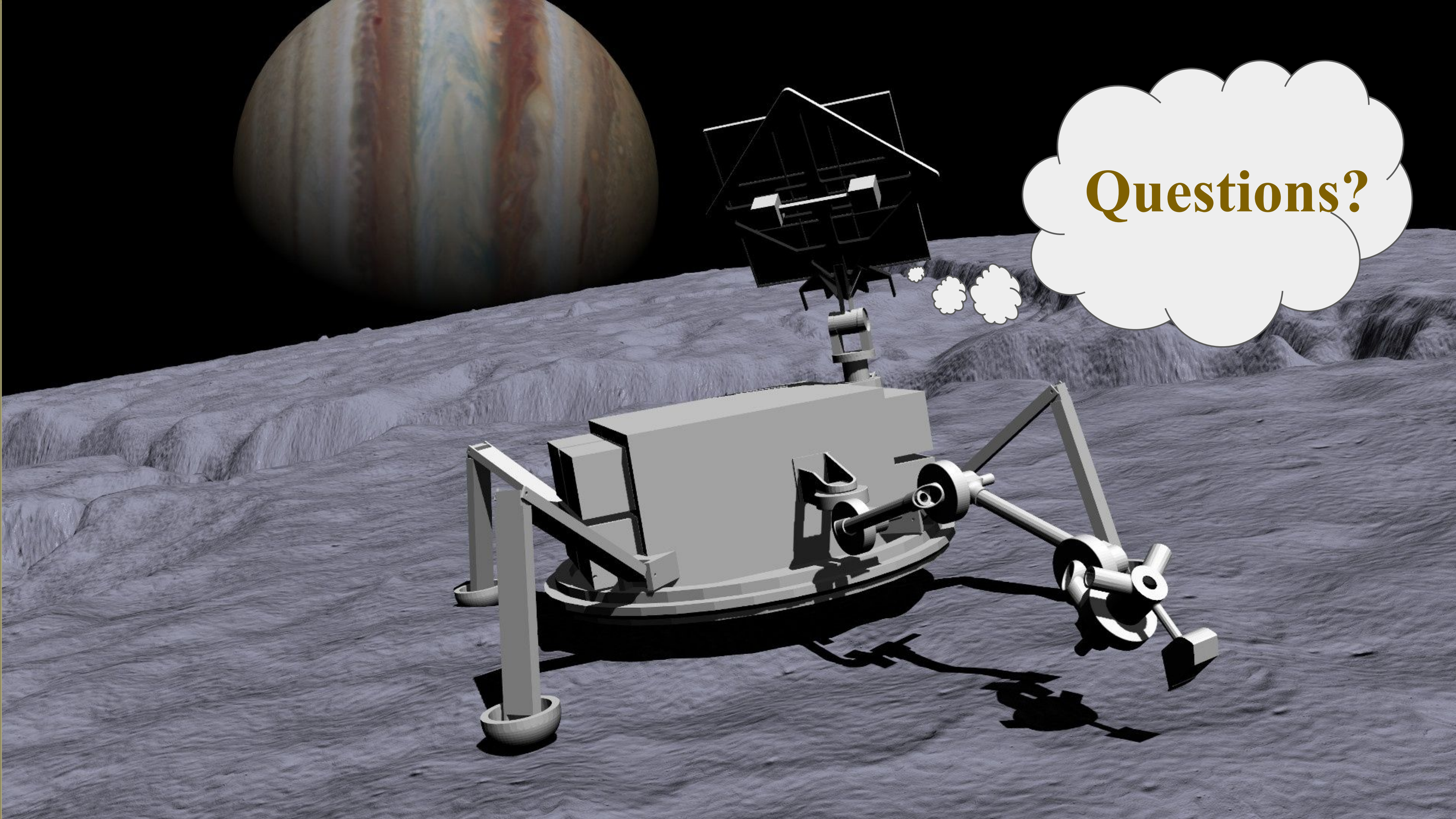
Ames Research Center

The OceanWATERS Team

present and past members


Questions?

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