The Robert M. Buchan Department of Mining

Queen's University

Autonomous Digging

Reducing the impact of communications delay for planetary mining

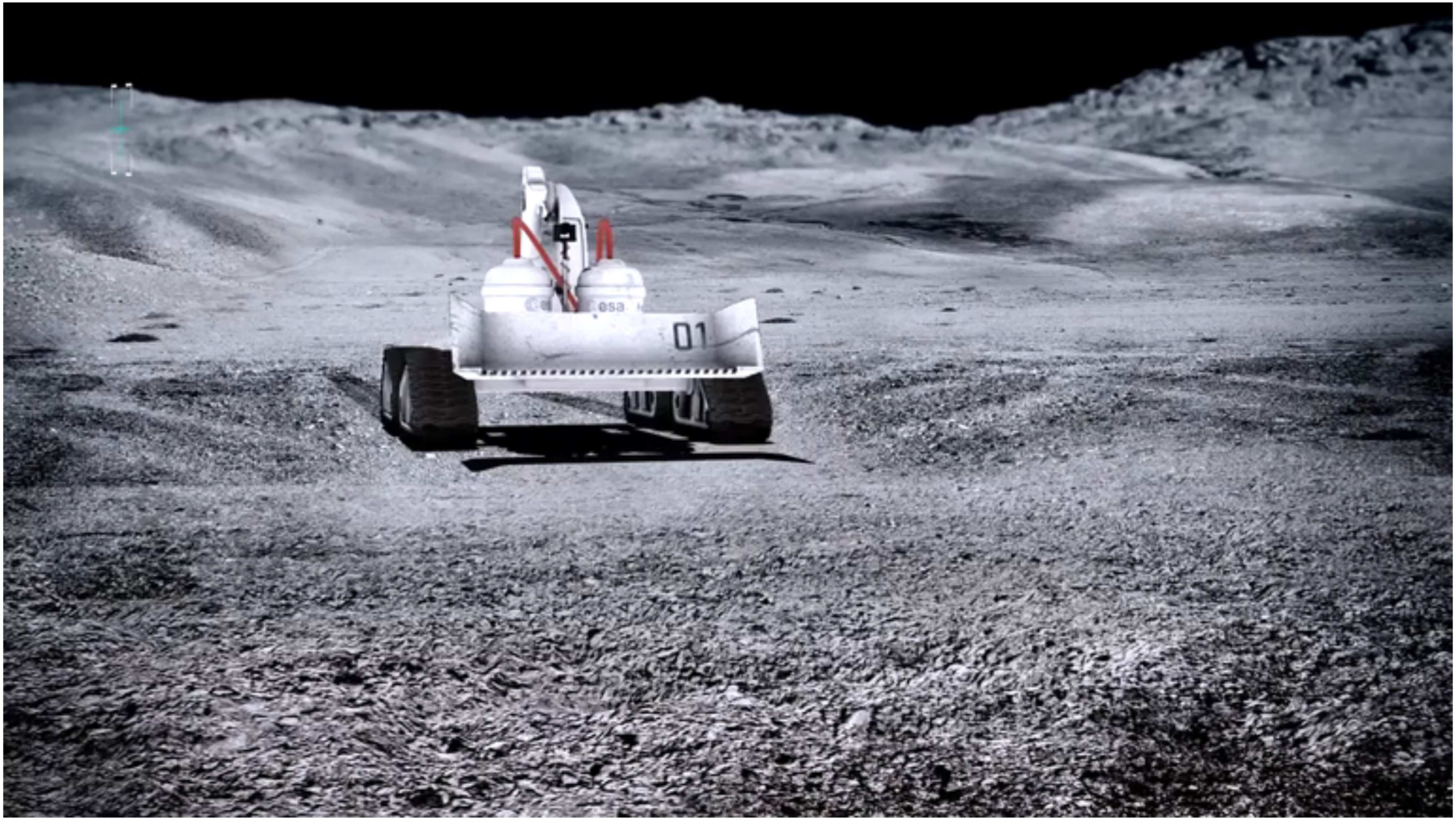
8/19/15

Andrew Dobson
Clearpath Robotics, Kitchener

Dr. Joshua Marshall
Queen's University Mining Systems Lab

CIM PTMSS 2015 Montreal, Abstract 763

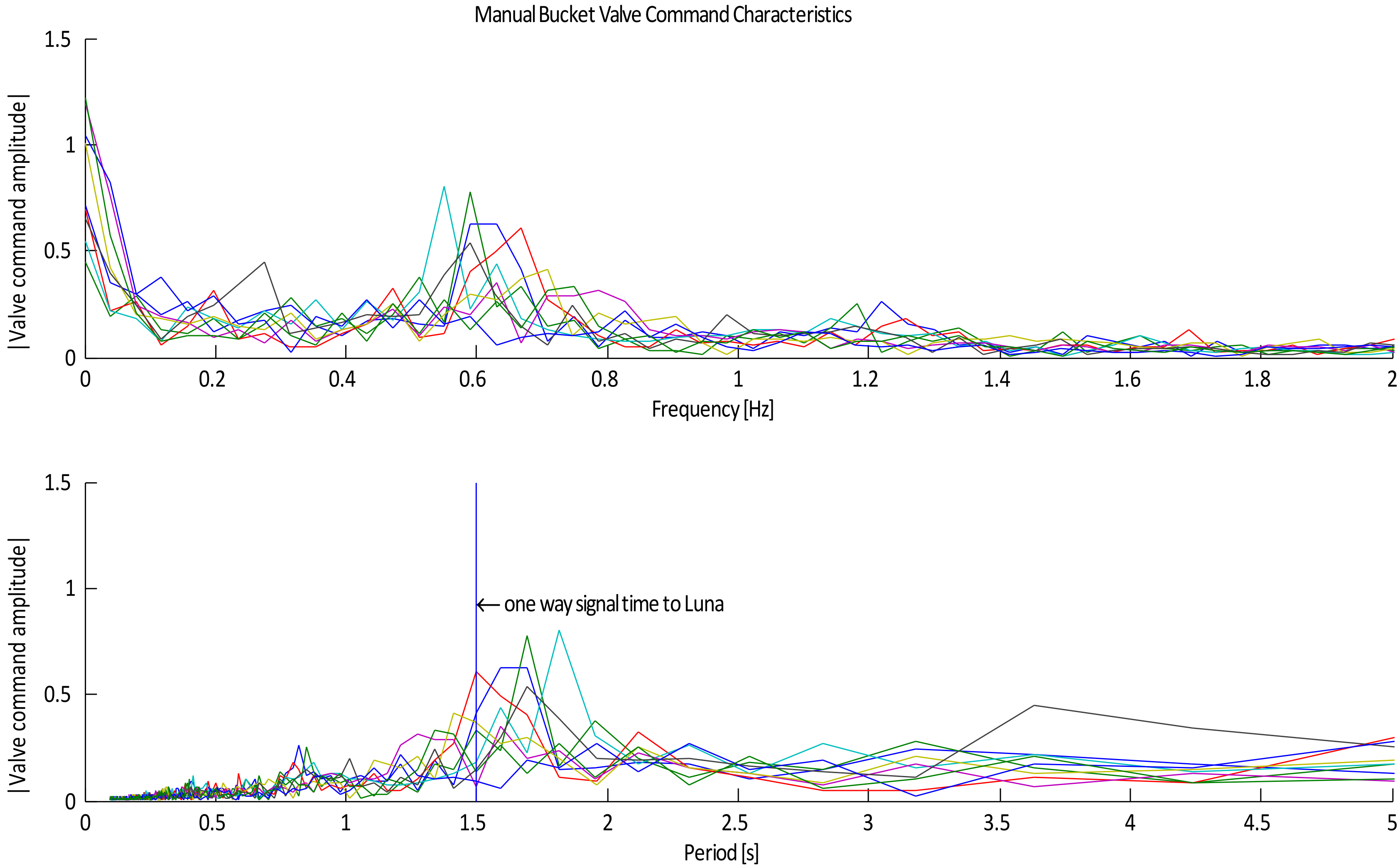
Remote Loading



ESA 2014 [1]

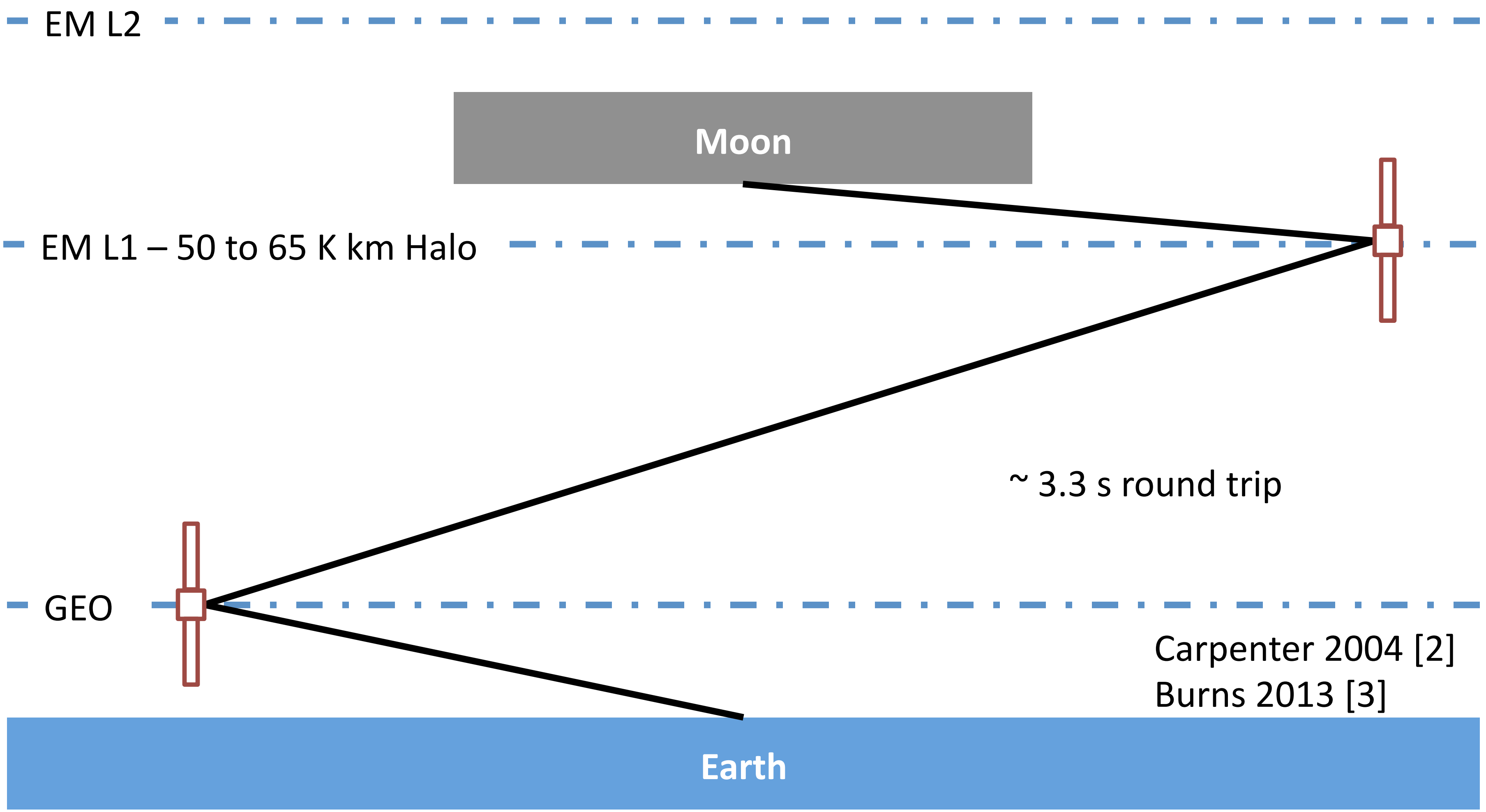
Robotic Loading

Key Results

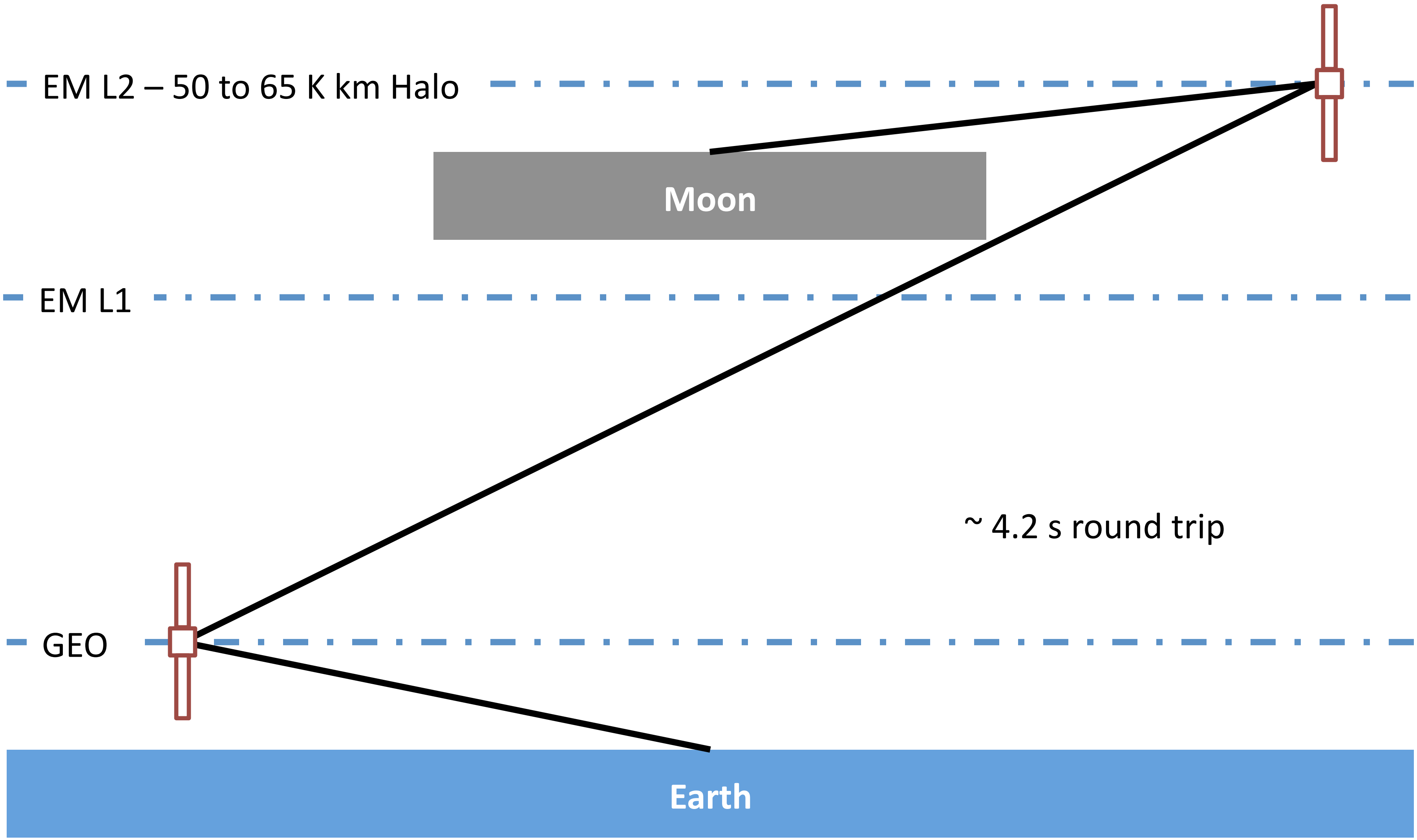


Manual Bucket Valve Command Characteristics
|Valve command amplitude|
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Frequency [Hz]
|Valve command amplitude|
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Period [s]
one way signal time to Luna

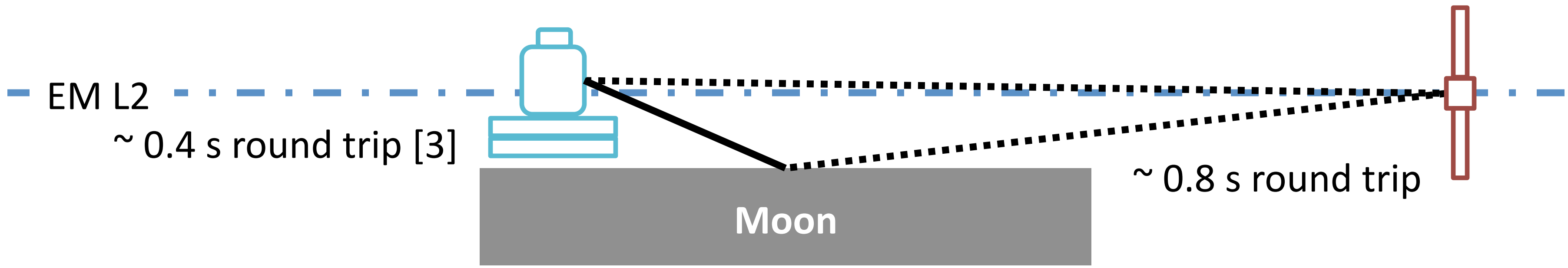
Communication Delay



Communication Delay



Communication Delay



EM L1

- 150 m/s per year delta-v [4]
- Real time telepresence limit ~ 0.3 to 0.5 s [5, 4]
- Expensive humans
- Squishy humans
  - Limited endurance
  - Beyond Earths magnetic field
  - Galactic cosmic ray exposure risk [3]

GEO

Earth

Overcoming Delay

- Prediction
  - Displays [5, 6, 7]
  - Virtual environment(s) [8, 9]
  - Force feedback and bilateral control [10, 11]
- Compliance control
  - Contact force controlled locally increasing delay error tolerance [5, 6]

< 2 s [7]

- Move and wait [5, 7, 12]
- Automation and supervisory control [7, 12]

> 10 s [7]

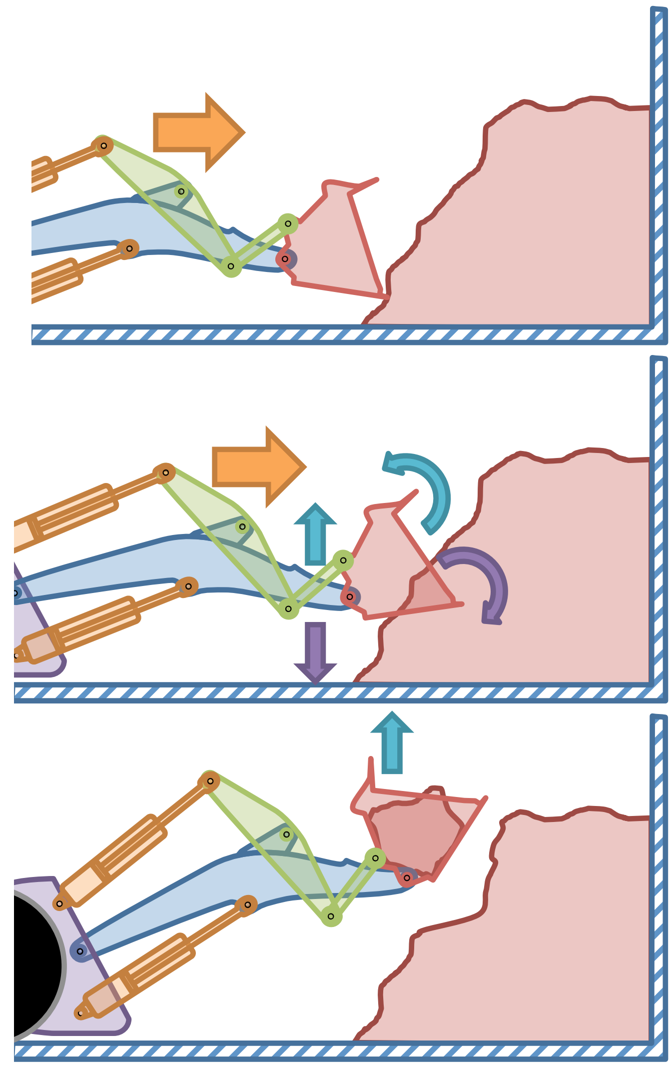
Test Platforms

Algorithm

1. Go to entry pose
2. Detect entry
3. Activate admittance controller
   - Control admittance between bucket and pile
   - Automatically avoid force concentrations

$$v = k \cdot (f_T - f_S)$$

4. Detect maximum bucket curl
5. Go to weighing pose



Why Auto Load on Earth?

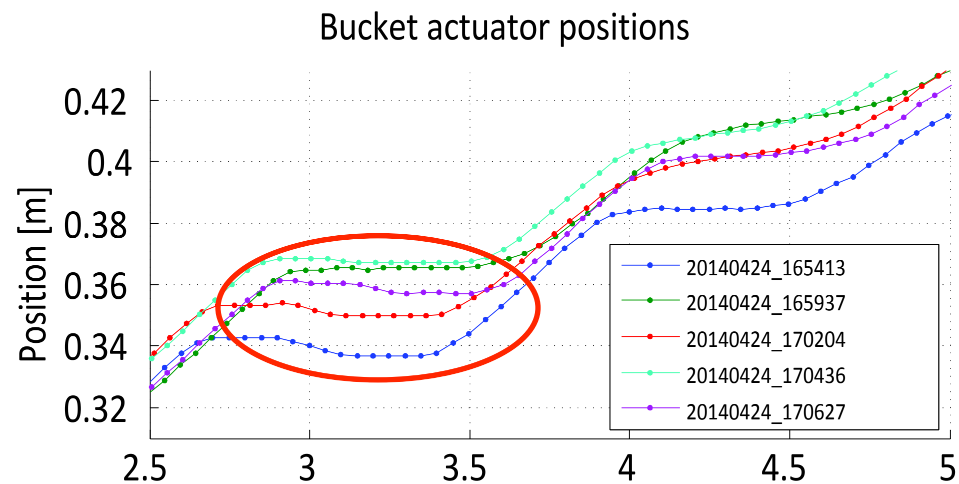
- Productivity
  - Automate the entire LHD cycle
  - ↑ productivity [14]
  - ↑ consistency [15]
  - Turn all operators into expert operators [15]
- Reduce safety costs
  - Distance operators from worksite [16]
  - Work more hazardous stopes [17]
  - Increased sensing [18]
- Reduce operating costs
  - Tune loading to match hauling equipment [19]
  - More predictable consumable consumption [17, 19]

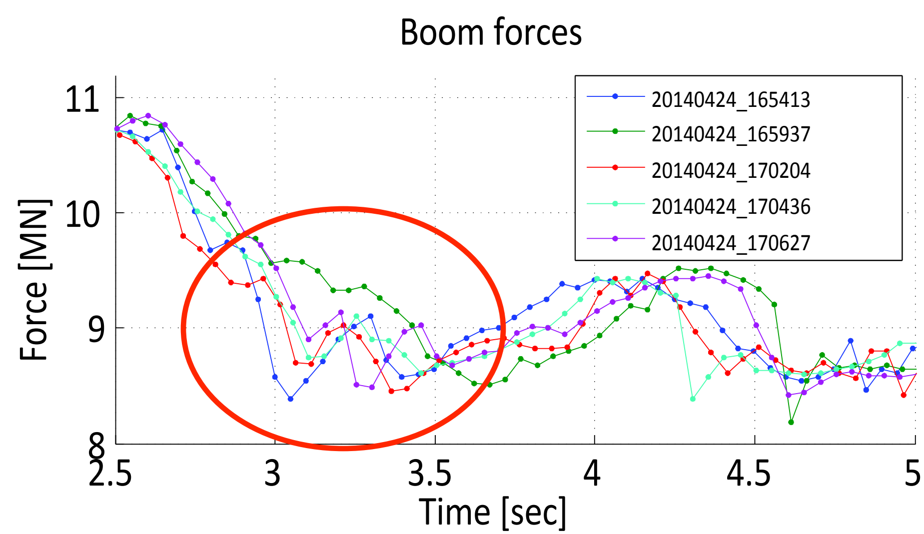
Previous Attempts

- Scripted controllers
  - Several patents
  - Only works in homogeneous targets
  - Most notable: Caterpillars AutoDig system [20]
- Behaviour and fuzzy logic
  - Based on experimentally derived heuristics
  - Unpredictable results when conditions change
  - Most notable: Lever and Shi's CAT 980G work [21]
- Force feedback controllers
  - Impedance ← better for target shaping
  - Admittance ← better for bucket filling

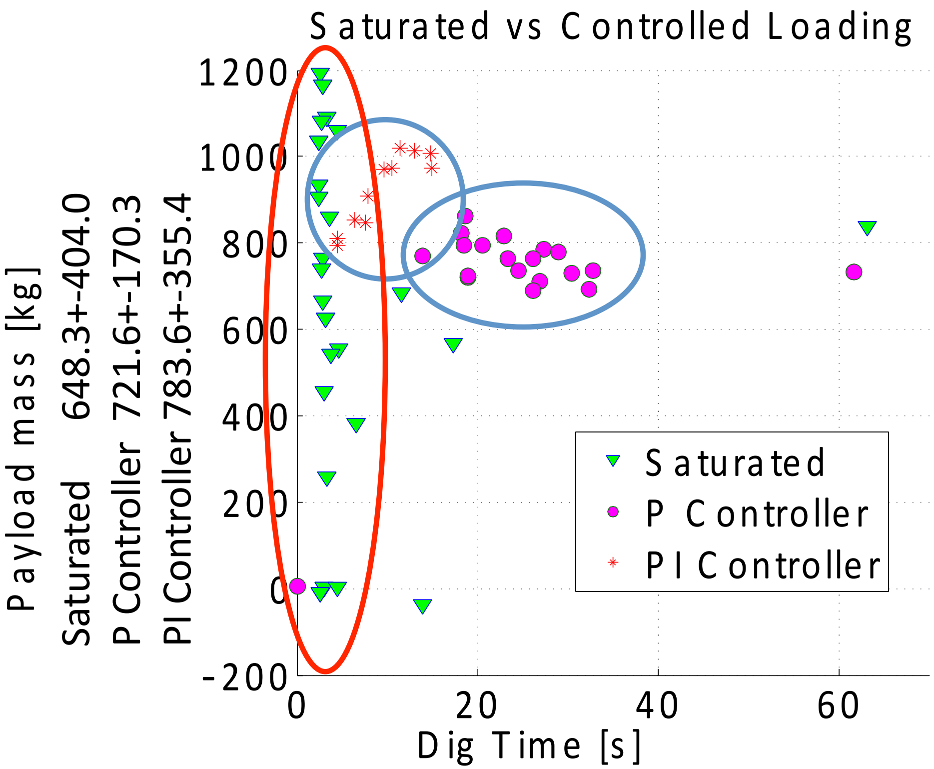
Force Control

- Impedance (Z)
  - $f=Z\cdot(v-v_t)$
  - Requires a target **velocity or path**
  - Most notable: Maeda et al. [22]
- Admittance (Y)
  - $v=Y\cdot(f-f_t)$
  - Requires a target **force**
  - Most notable: Marshall et al. [23] Seraji [24]

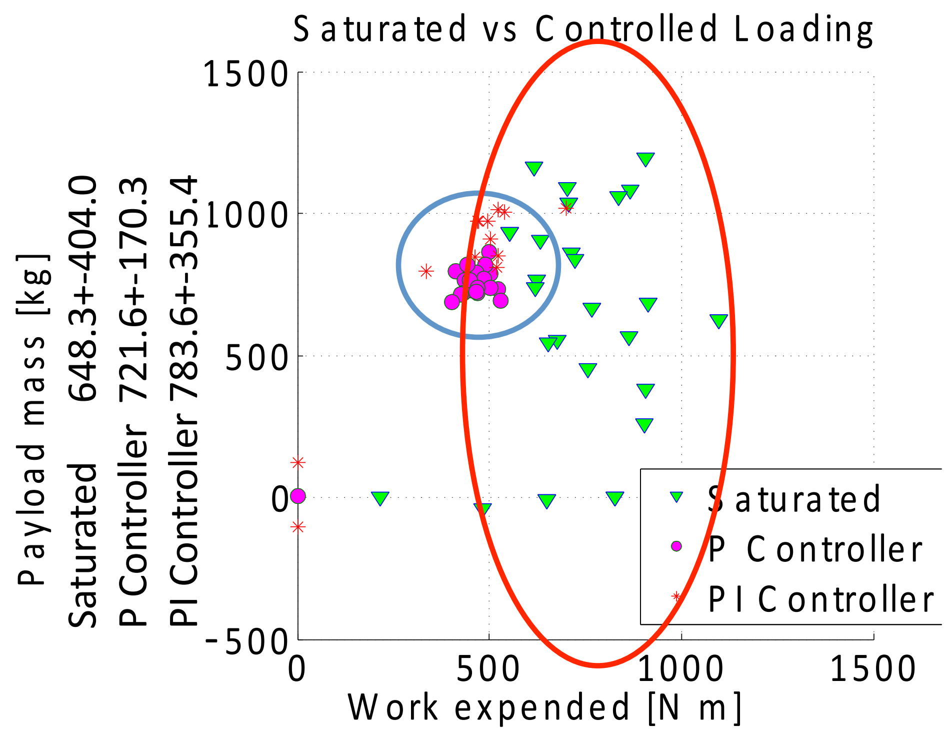




MSL Results



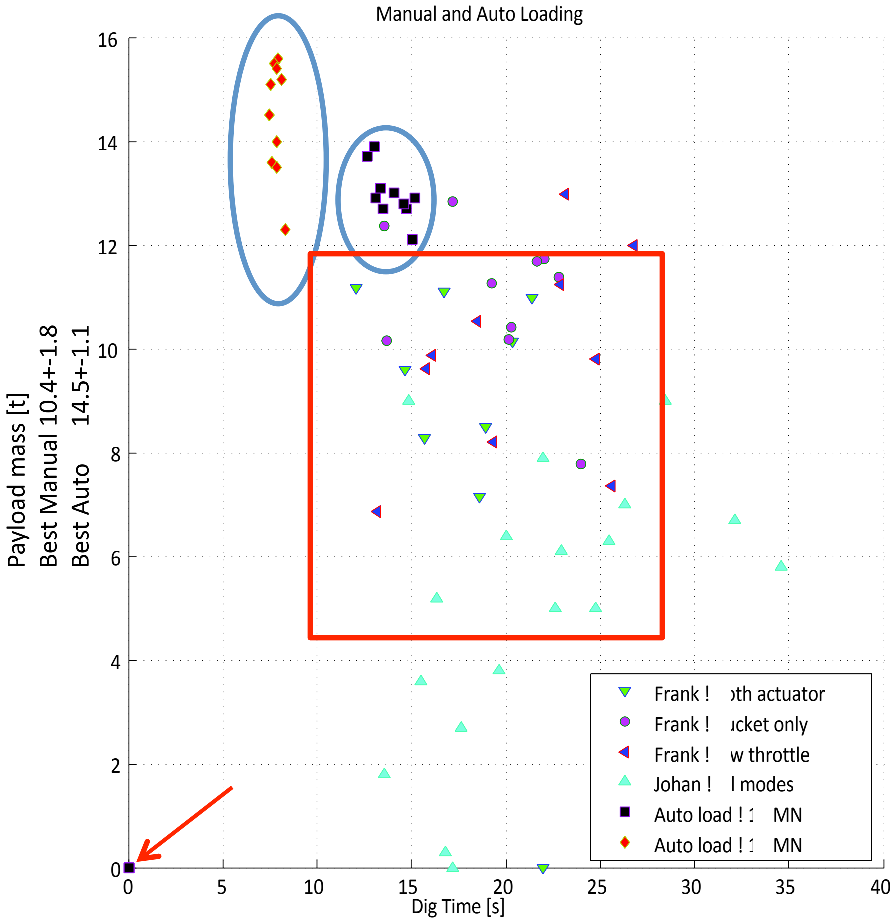
Saturated 6.2+-11.1
P Controller 24.3+-11.2
PI Controller 8.1+-5.0



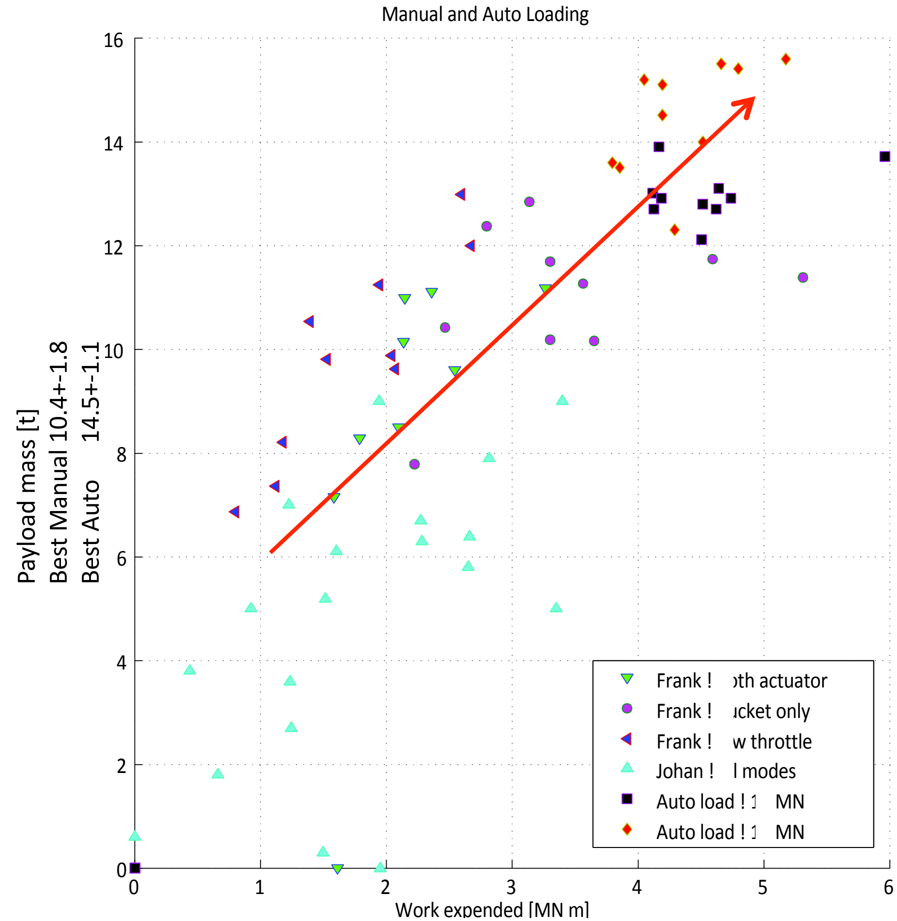
Saturated 731.4+-176.7
P Controller 443.6+-106.8
PI Controller 426.2+-204.5

S vs PI → $t\downarrow d$ ↑ 55%, $M\downarrow d$ ↑ 18%, $W\downarrow d$ ↑ 26%

ST14 Results



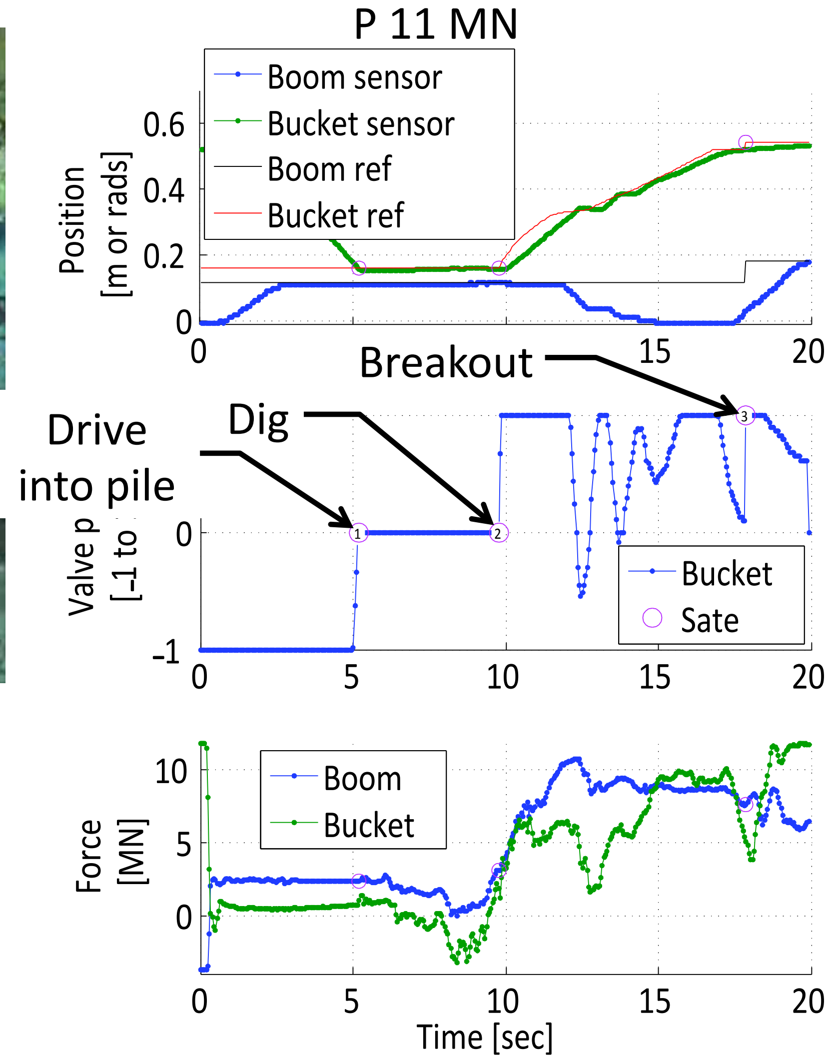
Best Manual 20.0+-4.1
Best Auto 7.8+-0.3



Best Manual 2.59+-1.17
Best Auto 4.36+-0.43

Man vs Auto → $t{\downarrow}d \downarrow 39\%$, $M{\downarrow}d \uparrow 39\%$, $W{\downarrow}d \uparrow 68\%$

ST14 Typical

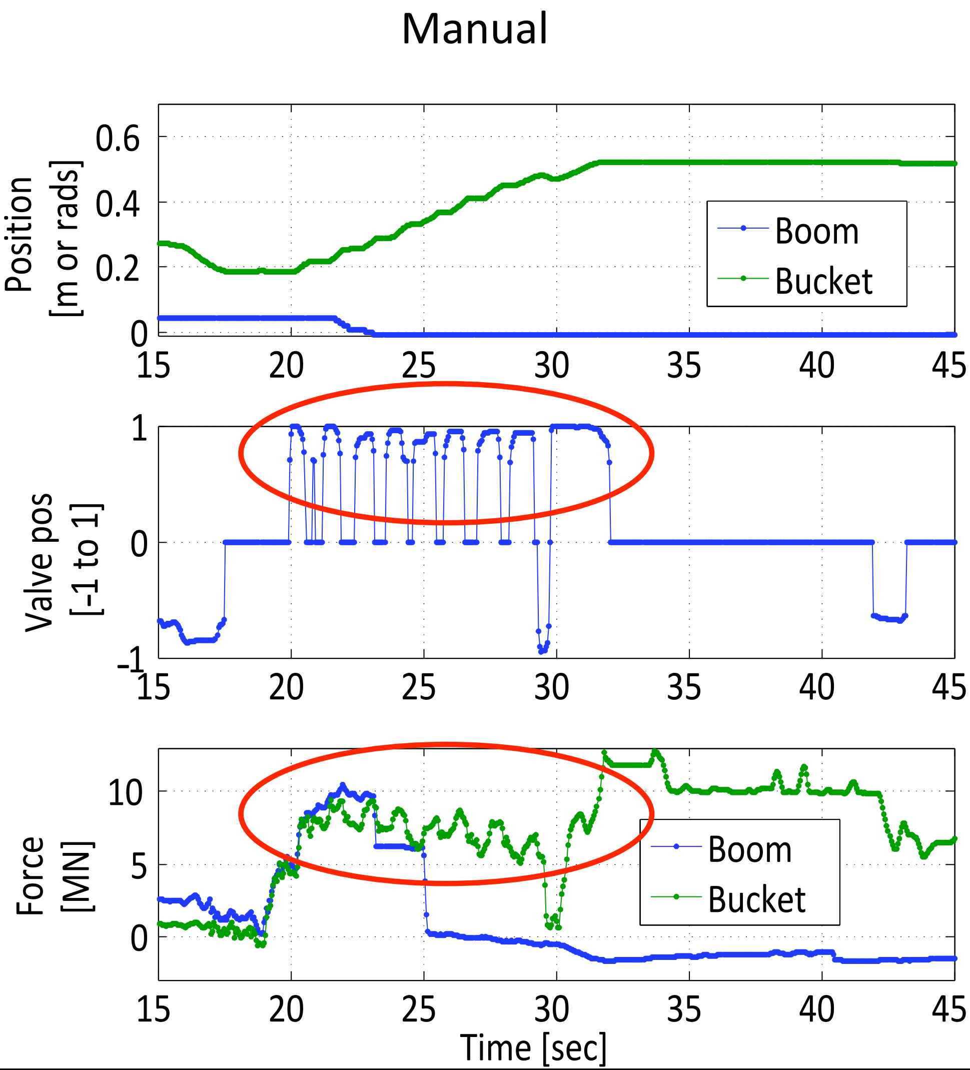


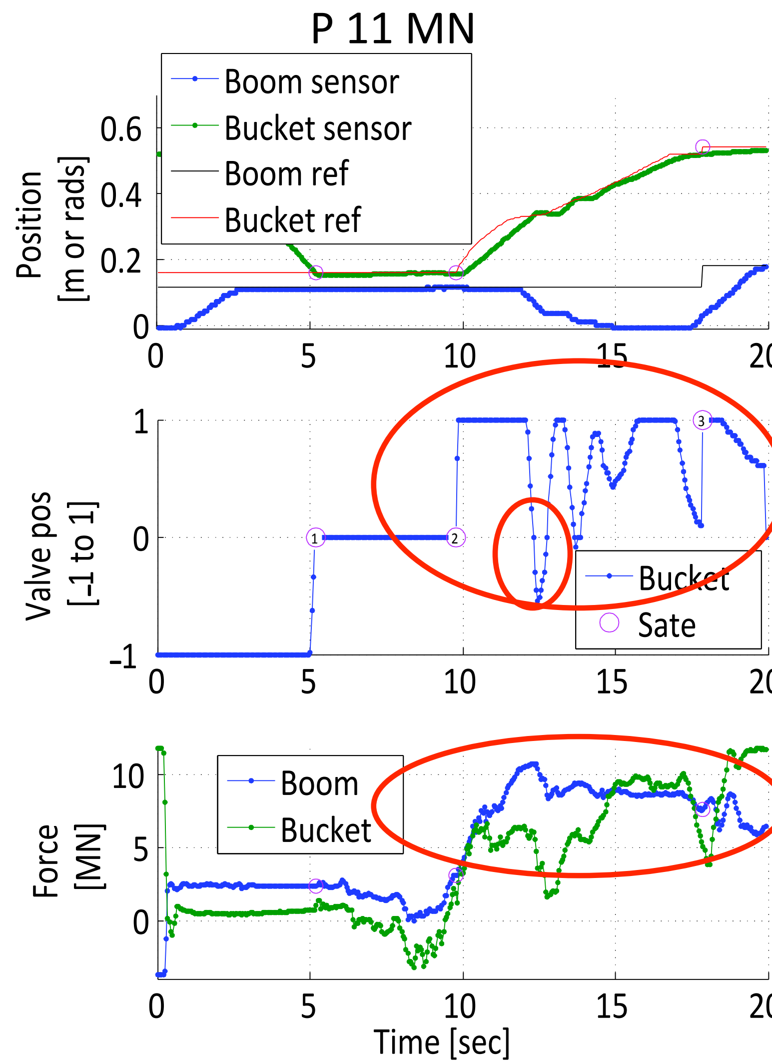
Controller:

$$v_A = k_A \cdot e_f$$

$$v_A = k_A \cdot (f_T - f_S)$$

Manual vs Admittance





Results and Contributions

- Why automate
  - Cost
  - Communications delay increases task time
  - Minimum delay 0.4 s
  - Mean manual digging command period ~1.6 s
- Productive and consistent loading algorithm
  - Dig time (t_d) ↓ 39%
  - Payload (M_d) ↑ 39%
  - Work (W_d) ↑ 68%
- Applicable to multiple vehicles and environments
- ST14 FSR2015 Paper: [24]

Thank You

msl.engineering.queensu.ca

Atlas Copco

NCFRN
NSERC Canadian
Field Robotics Network

RCCRT
Réseau canadien CRSNG
pour la robotique de terrain

This research was also supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) under grant 371452-2009.

References

[1] ESA Foster+Partners, November 2014, [Online]. Available: http://www.esa.int/spaceinvideos/Videos/2014/11/3D-printing_a_lunar_base

[2] J. R. Carpenter, D. Folta, M. Moreau, and D. Quinn, "Libration Point Navigation Concepts Supporting the Vision for Space Exploration," AIAA, 16-19, 2004.

[3] J. Burns et al., "A lunar L2-Farside exploration and science mission concept with the Orion Multi-Purpose Crew Vehicle and a teleoperated lander/rover," in Advances in Space Research, Vol. 52, 2013, pp. 306-320.

[4] D. F. Lester, H. A. Thronson, "Human space exploration and human spaceflight: Latency and the cognitive scale of the universe." Space Policy 27, 2011 89–93.

[5] T. Sheridan, "Space teleoperation through time delay: review and prognosis." Robotics and Automation, IEEE Transactions on 9, no. 5, 1993, pp. 592-606.

[6] A. Bejczy, W. Kim, "Predictive Displays and Shared Compliance Control for Time- Delayed Telemanipulation," in IROS, 1990. Proceedings, IEEE International Workshop on Intelligent Robots and Systems, 1990, pp. 407-412.

[7] K. Hambuchen, R. Burridge, and W. Bluthmann, "Forming human-robot teams across time and space," GLEX, 2012.

[8] L. Huijun, and A. Song, "Virtual-environment modeling and correction for force-reflecting teleoperation with time delay," Industrial Electronics, IEEE Transactions on 54.2 2007, pp. 1227-1233.

[9] R. Winck, S. Sketch, E. Hawkes, D. Christensen, H. Jiang, M. Cutkosky, and A. Okamura, "Time-delayed teleoperation for interaction with moving objects in space." In Robotics and Automation (ICRA), IEEE International Conference on, 2014, pp. 5952-5958.

[10] T. Kotoku, "A predictive display with force feedback and its application to remote manipulation system with transmission time delay." Intelligent Robots and Systems, Proceedings of the 1992 IEEE/RSJ International Conference on. Vol. 1. IEEE, 1992.

[11] C. Preusche, D. Reintsema, and G. Hirzinger, "Robotics component verification on iss rokviss-preliminary results for telepresence." Intelligent Robots and Systems, IEEE/RSJ International Conference on. IEEE, 2006.

[12] T. Fong, M. Diftler, and D. Mittman, "The Human Exploration Telerobotics Project: Objectives, Approach, and Testing," In Aerospace Conference, IEEE, 2012 pp. 1-9.

References (cnt)

[13] J. Donovan, “Underground automation: Key learnings review," Barrick, Toronto ON., Report, March 2008.

[14] P. Lever, R. Pakalnis, P. Hughes, R. Pakalnis, P. Hughes, C. Brannon, G. Carlson, and T. Casten, SME Mining Engineering Handbook, 3rd ed., P. Darling, Ed. Society for Mining, Metallurgy, and Exploration Inc. (SME), 2011.

[15] D. R. Wilburn, R. L. Vasil, and A. Nolting, \Exploration review," Mining Engineering, vol. 63, no. 5, 2011.

[16] A. Gustafson, H. Schunnesson, D. Galar, and U. Kumar, “Production and maintenance performance analysis: manual versus semi-automatic lhds," Journal of Quality in Maintenance Engineering, vol. 1, no. 19, pp. 74 { 88, January 2013.

[17] J. Larsson, “Unmanned operation of Load-Haul-Dump vehicles in mining environments,“ Masters, Orebro University, Orebro Sweden, November 2011.

[18] A. Uzbekova, A. Clement, E. Mort, G. Smith, and R. Butcher, “Kanowna belle minegem trial report," Barrick Gold of Australia, Caterpillar and WesTrac, Level 10, 2 Mill St. Perth WA 6005, Report, November 2010.

[19] Caterpillar, “Wheel loaders: Aggregate autodig operator tips: video," Caterpillar Safety Services, Accessed October 2014 2002, [Online]. Available: https://safety.cat.com/cda/layout?m=129939&x=7&id=496053

[20] X. Shi, P. Lever, and F. Wang, Autonomous Rock Excavation: Intelligent Control Techniques and Experimentation, ser. Series in intelligent control and intelligent automation. World Scientific, 1998.

[21] G. J. Maeda, D. C. Rye, and S. P. N. Singh, "Iterative autonomous excavation," in Field and Service Robotics, ser. Springer Tracts in Advanced Robotics, K. Yoshida and S. Tadokoro, Eds. Berlin Heidelberg Germany: Springer Berlin Heidelberg, 2013, vol. 92, pp. 369-382.

[22] J. Marshall, “Towards autonomous excavation of fragmented rock: Experiments, modelling, identification and control”, Master of Science: Engineering, Queen's University, Kingston, On. Canada, August 2001.

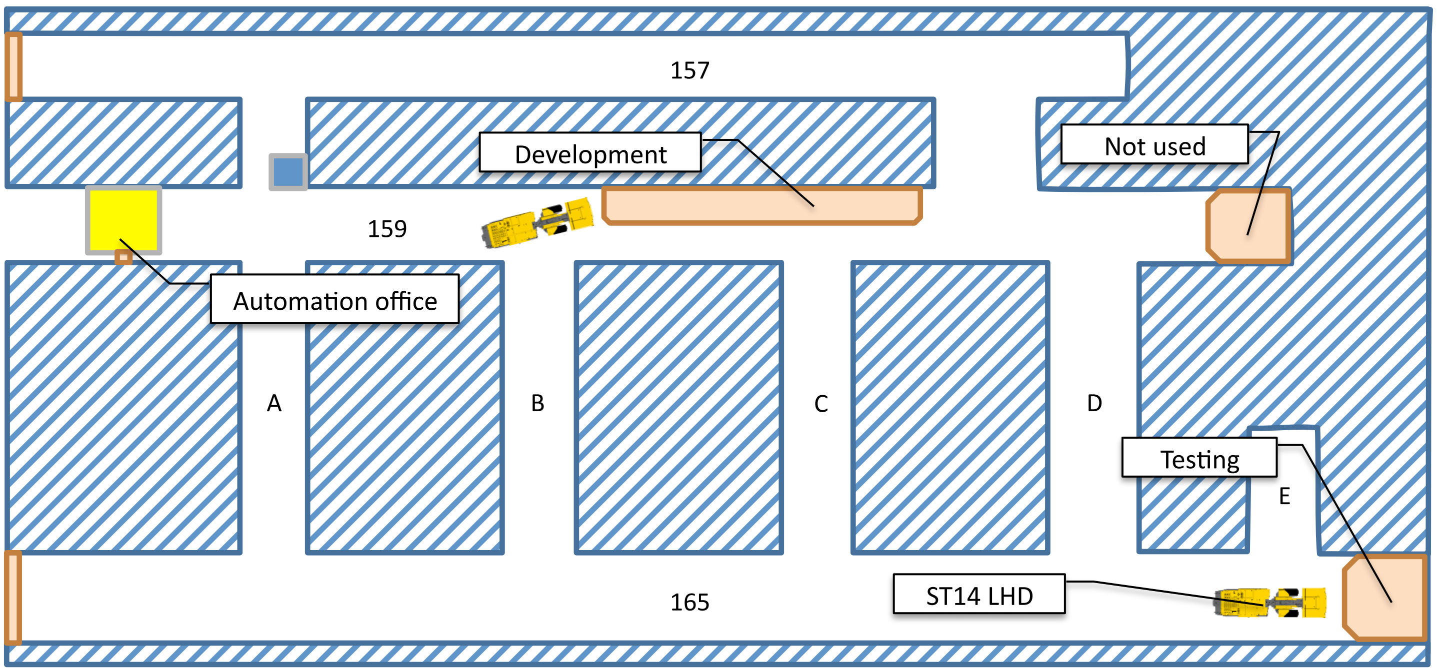
[23] H. Seraji, “Adaptive admittance control: an approach to explicit force control in compliant motion,” in Robotics and Automation, 1994. Proceedings., 1994 IEEE International Conference on, vol.4, 1994, pp. 2705–2712.

[24] A. Dobson, J. Marshall, J. Larsson, “Admittance Control for Robotic Loading: Underground Field Trials with an LHD” in Field and Service Robotics 2015, Toronto ON., no 7, June 2015.

Next?

Future work

- Working mine → Production data set
- Digging model → offline tuning
- Auto dig study → dig planner design



Experimental Method

- Goal was always dig efficiency not controller stability
- Access to real hardware (reduced need for modelling)
- Typical field research issues
  - Sourcing
  - Qualification
  - Calibration
  - Breakdowns
  - Weather
  - Comms

Muck Piles

ST14 Consistency