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HERCULES: ANALOGUE TESTING OF A CANADIAN LUNAR ROVER PROTOTYPE

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In 2010, the Canadian Space Agency (CSA) commenced the "Exploration Surface Mobility" (ESM) initiative that funded development of an architecture of systems with a central focus on surface mobility, including core vehicles, subsystems, utility payloads and science instrumentation. In 2012 and 2013, the 3 year development was completed with these systems delivered and tested at the CSA Analogue Terrain in Quebec, Canada. A key component of ESM is Hercules, a class of lunar rover prototype developed by MDA in conjunction with a team of 14 partners under the Lunar Exploration Light Rover (LELR) project. Each Hercules rover is a medium-class exploration system for science, prospecting, surveying and *in situ* resource utilization (ISRU) mission scenarios, with upgradability to short distance crew capability. The rover system is comprised of a rugged mobility platform, substantial payload accommodation, a comprehensive sensor suite for high-latency tele-operation and autonomy, and modular software designed for upgradeability and payload compatibility. Two Hercules rovers were put to the test at various points throughout the program, from mobility testing at vehicle proving grounds demonstrating 25° gradeability under maximum payload, to autonomous guidance, navigation, and control testing demonstrating 5 km/h autonomous driving, and ultimately culminating in analogue field testing at the Canadian Space Agency demonstrating tele-operation at up to 10 k/h under the effects of lunar latency and bandwidth constraints. The SL-Commanders are a second pair of vehicles developed as early testbeds for Hercules to support manned, tele-operated and simplified autonomous modes of operation. Based on an electric version of a commercial ATV design from BRP, the SL-Commander program helped catalyze a new line of commercial electric vehicles from BRP that is manufactured exclusively in Canada. This represents a significant, direct and tangible return on national space exploration technology investment stemming from CSA's ESM program. Other systems under ESM include the autonomous and highly terrainable Mars Exploration Science Rover (MESR), next-generation power, communications and vision systems, as well as payloads like a 3D microscope and mini-corer. Hercules and other ESM systems are now available to support planetary analogue scenarios, as cooperative elements alongside international lander and / or mobility systems, or as host vehicles for international exploration science and ISRU payloads. ESM has collectively advanced both partnerships and technology developments ahead of a number of upcoming international exploration missions from lunar precursors such as Resource Prospector to future Mars missions like ExoMars and Mars2020.

I. INTRODUCTION

Surface exploration of other planetary bodies continues to be a focus of space agencies worldwide. The past and ongoing successes of Apollo, Lunakhod, Pathfinder, Mars Exploration Rover (MER), and Mars Science Laboratory (MSL) obviate the scientific value of observations taken at multiple selected points on the surface. The anticipated Chang'e, Luna, Chandrayaan, ExoMars, SELENE, Resource Prospector, and Mars2020 rover missions underscore this value, and exemplify the international community's commitment to surface exploration [1].

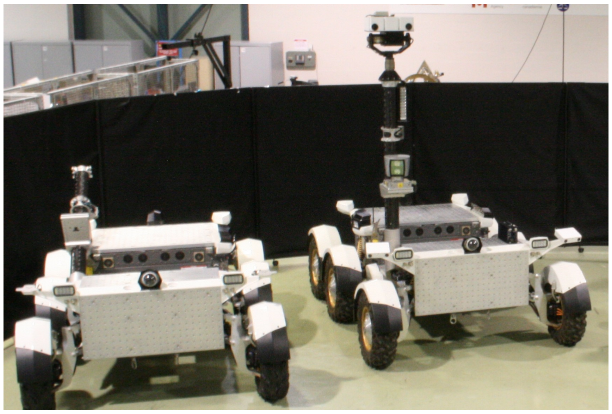

Figure 1: CSA's Hercules rovers.

In alignment with the drive for planetary surface science, the Canadian Space Agency (CSA) initiated the Exploration Surface Mobility (ESM) program in 2010. The objective of this program is to develop fully-functional prototypes of planetary exploration systems – both rovers and instruments – which can be used in analogue mission deployments to refine operations and retire risks for future flight missions. The various elements of the program are intended to be interoperable, so that a wide variety of mission classes (e.g., Mars sample collection, Lunar *in situ* resource prospecting) can be emulated through an appropriate configuration of the prototypes.

This paper discusses one class of these prototypes: the Hercules Lunar Exploration Light Rovers (LELR), shown in Figure 1. Hercules was designed for utilitarian and light mobility tasks, while planning for a potential future upgrade to crew accommodation. In line with its intended use for operations refinement and mission risk mitigation, its development was guided to produce a representative, capable, and field-deployable rover, rather than focusing on path-to-flight hardware development. The result is a rugged, powerful, and intelligent vehicle, ready for deployment in Lunar and Martian analogue terrains. Figure 2 shows the organization of Canadian government, industry, and academic partners who contributed to the development of the Hercules rovers.

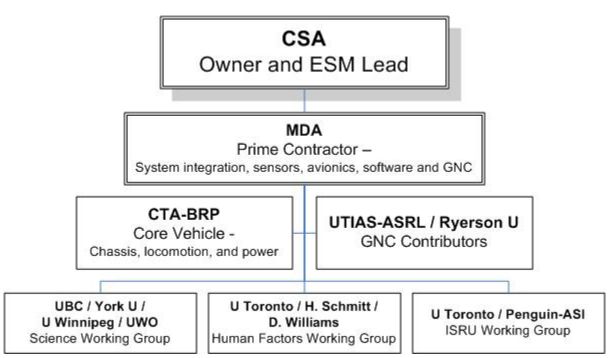

Figure 2: The government, industry, and academic partners who created the Hercules rovers.

The remainder of the paper is as follows: Section II describes the functional capabilities of the Hercules rover. Section III discusses related elements of the ESM program, and in particular, the SL-Commander vehicles, which served as early testbeds for Hercules hardware and software components. The main focus of this paper is Section IV, which describes the many field tests of the LELR used to characterize its performance and prove its functional capabilities and deployment readiness. Future directions for the ESM program in general and the Hercules in particular are provided in Section V.

II. CAPABILITIES OF THE HERCULES ROVER

Hercules is one of many planetary rover prototypes currently in operation worldwide. The ESM program itself includes a number of other rovers which are described in Section III. NASA has several rovers used for risk reduction through analogue field missions, including FIDO [2], Scarab [3], K-REX [4], ATHLETE [5], and SEV [6]. The ESA Exomars Breadboard Rover Chassis, "Bridget" [7], is also being used for field trials [8], but does not have the same level of integrated mission emulation which LELR can provide. The Eurobot Ground Prototype (EGP) [9] has related capabilities, but is focused for research indoors rather than in the field.

Canada has previously performed planetary analogue exploration missions, including geology [10], sample return [11], and *in situ* resource utilization [12]. Hercules and the related elements of the ESM program further extend Canada's capability to perform analogue mission deployments, which continue to be crucial steps toward flight readiness.

The Hercules was designed to perform three classes of operational scenario: autonomous science and exploring, tele-operated resource prospecting and construction, and crewed exploration. These scenarios and their impacts on the design were discussed in a previous paper [13], written before Hercules was completed. The key performance parameters of Hercules with respect to deployment capability are shown in Table 1.

The core vehicle, comprised of the chassis, locomotion, and power subsystems, was designed and built by Bombardier Recreation Products' Centre de technologies avancées (CTA-BRP). The chassis design is a fusion of traditional planetary rover kinematic suspension with terrestrial vehicle dynamic suspension. The former allows the vehicle to climb 30 cm obstacles while maintaining a level body angle, while the latter absorbs vibration and impact at high speed, which is critical for a human-rated vehicle. The all-wheel drive with selectable speed and torque modes provides the power for climbing 25° grades while fully loaded and crossing rough terrain without loss of traction. Hercules

Table 1: Key performance parameters of the Hercules rover.

Parameter	Specification
Payload Accommodation	
Maximum payload mass	300 kg
Payload mounting	Front, rear, top, and mast
Payload data and power	10× wired Ethernet 10× 10 A @ 24 VDC
Field Deployability	
Operating temperature	-10°C to +40°C
Deployment time	~2 hours from completely stowed configuration
Ingress protection	IP54 by design (not formally tested)
Maximum range on a single charge	> 15 km @ 10 km/h by design, tested to 24 km
Gradeability	25° on hard surface, 15° on dry sand
Ground clearance	38 cm
Maximum obstacle	30 cm (all speeds), 10 cm (high speed)
Night operations	Onboard illumination and active sensing
Control modes	Teleoperated, interactive autonomous, and scripted autonomous
Vehicle Performance	
Maximum speed	10 km/h (teleoperated), 5 km/h (autonomous)
Braking distance	3.6 m from 13 km/h
Minimum turning radius	1.5 m, with point turn capability
Wheelbase	2.3 m
Track width	1.7 m
Rollover threshold	36.9°
Mass (without payloads)	870 kg

takes advantage of a hybrid steering mode where the front wheels are steered and the rear wheels act in skid-steered fashion. This design provides the precision of Ackermann steering for most situations while retaining the flexibility of skid-steered tighter turns and point turns when required. Another key feature of Hercules is its range of operational temperatures from -10°C to +40°C, allowing it to be deployed in both cold-climate (e.g., some Arctic summer terrains) and desert analogue terrains. The vision head, avionics bays, and drive components are ingress protected from dust and water, so the rover can withstand light rain or snow without damage.

Hercules's payload accommodation (see Figure 3) was designed to provide a flexible and adjustable interface for a wide range of payloads, which can be attached to the top plate (1 × 2 m), front or rear plates (0.5 × 1 m each), or mast plate (0.2 × 0.4 m).

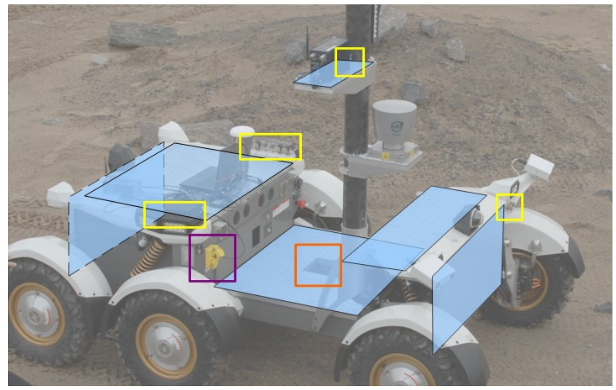

Figure 3: Payload accommodation features: generous mounting plates (blue), data and DC power connectors (yellow), AC power (purple), and cutout for centre-mounted drill (orange).

The maximum payload mass is 300 kg while the top payload plate can accommodate a payload as large as 1 × 1 × 1.5 m. In addition, the centre panel of the top plate can be dropped to host taller payloads (such as an ISRU drill), or be used as a footwell for crew accommodation. Payload power is available through ten onboard outlets each capable of providing 24 V, 10 A service, while communications are provided by ten onboard wired Ethernet connections.

Situational awareness for tele-operators and on-board autonomy is provided by a comprehensive suite of 2-D and 3-D imagers and navigation sensors (see Figure 4). A sensor mast holds a high-speed lidar, a 5 Mpixel stereo camera pair, an 8 Mpixel zoom camera, sun sensor, tilt sensor and high-intensity driving light. Body mounted sensors include a navigation-grade inertial measurement unit (IMU), two hazard detection stereo cameras, an optical odometer, streaming drive cameras and floodlights for worksite operations. Together, these sensors provide up to 96% ground coverage (depending on payload configuration) in the area immediately surrounding the rover (see Figure 5). Data products from the sensors are available to the on-board autonomy and remote operators in either real-time or on-demand modes, configurable to the mission scenario being emulated.

A key capability of Hercules with respect to analogue missions is the ability to perform fully autonomous operations, for example, precision drive to place the rover within reach of a science target, or autonomous driving to a waypoint beyond the on-board sensors' field of view. The rover system has a full range of autonomous guidance, navigation, and control (GNC) functions developed by MDA, the University of Toronto Institute for Aerospace Studies' Autonomous Space Robotics Laboratory (UTIAS-ASRL), and Ryerson University. Prior to their integration in the LELR, each of these components had been thoroughly field tested in

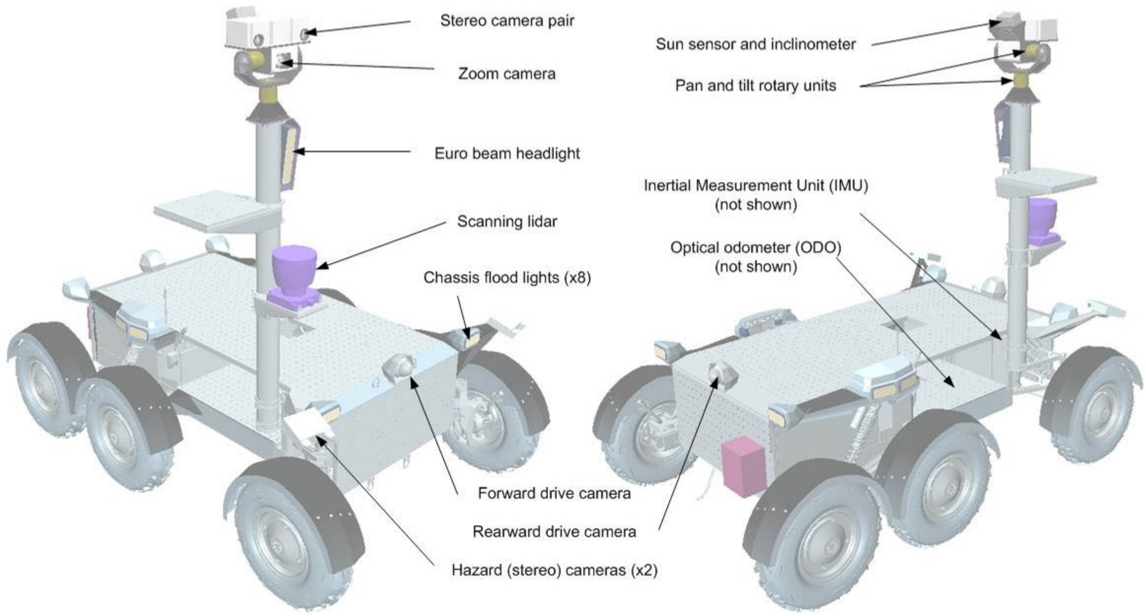

Figure 4: The Hercules sensor suite.

Figure 5: Simulation of the fields of view of the 2D and 3D sensors: lidar (red), zoom camera (green), front and rear drive cameras (cyan and blue), hazard cameras (white and yellow), and stereo cameras at 90° tilt (magenta). Shadow to starboard is due to the mast mounting plate (visible in Figure 3), which can be removed if desired.

planetary analogue environments. The key GNC components are:

- Terrain assessment: evaluation of slopes, positive and negative hazards, and roughness of the terrain.
- Path planning: finding a safe, traversable path from the current position to the goal location.
- Relative and absolute localization: determining position and attitude with respect to the starting location (relative) [14] or a known world map without the use of external navigation aids (absolute). Includes celestial heading estimation using a sun sensor [15], developed by UTIAS-ASRL and Ryerson University.
- Path tracking: computing linear and angular rate commands to keep the rover on the planned path.
- World map building: retains and stitches lidar scans to build up a map of the known environment.
- Autonomous supervisory control: sequencing and recovery from specific faults.
- Visual Teach and Repeat (VT&R): the ability to retrace a previously taught trajectory with a single command [16], developed by UTIAS-ASRL.

A more thorough technical description of the GNC subsystem can be found in an earlier paper on the Mars Exploration Science Rover (MESR) [17].

The software architecture of the Hercules system includes several key features to support planetary analogue missions. The on-board software architecture uses a modular approach, where each key function of both the hardware and data processing is self-contained within its own executable, which allows them to be easily upgraded or swapped out to investigate an alternate approach. A flight-like Rover Executive handles all of the communications with the Rover Control Station (RCS), executes command scripts, and controls the power system so that all of the rover hardware (including the processors themselves) can be power cycled remotely. The rich scripting language for the Executive provides the analogue mission operator with access to all rover and integrated payload functions. The RCS provides a human-machine interface (HMI) for operating the LELR, and can be run from a rugged laptop at the field site, or from a remote "mission control" centre such as the CSA Exploration Development and Operations Centre (ExDOC).

Figure 6: The SL-Commander rover.

III. RELATED ELEMENTS OF THE ESM PROGRAM

During the early development of Hercules, a second pair of vehicles were created as early testbeds to support manned, tele-operated and autonomous modes of operation. These vehicles, called SL-Commanders, were based on an electric version of a commercial ATV design from BRP. In addition to the drive-by-wire capability needed for tele-operation, these rovers had a simplified (planar) version of autonomous precision drive, and an autonomous convoy following function developed previously by the University of Toronto, Defence Research and Development Canada (DRDC), and MDA [18]. The SL-Commander program helped to initiate a new line of commercial electric vehicles, manufactured exclusively in Quebec, Canada, representing a significant, direct and tangible return on national space exploration technology investment stemming from CSA's ESM program.

The ESM program is also comprised of several other micro-, Mars, and Lunar rovers which span a wide class of capabilities. ESM also includes an array of manipulators, science payloads, vision systems, and planetary-analogue infrastructure components. Further details can be found in a summary article [19].

Figure 7: Some initial tests at CTA-BRP: static slope stability (left) and 30 cm obstacle crossing (right).

IV. FIELD TESTING THE HERCULES ROVERS

Hercules was tested incrementally, starting with the core vehicle in the assembly shop and parking lot, moving through outdoor core vehicle testing, laboratory and parking lot testing with the higher level software, and finally outdoor testing of the completed system in lunar-analogue terrain. This section presents highlights from the outdoor tests campaigns.

The first set of outdoor verification tests were performed at CTA-BRP, where the core vehicle's manoeuvrability, point turning, and obstacle crossing were tested (see Figure 7). In each of these tests, the vehicle was driven by an onboard pilot using a hand controller. Test masses were added to the mast and top payload plates to emulate both the loading and centre-of-mass change due to the maximum payload (300 kg).

The core vehicle was also tested using BRP's proving grounds for commercial all-terrain vehicles (ATVs), which includes a wide variety of soil and rock types as well as known slopes. Hercules notably passed the 25° slope gradeability test, in both direct climbing and cross-hill traverses (see Figure 8).

Figure 8: Core vehicle tests at BRP's ATV proving grounds (top), including 25° slope climbing (middle) and cross hill traverse (bottom).

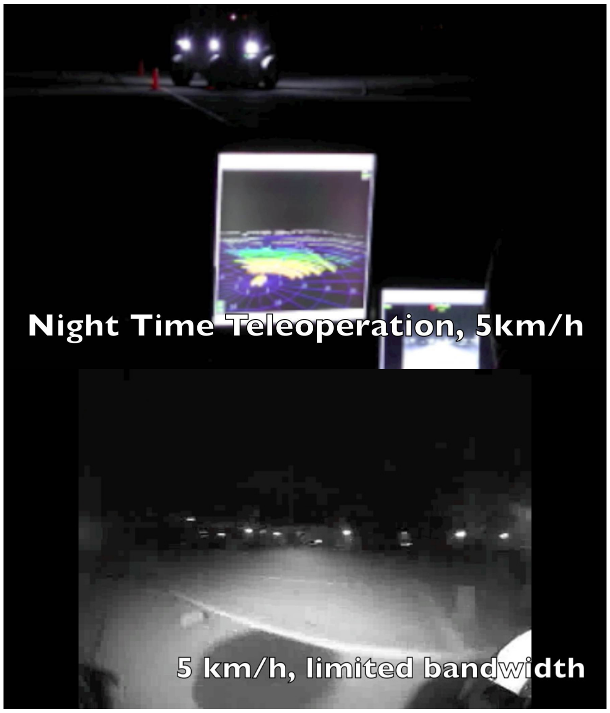

Figure 9: Night time tele-operation test at 5 km/h in the MDA parking lot. Top: External view of rover and live 3D point cloud and drive camera displays. (Note that operator could not directly observe the rover during the actual test.) Bottom: Drive camera view compressed to meet the lunar bandwidth constraint.

Having proved the capability of the core vehicle, the next set of outdoor trials tested the integration of vehicle with the high-level Executive and GNC software, including the interface to the RCS. Early functional testing was performed in MDA's parking lot, with later tests to tune the system performed at a private farm in Ontario. One particularly noteworthy test was night time tele-operation under lunar-representative bandwidth constraints (see Figure 9). This test concluded that driving in darkness with the LELR's illumination enabled resulted in no loss of situational awareness; hence, to the operator, driving at 5 km/h at night felt indistinguishable from driving in the day.

The remainder of Hercules testing focused on its ability to perform mission operations in lunar-analogue terrain. To that end, the CSA Analogue Terrain (AT) facility was used as the test venue. Tele-operation was tested again, under both bandwidth (700 kbit/s maximum) and latency (3 seconds round trip) conditions. With the use of a predictive display at the RCS, 3 km/h was found to be a comfortable speed in hazardous terrains (see Figure 10), and experienced tele-pilots were able to drive up to 5 km/h. The maximum speed of tele-operation under lunar-representative communication conditions was 10 km/h on relatively benign terrain.

Figure 10: Climbing the stairs at CSA AT during tele-operation test with 700 kbit/s bandwidth limit and 3 second delay.

Fully autonomous traverses were also demonstrated in the CSA AT. A comprehensive example run is shown in Figure 11: starting near the edge of a boulder field, the rover was localized by an operator with respect to an *a priori* map of the environment. The operator then picked a series of three waypoints from the map and sent these to the rover Executive using a command script. Hercules then used its onboard GNC functions to plan and execute a series of short traverses at 3 km/h to achieve the final goal. It is worth noting that the final waypoint was on top of a plateau, accessible by a ramp of limited traversable width. Hercules was able to plan and safely track a path through this bottleneck to complete the traverse. Another demonstration showed that the relative localization system is accurate enough to manoeuvre the rover such that a target of scientific interest is within the rover's workspace (e.g., reachable by an onboard manipulator or viewable by the high-resolution zoom camera or a science instrument) (see Figure 13). The maximum speed tested under autonomous control was 5 km/h on relatively benign terrain.

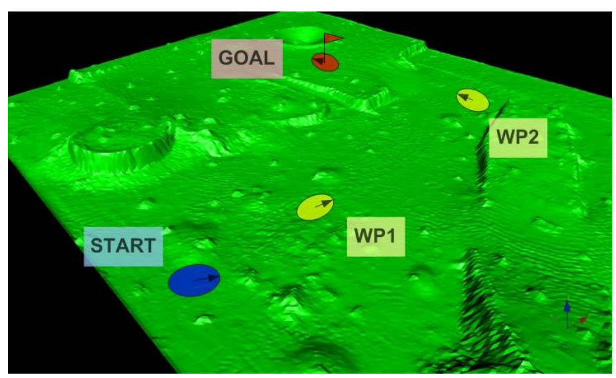

Figure 11: Graphic showing the start location (blue) of the autonomous traverse, and intermediate (yellow) and goal (red) waypoints selected by the operator from the 3D map. The goal was on top of a plateau, which could not be imaged by the onboard sensors from the starting location.

Figure 12: Hercules performing a fully autonomous drive in the CSA AT. Still frames show the rover successfully executing the traverse shown in Figure 11.

Figure 13: Hercules performing an autonomous precision drive to place the rock within the workspace of the rover.

The team from MDA and UTIAS-ASRL were also able to tune the VT&R system for the large Hercules rover, and perform a successful demonstration from one corner of the AT to the other. At one point in the Repeat phase the rover lost traction when climbing a hill that was terrainable in the opposite direction during the Teach phase; however, after a brief tele-operated intervention, the VT&R system was able to relocalize the vehicle and complete the traverse (see Figure 14).

The second Hercules vehicle was completed through to tele-operation testing. However, it has a reduced sensor suite, so will not be capable of performing autonomous precision drives until the outstanding sensors are integrated.

Figure 14: Successful VT&R traverse spanning the length of the CSA AT, returning to the starting point (marked by orange cones).

V. FUTURE WORK

CSA will be integrating other ESM payloads with Hercules and performing analogue testing in the AT as part of the ongoing ESM program. Drivers for the ubiquitous Robot Operating System (ROS) are currently being written for both Hercules and SL-Commander in order to provide easier access for academic, industry, and international research groups to use these vehicles as experimental platforms in collaboration with CSA. Future work may also include additional or upgraded software modules, or enabling autonomy on the second vehicle by completing its sensor suite.

Hercules and other ESM systems are now available to support planetary analogue scenarios, as cooperative elements alongside international lander and / or mobility systems, or as host vehicles for international exploration science and ISRU payloads. The ESM program has advanced both partnerships and technology developments ahead of upcoming international exploration missions such as Resource Prospector, ExoMars and Mars2020.

VI. ACKNOWLEDGEMENTS

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