



Cratos: The Evolution of a Robotic Vehicle

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Abstract

Cratos was originally designed to evaluate a small footprint, low-power, tracked vehicle for traversing a crater face and for scraping regolith from a crater basin on the lunar surface. These activities require a power-to-weight ratio such that the vehicle is able to pull its entire mass vertically off the ground with the power from one track. Further complicating matters, the available power-units that fit the vehicle's approximate 1 m³ volume, restrict power consumption to 100 W. Lastly, the vehicle is required to telemeter data from an array of sensors to a remote control station for further study. This unique mix of design constraints lead to the creation of a versatile mobile sensor platform, described in this paper, capable of performing a myriad of functions beyond the scope of its original purpose.

1.0 Introduction

Early collaborative work with the Robotics Institute of Carnegie Mellon University, introduced the NASA Glenn Research Center design team to established robotic platforms such as IceBreaker whose purpose was to travel to the cold traps within craters on the Lunar South Pole in search of ice (Ref. 1). IceBreaker was designed to land directly into a crater using integrated thrusters built into the frame. After landing, a six wheeled locomotion system would ferry the vehicle to various waypoints where a drill would take core samples in the crater basin for analysis. Most of the drilling operation would occur in shadow within the crater basin. Because it was powered through photovoltaic panels, the vehicle was required to move periodically to spots away from the shadow of the crater rim where the sun could illuminate its photovoltaic panels. This design produced a vehicle with a large footprint and a large volume to accommodate the landing mechanism and the batteries required to traverse the long distances between charging locations. In order to reduce the size and power requirements of these vehicles, both Carnegie Mellon and NASA Glenn initiated studies of smaller tracked vehicles which could potentially climb the crater wall to recharge more frequently in the sunlight on the surface. These studies produced a tracked version of IceBreaker (Ref. 2) as well as an articulated six-wheel version called Scarab (Ref. 3). NASA Glenn also created a low cost, energy efficient test platform called Cratos which was designed

to evaluate a tracked vehicle configuration for descending and ascending the crater walls of a lunar landscape.

Cratos was also envisioned as an enabler for proofing ceramic track components designed by the NASA Glenn Materials Division. Ceramic track components were considered because of the potential for cold welding at metal-to-metal interfaces at the extremely low temperatures in the cold traps of the lunar craters. The temperatures in these cold traps hover around 24K (Ref. 1). Program funding issues curtailed this work before significant progress was made toward the design of ceramic track components. However, Cratos continued to go through many growth stages as well as changes of mission. Throughout these changes, energy efficiency, low cost and a small footprint remained as primary design goals. The power source was constrained to 100 W and the footprint to less than a square meter. To maintain low cost, commercial off-the-shelf components were used where possible. In spite of these design constraints, Cratos has engaged in diverse testing and development tasks which have included the movement of a substantial volume of simulated lunar regolith, pulling other mobile platforms three to four times its own mass, climbing steep grades with stability and control and inserting smaller vehicles onto commuter busses and trains. The evolution of the Cratos design has molded Glenn's robotic concept vehicle into a multi-faceted sensor platform whose namesake, Cratos, was derived from the Greek mythological figure that personified strength and power and whose name also reflects the original purpose of the vehicle which was to traverse the crater walls on the moon. The rationale for and the details of the design of Cratos as well as the various roles performed by Cratos will be discussed in this paper. Lastly, this paper will cover anticipated future roles Cratos could fill within various projects.

2.0 Design

In order to expedite the design process and maintain a reasonable cost, commercially available components with proven track records for durability were incorporated into the vehicle. These components, seen in Figure 1, included the track and associated drive pieces from a Honda power carrier, low-power high-torque Dayton gear motors, IEI Technology Corp linear actuators, and Bosch extruded aluminum tubing for framing.

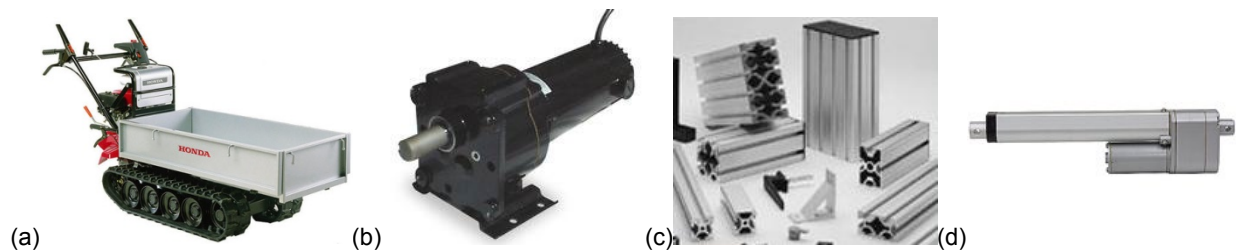


Figure 1.—(a) Power carrier. (b) Gear motor. (c) Bosch extrusions. (d) Linear actuator.

In contrast to the commercially available mechanical components, most of the vehicle's electronic control systems had to be custom-designed to meet the design requirements for this unique mobile test bed. The main controller for Cratos could have been realized using one of several commercially available systems, but often their built-in communication networks utilized proprietary data packet structures for telemetering the sensor data that was not compatible with Cratos data requirements. Furthermore, the industrial computer-based systems were too power hungry for our power budget. Consequently, it proved more expedient to design a custom control system.

This custom design produced a flexible controller, shown in Figure 2, with 16 pulse-width-modulation (PWM) outputs to drive the various system motors, six relay outputs, two external interrupts, 16 analog/digital input/output lines, a RS232 serial port and a radio-link. The radio link utilizes Maxstream's 900 MHz Extend-Radio with a maximum 40 mile range when using its full 1 W of power. Data and control packets are transmitted between the controller and either a hand-held remote (Figure 3) or a PC running LabView that emulates the remote and records the sensor data (Figure 4).

In its current configuration, shown in Figure 5, Cratos has an electronic gyro to measure rotation about the vertical axis, a 2-axis accelerometer configured for use as a 2-axis tilt sensor, current sensors to monitor power usage, optical encoders for both track motors and a battery voltage/amp-hour monitor. Cratos also provides a video link via a RF transmitter separate from the controller link. Lastly, a GPS unit is included which can interface to the controller through the RS232 serial line. At the heart of the controller are two 8051 core processors from Silicon Laboratories with pipelined architecture running at 25 MIPS. One processor controls all of the communication, motor control and battery monitoring while the other controller is used to read the digital/analog and interrupt inputs as well as implement the user code (Figure 6). All of the code is written in C and includes modules for easy I/O setup, motor control and radio network (RNET) communication between the controller and host. The JTAG interface between the PC and microcontrollers allows for quick troubleshooting during debugging sessions.

Status indicators for program fault, RNET fault and low battery power give the user a quick snapshot of the controller operational state.



Figure 2.—Glenn Controller.



Figure 3.—Hand-held remote.

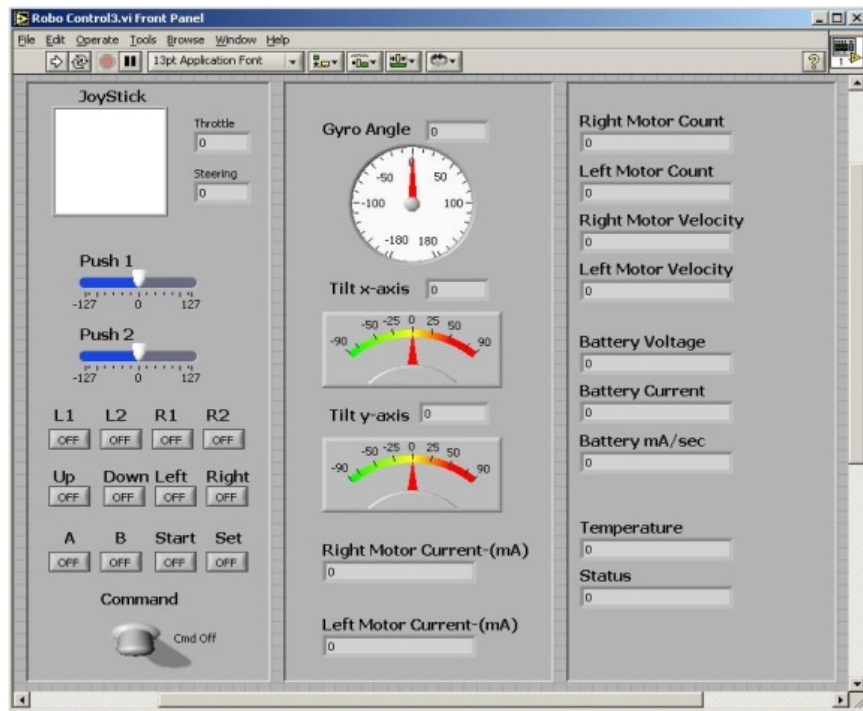


Figure 4.—LabView remote and data logger.

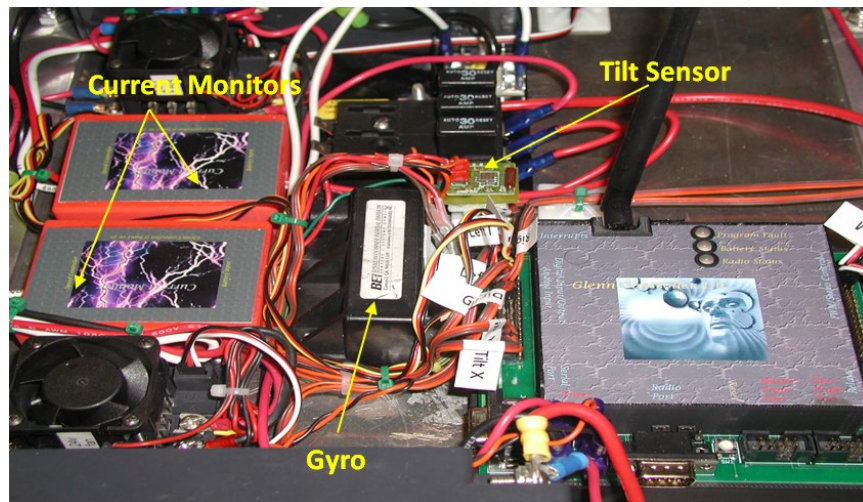


Figure 5.—Gyro, tilt sensors, current monitors.

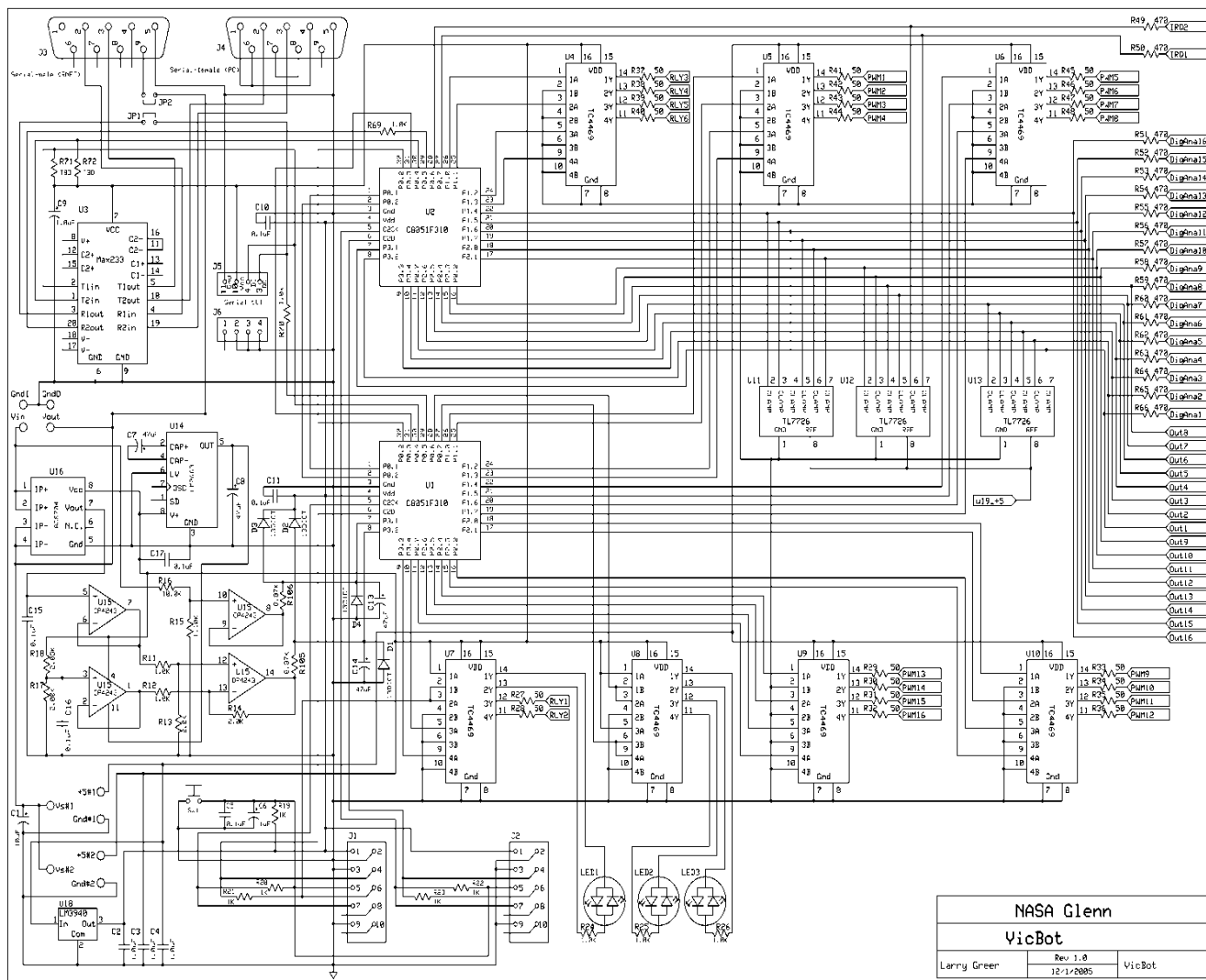


Figure 6.—Schematic of Cratos Controller.

The communication protocol was constructed to accommodate the state machine running inside the hardware control processor. Consequently all processes, including the radio network communication, PWM servo control and the SPI link between the hardware control and user microcontrollers are synchronized to the servo cycle of 50 Hz. This constraint limits the 9600 baud transfer over the radio network to a maximum data block size of 20 bytes. The hand-held remote or PC remote emulator continuously transmits control packets to the robot controller receiver in order to maintain a link to the robot (Table I). After validating the command packets, the robot controller responds every 20 msec with one of four possible data packets specified by the data queue within the user program. Subsequent data packets are transmitted as the radio network rotates through the user specified data packet queue (Table II to Table V). Both command and data packets are transmitted at 9600 baud using 8-bit data with 1 start bit, 1 stop bit and no parity.

TABLE I.—COMMAND PACKET SENT
TO ROBOT CONTROLLER
[Right and left motor open-loop command packet]

Byte no.	Byte value	Byte description
1	0x55	Preamble
2	0x55	Preamble
3	0x55	Preamble
4	0x55	Preamble
5	0xFF	Header1
6	0xAA	Header2
7	0xFF	Identifier (0xF0 → 0xFF)
8	Data	Joystick1 x-axis (*steering wheel 0x0 → 0xFE)
9	Data	Joystick1 y-axis (*throttle 0x0 → 0xFE)
10	Data	Joystick2 x-axis (0x0 → 0xFE)
11	Data	Joystick2 y-axis (0x0 → 0xFE)
12	Data	Switches 0-7
13	Data	Switches 8-15
14	Data	Aux1 (Joystick1 wheel 0x0 → 0xFE)
15	Data	Aux2 (0x0 → 0xFE)
16	Data	Aux3 (Joystick2 wheel 0x0 → 0xFE)
17	Data	Aux4 (0x0 → 0xFE)
18	CRC16	hi-byte of CRC16
19	CRC16	lo-byte of CRC16

*Note-For steering mode, otherwise revert to x-y joystick in tank mode

Unfortunately, for each new data packet added to the radio network queue, another 20 msec delay is added to the total time required to cycle through the entire sensor suite. This attribute should be taken into consideration when determining the time period between sensor readings transmitted through the radio network.

TABLE II.—MOTOR TICS DATA PACKET
RECEIVED FROM ROBOT CONTROLLER

Byte no.	Byte value	Byte description
1	0x55	Preamble
2	0x55	Preamble
3	0xFF	Header
4	0x0	Data Type--Indicator for right & left motor tics data
5	Data	hi-word,hi-byte of right motor tics
6	Data	hi-word,lo-byte of right motor tics
7	Data	lo-word,hi-byte of right motor tics
8	Data	lo-word,lo-byte of right motor tics
9	Data	hi-word,hi-byte of left motor tics
10	Data	hi-word,lo-byte of left motor tics
11	Data	lo-word,hi-byte of left motor tics
12	Data	lo-word,lo-byte of left motor tics
13	CRC16	hi-byte of CRC16
14	CRC16	lo-byte of CRC16

TABLE III.—GYRO AND TILT SENSOR DATA
PACKET RECEIVED FROM ROBOT CONTROLLER

Byte no.	Byte value	Byte description
1	0x55	Preamble
2	0x55	Preamble
3	0xFF	Header
4	0x4	Data Type--Indicator for gyro and tilt sensor output
5	Data	hi-byte gyro degrees
6	Data	lo-byte of gyro degrees
7	Data	hi-byte of x-axis tilt
8	Data	lo-byte of x-axis tilt
9	Data	hi-byte of y-axis tilt
10	Data	lo-byte of y-axis tilt
11	0	not used
12	0	not used
13	CRC16	hi-byte of CRC16
14	CRC16	lo-byte of CRC16

TABLE IV.—BATTERY HEALTH DATA PACKET
RECEIVED FROM ROBOT CONTROLLER

Byte no.	Byte value	Byte description
1	0x55	Preamble
2	0x55	Preamble
3	0xFF	Header
4	0x0B	Data Type--Indicator battery health parameters
5	Data	hi-byte of battery voltage (mV)
6	Data	lo-byte of battery voltage (mV)
7	Data	hi-byte of battery current (mA)
8	Data	lo-byte of battery current (mA)
9	Data	hi-word, hi-byte of used battery capacity (mA-sec)
10	Data	hi-word, lo-byte of used battery capacity (mA-sec)
11	Data	lo-word, hi-byte of used battery capacity (mA-sec)
12	Data	lo-word, lo-byte of used battery capacity (mA-sec)
13	CRC16	hi-byte of CRC16
14	CRC16	lo-byte of CRC16

TABLE V.—BUCKET POSITION DATA PACKET
RECEIVED FROM ROBOT CONTROLLER

Byte no.	Byte value	Byte description
1	0x55	Preamble
2	0x55	Preamble
3	0xFF	Header
4	0x0C	Data Type--Indicator for Bucket values
5	Data	hi-word, hi-byte load cell
6	Data	hi-word, lo-byte load cell
7	Data	lo-word, hi-byte load cell
8	Data	lo-word, lo-byte load cell
9	Data	hi-byte of bucket weight
10	Data	lo-byte of bucket weight
11	Data	hi-byte of bucket angle
12	Data	lo-byte of bucket angle
13	CRC16	hi-byte of CRC16
14	CRC16	lo-byte of CRC16

3.0 Evolution

As previously mentioned, Cratos has evolved to suit the needs of various mission requirements. Initially, the mission was to examine the ability of small tracked vehicles to traverse the steep grades of lunar craters. This small platform proved to be a very effective, but slow climbing machine. Maneuverability was excellent for both ascent and descent on the lunar simulant (Figure 7). After further examining mission requirements, a new feature was added that allowed for efficient excavation and transportation of large volumes of lunar regolith. The center mounted bucket effectively used the existing volume and mass of the machine to produce an efficient soil mover. Now outfitted with a bucket and a powerful linear actuator, Cratos could easily dig, lift and transport 200 lb of regolith (Figure 8).

This newly acquired ability lead to several endurance tests to determine the feasibility of using this 100 W machine to build ramps and bury structures with lunar regolith. Cratos proved that small platforms can do useful work toward completing lunar mission objectives such as transporting regolith to oxygen generators and protecting structures from harmful radiation by burying them with a protective shield of lunar regolith (Figure 9 and Figure 10).

It was also envisioned that small robotic vehicles might be required to pull larger specialized mobile platforms to specified locations on the lunar surface. With this in mind, Cratos was fitted with a ball hitch and performed experiments pulling various sized platforms over level and uneven terrain (Figure 11).



Figure 7.—Cratos ascending a steep grade on lunar simulant.



Figure 8.—Cratos moving volcanic soil on Hilo in Hawaii.



Figure 9.—Cratos burying a tarp with lunar simulant.

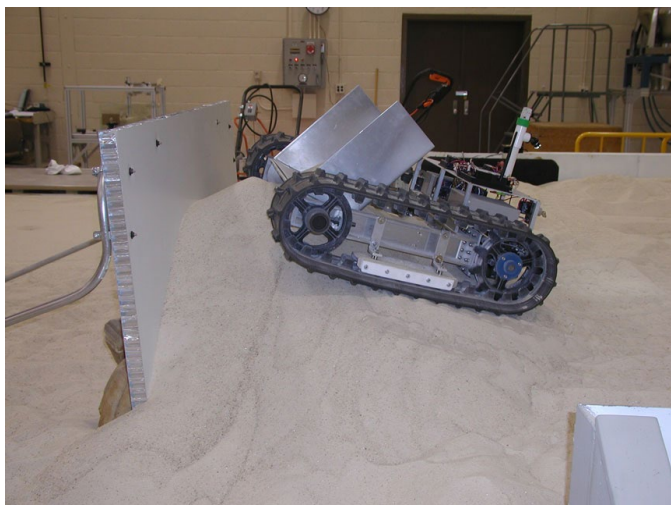


Figure 10.—Cratos building a ramp with lunar simulant.



Figure 11.—Cratos pulling a large trailer.



Figure 12.—Cratos carrying a smaller inspection robot for deployment on a city bus.

The latest incarnation of Cratos is a delivery robot for a smaller inspection robot that Homeland Security would use to scan for bombs on public transportation. The lifting mechanism for the bucket on Cratos served as the perfect delivery tool for a ramp holding a smaller inspection robot (Figure 12). Cratos can maneuver the ramp into the narrow stairwell of city busses to provide an easy entry for the smaller inspection robot. Prior to this demonstration, the general consensus was that it was an extremely complicated engineering effort to make a single robot climb the steep narrow stairwells of city busses and still have a small enough footprint to navigate around and under the seats to scan for suspicious objects.

The control station was redesigned to easily switch between the two robots with a touch of a button. The control station display was also able to show the various camera views from Cratos (top of the ramp, normal driving camera) which facilitated the insertion of the ramp into the bus.

4.0 Conclusion

Cratos has proven itself as an engineering development workhorse by providing a dependable, flexible test platform for a host of mission objectives. It has performed several tasks previously thought to be in the domain of the larger robotic machines. With the high costs of launching equipment into space, Cratos supports the notion that several low weight, low power machines would be a less risky and probably lower cost approach for future lunar mission objectives when compared to the single massively complicated “do everything” robotic platforms. First of all, several smaller machines can provide redundancy for the case of the unforeseen catastrophic failure. Secondly, a case can be made to show the cost of several smaller less capable machines could be significantly less than that of a single massive, complicated robotic platform. Lastly, there are several cases where it can be shown that two or more machines working in concert can outperform a single machine performing the same tasks. Such was the case for robotic inspection of city transportation for the Department of Homeland Security where two robotic platforms greatly simplified the task of ingress onto city busses.

5.0 Future

The simplicity of the subsystems that comprise Cratos produces a highly adaptable, flexible and reliable platform. The simple design makes for quick and easy changes which facilitates the successful completion of multiple mission objectives. However, the simplicity of the control system also handicaps Cratos when attempting to implement more computationally intense control tasks. Consequently, a more computationally powerful version of Cratos is desired which will allow for greater flexibility in software/hardware support. Fortunately, while Cratos was evolving to meet the tasks of the various projects, new commercially available controller

platforms, such as the CRio control system from National Instruments, were produced that would provide improved computational power and still meet the low-power consumption and hardware flexibility requirements.

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