Investigation of Stepper Motor Controllers for Ultra-Low Temperature Environments

Technical Report

Richard Patterson
NASA Glenn Research Center
Cleveland, Ohio

Roger Stone
NASA Goddard Space Flight Center
Greenbelt, Maryland

Ahmad Hammoud
QSS Group, Inc.
NASA Glenn Research Center
Cleveland, Ohio

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Background

The operational environment for some of the electronics planned for use in the Next Generation Space Telescope (NGST) mission requires devices and components capable of surviving and working efficiently under cryogenic temperature conditions. This particularly applies to stepper and other motors and their associated control and logic drives. These motors, which are designed to drive filter wheels and provide steering and alignment for other camera assemblies, are expected to encounter temperatures as low as 30 K [1]. In addition, some of the electronics will be required to operate near infrared where thermal noise need to be avoided or kept to a minimum. In order to meet these challenges, the electronics should be able to operate reliably at cryogenic temperatures, simplified circuit configurations with minimum device count in the cold region need to be implemented, and interface wiring between the cold and hot temperature regions of the electrical system must be kept to a minimum.

At present, most manufacturers specify –40 °C as the lowest temperature for operation of their commercial-off-the-shelf electronic components. Even the military-grade devices are rated for operation down to only –55 °C. These low temperature boundaries are due to limitations in the materials being used in the manufacture of the devices or due to the inherent design and processes techniques. Many missions, such as NGST, require electronics that will operate below today's specification limits. In addition to surviving the hostile environment, low temperature electronics are expected to result in more efficient systems than those at room temperatures. This improvement results from superior electronic, electrical, and thermal properties of materials at low temperatures [2]. In particular, the performance of certain semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature (-196 °C) [3]. At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity [4]. An example is the power MOSFET that has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance $R_{DS\ (on)}$ resulting from increased carrier mobility [5]. Such devices, which are typically used for switching or control, must certainly be considered in the design of a motor drive system for use in the NGST mission.

Scope of Work

In a collaborative effort with the NGST Program Office at NASA GSFC, the Low Temperature Electronics Group at NASA Glenn Research Center pursued investigations of motor controllers geared for the cryogenic environment of the NGST mission. This work, which was also supported by the NASA Electronic Parts and Packaging (NEPP) Program at the Jet Propulsion Laboratory (JPL), focused on addressing the following tasks:

1. Assess the feasibility of developing a motor control system to change camera filters for the Next Generation Space Telescope where the motors and some of the motor controller components would be operating at a temperature of about 30 K.

2. Identify the best controller circuit topology to minimize the number of needed motor select/control wires that would penetrate through the NGST sun shield in order to reduce heat transfer from the hot side to the cold side of the sun shield.

During the initial phase of this activity, the following conditions were proposed:

1. Only one motor will operate at a time
2. The motor will be a stepper type, and the controller will be a four-phase output.
3. Only one controller will be used, and so there must be a method to select the motor to be driven.
4. The NGST motor to be used is not yet selected, but the required current to drive the motor was estimated to be 0.25 to 1.0 Amps. Resistance for low thermal conductivity wires from the hot side to the cold side was estimated to be 50 to 200 Ohms. Motor wire resistance at 30 K was estimated to be about 1/10 th of its room temperature value, although actual values were not yet known.
5. The motor select/control system could connect to as many as 30 motors on the cold side of the sun shield.

Experimental Studies

The initial circuitry was drawn up keeping in mind that the four phases of the motor must be controlled and timed, and that the motor to be driven had to be electrically selected. Most unipolar motor drives are low-side drives, that is, the switching transistors that drive each of the four phases of the motor are located between the motor winding and ground. For a low-side control, the emitter of each npn bipolar switching transistor (or the source of each n-channel FET) is held at ground. High-side switching, on the other hand, requires the placement of the switching element between the positive side of the power supply and the motor winding. As a result, the emitter of a high-side npn switching transistor (or the source of an n-channel FET) can change voltage, and this can make control of the switch more complicated.

Motors and Controllers

Candidate commercial-off-the-shelf motor controllers, that would be located (in major part) on the hot side of the sun shield near room temperature, were identified and acquired for evaluation. The four-phase switching transistors, which are driven by the outputs of the controller, and some logic devices, could be located on cold side of the sun shield (if necessary). The three controllers selected for this work are listed in Table I.

Table I. Specifications of stepper motor controllers. [6-8]

Manufacturer	Haydon, Inc.	Simple Step, Inc.	E-Lab Digital Eng.
Part #	39105	SSXYZ	EDE 1200
Input voltage (V)	7.5 - 32	7.5 – 45.5	3- 5.5
Current/Phase (A)	0.75	0.1 – 2.0	0.2
Drive	Unipolar/Bipolar	Unipolar/Bipolar	Unipolar
Stepping	Switch selectable	Programmable	Switch selectable

Several stepper motors were acquired for evaluating the performance of the selected controllers. Table II lists some of the specifications of these motors.

Table II. Specifications of selected stepper motors. [9,10]

Manufacturer	Sanyo Denki	Lin Engineering	Lin Engineering	Lin Engineering
Part #	103H5205-0400	213-10-12	4018S-20	4218S-15
Current/Phase (A)	0.7	0.3	0.3	0.5
Resistance/Phase (Ω)	5	12	39	15
Inductance/Phase (mH)	3	2	25	22
Torque (oz.in)	28.3	5.5	15	35
Inertia (oz.in^2)	0.2	0.06	0.09	0.15
Weight (lb)	0.45	0.25	0.44	0.4
Leads	6	6	6	4
Size	17	14	17	17
Step (degrees)	1.8	1.8	1.8	1.8

The performance of the controllers was examined by driving the motor with the controller phasing switches (warm silicon MOSFETs on the low-side of the motor) and by using ultra-cold high-side switches to represent ultra-cold motor selection switches. The prime area of interest was on the ultra-cold motor selection switches. In the early phase of the work, two different types of transistors were utilized as the ultra-cold switching elements. These comprised of a germanium-type (Ge) npn transistor (2N1302) and a heterostructure bipolar silicon-germanium (HBT SiGe) transistor (SGA9289). Phase controller boards were constructed with a motor control integrated circuit, some passive components, and the silicon MOSFET phase-control switches. The motor selection switching transistors were mounted on separate boards so that they could be evaluated under cryogenic temperatures. Due to complexity of the Simple Step controller, which was a triple axis controller and required programming and special connector fixtures, it was excluded from this preliminary evaluation. The two other controllers were evaluated in combination with the motor-select transistors (which were held at room temperature (20 °C) and also at liquid nitrogen (-196 °C) temperature).

The Haydon controller did not perform well with any of the phase-control transistors. Loading effects, i.e. over-current conditions, were observed even at room temperature upon using any of the motors as the load. Unlike the Haydon controller, the EDE 1200 counterpart performed well with the supplied MOSFET phase-control transistors, with both types of motor-select switches, and with any of the motors connected as the load. The two types of motor-select transistors were found to function properly at 20 °C as well as at –196 °C. These motor-select transistors were also able to switch-on for “cold start” under the cryogenic temperature of –196 °C.

Current-Sharing

Although the two types of transistors performed well between 20 °C and –196 °C, their current handling capability may not be sufficient to drive the stepper motor, especially at very cold temperatures. Two separate circuits, each consisting of two transistors of the same type connected in parallel, were built and tested to check for current-sharing characteristics of these types of devices. These tests were performed in the temperature range of 20 °C to –196 °C. While the silicon-germanium HBT transistors (SGA9289) performed very well throughout the test temperature range, the germanium-based transistors (2N1302), on the other hand, required some bias adjustment so that the circuit current could be equally shared between the two devices. Based on the results obtained so far, it was concluded that transistors with higher current ratings, as well as other types of switching transistors, should be evaluated in order to address the requirements of the NGST stepper motor application.

Switching Devices

In the nest phase, a major effort was conducted to identify transistors and other switching devices that were suitable for cryogenic operation and could potentially be used with the stepper motor controller circuit. A large array of switching devices from various manufacturers was acquired for evaluation. These transistors included bipolar as well as MOSFET devices. The hexfet mosfet transistors included N- and P-channel devices. In addition to different power ratings, selected transistors were chosen for their base material, such as germanium (Ge), silicon-germanium (SiGe), and gallium-arsenide (GaAs). Transistors made of these types of materials had the best chance for ultra-low temperature operation. Several devices of each type of transistor were acquired for evaluation. A test matrix was generated covering several parameters and test conditions. These test variables included the following:

- The test temperature ranged from 20 °C to –263 °C (10 K).
- Family curves of each transistor included I_D (drain current) versus V_D (drain voltage) or I_C (collector current) versus V_{CE} (collector voltage) switching characteristics, gate threshold voltage or current gain, and voltage breakdown.
- Transistors were used in conjunction with the EDE 1200 controller in the motor control test.
- Electrical stressing applied on and off at specific test temperatures for several cycles. Various bias conditions were applied to the gate (G) and to the drain (D) to obtain desired drain current (I_D).
- Cold-start at cryogenic temperatures.

These test variables in conjunction with the devices tested are listed in Table III. Information on each transistor by manufacturer, part number, specifications, and number of devices tested is given in details. Table III includes also a brief description on the performance of each particular device under a specific test condition. It can be clearly seen that while some devices experienced changes in their switching characteristics with temperature, others remained unaffected. The IRFD220, IRFP360, and IRF630, for example, exhibited excellent stability in their performance with temperature down to 10 K. The SGA9289, TGF120, and SHF0589 devices, on the other hand, underwent changes, with varying degrees, in their switching characteristics as the temperature was decreased. At the test temperature of 80 K, the 2N1302 transistors degraded sharply but they recovered when temperature was brought back to higher levels. The effects of low temperature seemed to depend on the type of the device, including material packaging, doping, and possibly processing techniques. In contrast to cryogenic exposure, electrical stressing was found to influence the performance of devices from the same type. This variation in performance under electrical cycling was observed within the IRF640 and IRFD024 device category. On the other hand, all devices of the IRFD220 and IRF630 exhibited good and consistent behavior when cycled under power-on conditions at cryogenic temperatures.

Logic Devices

Several logic integrated circuits (IC's) were obtained for evaluation as a function of temperature. These logic chips were all based on CMOS technology due to its known good performance under extreme temperatures. The devices included NAND and NOR gates, buffers and hex inverters. Manufacturers' specifications of these devices, test parameters, and results are all listed in Table IV. All of these devices seemed to work properly under exposure to cryogenic temperatures. Some of these devices were characterized with temperature down to –190 °C, while others were tested at temperatures as low as 10 K. Power cycling under cryogenic temperatures did not affect either the performance or the cold-start capability of these devices, as seen from the results in Table IV.

Control Circuits

The last activity in this phase of investigation was the demonstration of a simple control/drive circuit at cryogenic temperatures. A circuit consisted of a CMOS buffer controlling two MOSFET IRF630 switches was built and tested in the temperature range between 20 °C and –190 °C. A schematic of the circuit is shown in Figure 1. An inductive load, which is a representative of a typical motor winding, was connected to each output of the switching transistor. The circuit performed well without any deviation in characteristics with temperature down to the lowest test temperature of –190 °C. In addition, the circuit survived and functioned properly at that temperature under power cycling. This electrical stressing consisted of applying power on for 15 minutes, followed by power off for 30 minutes for a total of ten cycles, as shown in Table V.

Table III. Listing of switching devices, test parameters, and test results.

Device	Manufacturer	Features	Tests	Comments
SGA9289 (2devices)	Sirenza	SiGe HBT, 5V, 350 mA, 2.8W	- Motor control, T: 20 to -190˚C - Current-sharing, T: 20 to -190˚C - Motor control, T: 40 to 10K, 150 min - Family curves, T: 297 to 10K	- Devices performed well - Both devices performed well - Devices performed well - Devices o.k. with changes in characteristics
2N1302 (2)	Unknown	Ge NPN, 25 V, 300 mA	- Motor control, T: 20 to -190˚C - Current-sharing, T: 20 to -190˚C - Family curves, T: 297 to 10K	- Devices performed well - Improper sharing - Degradation at 80K; recovery afterwards
TGF120 (2)	TriQuint	GaAs HFET, 12V, 300 mA	- Family curves, T: 297 to 10K	- Devices o.k. with changes in characteristics
SHF0589 (1)	Sirenza	GaAs, HFET, 12 V, 1.2 mA, 14W	- Family curves, T: 297 to 10K	- Device o.k. with changes in characteristics
IRFD024 (1) (1) (2) (1)	Int'l Rectifier	Hexfet Mosfet, 60V, 2.5A, ±20V(GS), 0.1Ω, 1.3W	- Family curves, T: 297 to 10K - Motor control, T: 10K, on/off cycles - G: 4.7V, D: 1V, I: 800mA; T: 10K - G: 4.7V, D: 1V, I: 470mA; T: 77K - G: 4.7V, D: 1V, I: 500mA; T: 77K	- Devices functioned very well - Good operation through 15 applied cycles - Increase in leakage after 3 cycles - Increase in leakage & instantaneous breakdown after 10 applied cycles for one device, while another device performed well for 15 cycles - Good operation through 15 applied cycles
IRFD9024 (1)	Int'l Rectifier	Hexfet Mosfet, -60V, -1.6A, ±20V(GS), 0.28Ω, 1.3W	- Family curves, T: 297 to 10K	- Device functioned very well
IRFP360 (1)	Int'l Rectifier	Hexfet Mosfet, 400V, 23A, ±20V(GS), 0.2Ω, 280W	- Family curves, T: 297 to 10K - G: 5V, D: 1.2V, I: 810mA; T: 77K	- Device functioned very well - Good operation through 27 applied cycles
IRFD220 (2) (1)	Int'l Rectifier	Hexfet Mosfet, 200V, 0.8A, ±20V(GS), 0.8Ω, 1W	- Family curves, T: 297 & 77K - G: 5.5V, D: 2V, I: 250mA; T: 77K - G: 5.7V, D: 1V, I: 450mA; T: 77K	- Devices functioned very well - Good operation through 10 applied cycles - Good operation through 10 applied cycles
IRF640 (4) (1)	Int'l Rectifier	Hexfet Mosfet, 200V, 18A, ±20V(GS), 0.18Ω, 125W	- Family curves, T: 297 & 77K - G: 5.8V, D: 1V, I: 850mA; T: 77K - G: 5V, D: 1V, I: 225mA; T: 77K	- Devices functioned very well - 2 devices failed after 1 cycle; 1 survived 5 cycles before sharp degradation; 1 operated for 10 cycles but failed RT (post) measurements - Device operated through 10 cycles; ID deceases slightly
IRF630 (2) (1)	Int'l Rectifier	Hexfet Mosfet, 200V, 9A, ±20V(GS), 0.4Ω, 75W	- Family curves, T: 297 & 77K - G: 5.8V, D: 1V, I: 890mA; T: 77K - G: 5.5V, D: 1.5V, I: 640mA; T: 10K	- Devices functioned very well - Good operation through 10 applied cycles - Device performed well through 20 applied cycles; slight reduction in ID at cryo temp.

Table IV. Listing of logic devices, test parameters, and test results.

Device	Manufacturer	Features	Tests	Comments
CD4001BC	Fairchild	CMOS 2-input NOR gate, 5-15V, TTL, 700 mW	- Operation, T: 20 to -190˚C - Power cycling at -190˚C, 15 min. on/20 min. off	- Device performed well - Device performed well through 10 applied cycles
CD4011 BC	Fairchild	CMOS 2-input NAND gate, 5-15V, TTL, 700 mW	- Operation, T: 20 to -190˚C - Power cycling at -190˚C, 15 min. on/20 min. off - Operation & cold-start, T: 297 to 10K	- Device performed well - Device performed well through 10 applied cycles - Device functioned well w/250 Ω load
CD4049 BC	Fairchild	CMOS Hex inverting buffer, 5-15V, DTL/TTL, 700 mW	- Operation, T: 20 to -190˚C - Power cycling at -190˚C, 15 min. on/20 min. off	- Device performed well - Device performed well through 10 applied cycles
CD4041UB	Texas Inst.	CMOS Buffer, 5-15V, TTL, 500mW	- Operation & cold-start, T: 297 to 10K	- Device functioned well
CD74HC04	Texas Inst.	CMOS Hex inverter, 2-6V, LSTTL	- Operation & cold-start, T: 297 to 10K	- Device functioned well

Table V. Components of drive circuit and test results.

Device	Manufacturer	Features	Tests	Comments
CD4041UB/ IRF630	Fairchild/ Int'l Rectifier	CMOS buffer controlling 2 MOSFETS with inductive loads	- Power cycling at -190˚C, 15 min. on/30 min. off	- Circuit performed well through 10 applied cycles

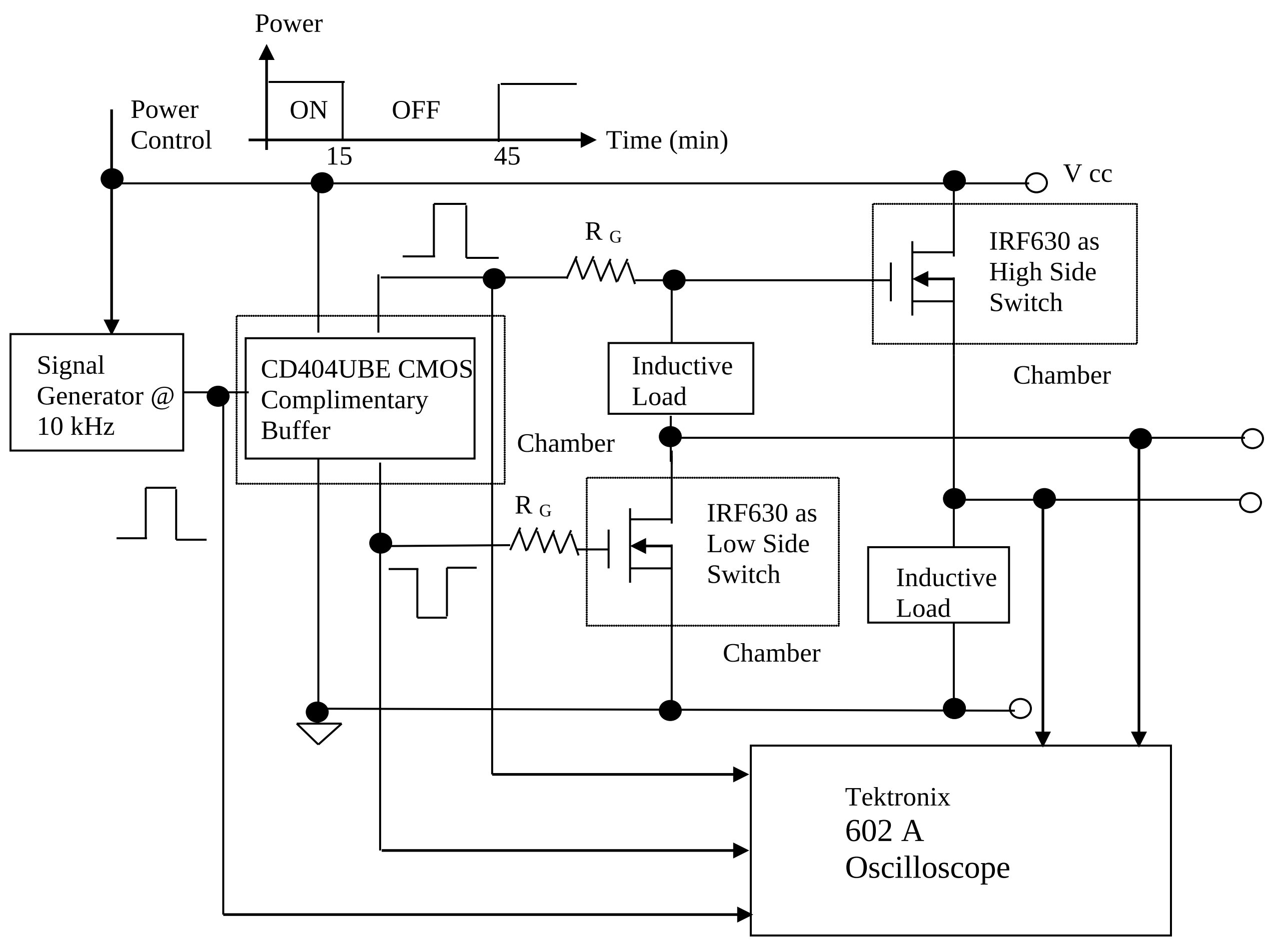

Figure 1 Schematic of the logic and switching circuit for testing high-side and low-side switching topologies.

Concluding Remarks

Electronic devices and circuits capable of operation in cryogenic environments are required in many space missions such as Next Generation Space Telescope (NGST), Mars Lander (MAR 07), and Galaxy Explorer (GALEX), to name a few. For example, stepper motors, which will be utilized to drive filter wheels for near-infra-red (NIR) cameras on the NGST mission, and their associated electronic circuitry will encounter operational temperatures as low as 30 K. A joint effort between the NASA Glenn Research Center and the NGST Program Office at NASA GSFC was established to look into the feasibility of development of a stepper motor controller for low temperature environments. Studies were performed in this work to address current state-of-the-art technology with regard to electronic components and circuit topologies that might contribute to meeting these requirements. An extensive search was performed on commercially available and recently developed devices and controller boards. A vast array of semiconductor transistors was evaluated, and a database on the effect of temperature on their switching characteristics was generated. Limited testing of logic devices was also performed at cryogenic temperatures. A simple but typical control circuit was constructed and evaluated at low temperature under power cycling. The preliminary results of this activity indicate that while some types of the transistors functioned properly under the extreme temperatures, others did not fare as well. CMOS-based logic gates and other integrated circuits looked promising for their good behavior at cryogenic temperatures. More comprehensive testing, however, is needed to fully characterize these devices and circuits under long-term electrical bias and thermal cycling so that reliability and efficiency can be established.

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Team Members

NASA Goddard Space Flight Center:

Dr. Mathew Jurotich, NASA GSFC, NGST Office.
Dr. Roger Stone, NASA GSFC, NGST Office.
Mr. Edward Divine, Swales, Inc., NASA GSFC.
Mr. Robert Meloy, QSS Group Inc, NASA GSFC.

NASA Glenn Research Center:

Mr. Richard Patterson, PI of this effort and Manager of Low Temperature Electronics Program, NASA Glenn Research Center.
Dr. John Dickman, NASA GRC.
Dr. Ahmad Hammoud, QSS Group, Inc., NASA GRC.
Dr. Malik Elbuluk, University of Akron, NASA GRC.
Mr. Scott Gerber, ZIN Technologies, Inc., NASA GRC.
Mr. William Levicky, Master's student, University of Toledo, NASA GRC.

Jet Propulsion Laboratory:

Dr. Charles Barnes, Manager of the NEPP Program.
Dr. Choon Lee.
Dr. Michael Newell.