REMOTE IMAGING SYSTEM ACQUISITION (RISA)

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ABSTRACT

NASA's Remote Imaging System Acquisition (RISA) project has the goal of producing a single robust and space-efficient imaging system. This paper will show the progress of the current RISA project iteration, tasked with implementing a Inter-Integrated Circuit (I^2C) communications controller on a radiation hardened Field Programmable Gate Array (FPGA), characterizing a liquid lens optical system, and adding a radiation hardened temperature sensor. The optical design focuses on small liquid lenses that can vary focal length with no moving parts. The chosen designs will allow this camera system to meet critical mission objectives and provide reliable service to NASA's astronauts.

KEY WORDS

RISA, liquid lens, FPGA, I^2C, temperature sensing

1 INTRODUCTION

The National Aeronautics and Space Administration's (NASA) mission statement is to "pioneer the future in space exploration, scientific discovery, and aeronautic research." NASA's goal to continue to lead the world in space exploration has resulted in numerous technological advances. The space shuttle program has enjoyed unprecedented success. However, the space shuttle has exceeded the original planned lifespan by lasting almost 30 years. To achieve future mission objectives NASA is currently developing the next generation spacecraft Orion. This spacecraft system is nearing the final stages of design and will replace the space shuttle which is scheduled for retirement in 2010. Starting in 2014 the Orion spacecraft is scheduled to dock with the International Space Station. Then in 2020 the Orion spacecraft is schedule to return astronauts back to the Moon, followed by a manned mission to Mars and beyond.

NASA's future manned space missions will require a single versatile imaging system which will be capable of fulfilling the requirements of many different mission objectives. A commercial camera system capable of meeting these requirements currently does not exist. To fill this void, the Remote Imaging System Acquisition (RISA) project began. NASA will need the RISA system to image the surface of Mars, the Moon and other celestial bodies. This system will be instrumental in monitoring the structural integrity of the spacecraft, assessing astronaut health and monitoring environmental conditions. The harsh space environment in which the camera system must operate injects very specific hardware constraints. The RISA imaging system requires a non-browning lens system and radiation hardened components in order to survive the extreme levels of radiation that exists outside the earth's protective magnetosphere.

The system under development needs to satisfy these requirements while conforming to strict space efficiency. The future Orion space vehicle will have significantly less storage space when compared to the current space shuttle. The limited space on the Orion vehicle will only allow space for a single imager. Thus, the RISA imaging system is deemed mission critical, level one.

The major design goals involve the work of three different disciplines: optical, electrical and computer. The optical objectives included the evaluation of a liquid lens system and its integration into the camera. The electrical design involves choosing a temperature sensor which is radiation hardened while having an I^2C output signal. The Phillips I^2C interface IC does not have a radiation hardened equivalent. Thus the I^2C chip will need to be removed and its functionality transferred into the Field Programmable Gate Array (FPGA) which is fully radiation hardened using VHDL software programming language.

2 METHODOLOGIES

2.1 LIQUID LENS EVALUATION

The iterative objectives for the optical design of the RISA camera focused on the characterization and analysis of the Varioptic Arctic 314 liquid lens. The unique attribute of these lenses is their ability to vary focal length by simply changing the applied voltage with no moving parts, simplifying the design for a compact variable focus system. The clear aperture of the lens is only 2.5 mm and it consists of three materials: thin glass for the first and last surfaces, an oil based liquid and a water based liquid. As the voltage changes to the liquid lens the radius of curvature of the intermediary surface between liquids also changes, adjusting the optical power for the device.

Preliminary testing was done in the Code V optical modeling software to determine the suitability of these lenses in the optical design. In order to have a close representation of the actual liquid lens, a detailed understanding of the mechanical layout and material properties was necessary, including material thicknesses, aperture diameters, indexes of refraction at specified wavelengths for the liquids in the lens, and radii of curvature for certain applied voltages. This was provided by the manufacturer’s data sheets for the optic.

The most important piece of information for modeling the device was the dispersive properties, since the trend of liquids does not follow that of typical glasses. Initially an approximated glass code was used to define the dispersive properties but this was unsuccessful. Importing specific indices of refraction corresponding to wavelength was necessary to remedy this. The data regarding the index of refraction for the liquids in the lens was provided in a table for 7 different wavelengths, at 20 degrees Celsius. Our model did not take into account any thermal effects and all analyses were performed at this temperature. It should be noted that liquids have a large response to temperature change and will need to be considered eventually. The following is a small schematic from Code V, displaying the liquid lens. The curved surface is the intermediary between the two liquids.

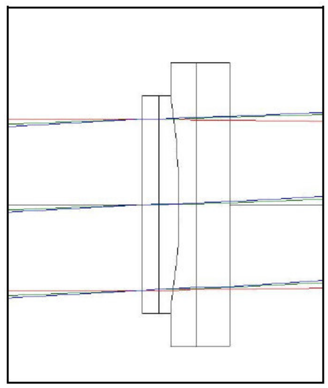

Figure 1. 3D Liquid Lens Model

The two outermost materials are the same Schott glass, D263T, while the liquids within are referenced as PC239 and H185B.

Our model was made for an moderate 50 V setting, which induces a radius of 9.72 mm for surface 3 and a PC239 material thickness of 0.25mm. The model calculates an effective focal length of 107.8292mm and is F/43.13. This is very close to the provided data, which estimated a focal length of ~112mm at this voltage. This supports the validity of our model for the liquid lens.

The following figures represent a portion of the Code V analysis for wavelengths varying from approximately 400 to 700 nm. The weighting of the wavelengths was photopic, to closely match the responsivity of the sensor. As observed in both the ray fan diagram Figure 2 and the spot diagram Figure 3, the primary aberration in the system is chromatic. This is shown as defocus for the various wavelengths in the ray fan (tilted rays) and varying spot size in the spot diagram. The spot sizes are roughly 39 microns RMS (diameter). The system also has approximately 10 mm of longitudinal chromatic aberration at this focal length.

The findings from this performance analysis were very helpful in determining the viability of our design choice. These lenses do not generate enough optical power and have too much chromatic aberration to implement them as a stand-alone imaging device. This analysis and the data on the Varioptic website show that the lenses need to be used in combination with another objective lens where the true benefit would be creating a variable focus system, easily controlled by voltage.

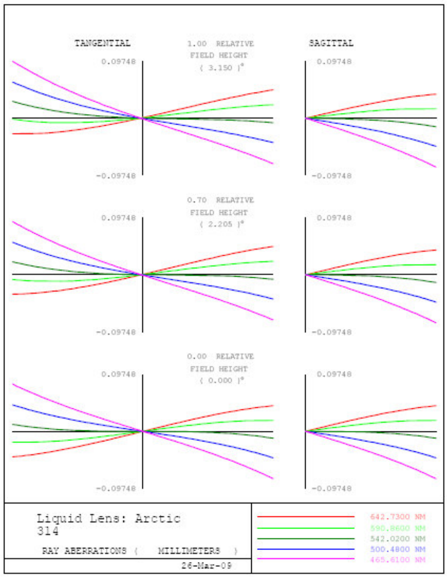

Figure 2. Fan Diagram

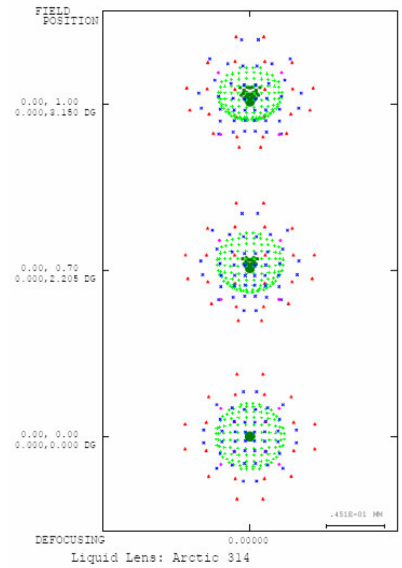

Figure 3. Spot Diagram

A compact system lens system was created using an off the shelf lens. The lens chosen was the Edmund Optics 12.5mm focal length megapixel finite conjugate micro video lens, part number NT58-205. To create a model of the lens system the original liquid lens Code V design is put in combination with the Edmund Optics micro-imaging lens and we were able to conduct testing of the entire variable focus system and evaluate performance.

The objective of the optical testing is to test the Contrast Transfer Function (CTF) and aberrations of the VPS-048 liquid lenses from Varioptic as illumination levels are varied and compare to a Double Gauss lens. The first lens tested was the Edmund Optics Double Gauss lens. The Figure 4 shows the CTF of the image.

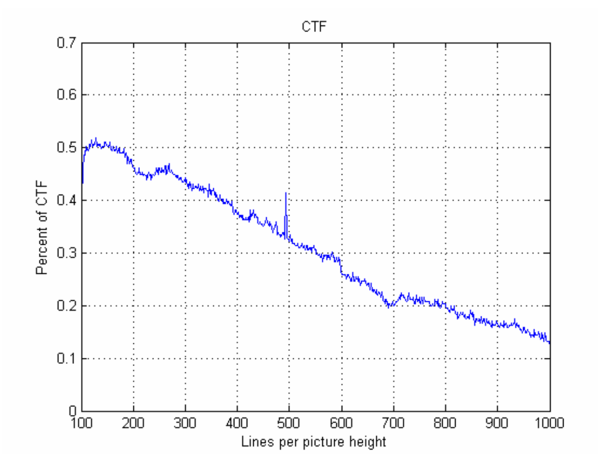

Figure 4. CTF of the double Gauss lens

It can be seen that the CTF is very good for the Edmund Optics double gauss lens. The ideal graph for CTF would have a straight line from the maximum contrast to the point where the contrast of the lines per picture height was zero. Next, the lens system containing the micro-imaging and liquid lens was tested in the same fashion. The MATLAB code was run and the CTF is shown in Figure 5. The CTF of the micro-imaging and liquid lens system is very similar to that of the double Gauss lens. The differences are that the percent of CTF at 1000 lines per picture height of the double Gauss is about 0.13 while the percent of CTF at the same point for the micro-imaging and liquid lens system is about 0.1. The double Gauss lens also is much more linear and this is closer to the ideal CTF. Overall, this test shows that the liquid lens does not introduce significant aberrations when it is used in combination with another lens and it will not degrade the image quality.

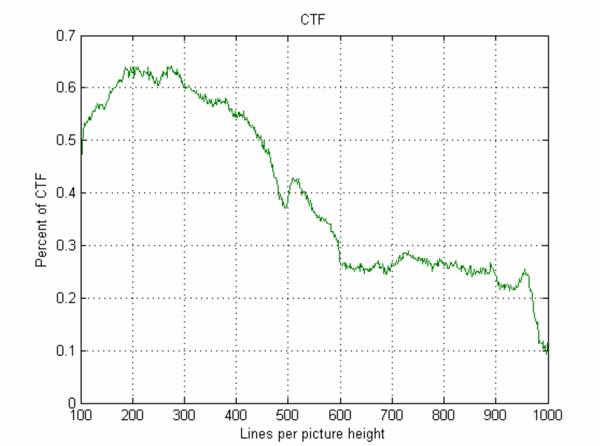

Figure 5. CTF of the micro-imaging and liquid lens system

Longitudinal chromatic aberration was also tested using wavelengths 436nm, 550nm, and 656nm which corresponded to blue, green, and red respectively. The test was done with the liquid lens power supply at 50V because this is how we simulated the lens in Code V. In Code V we calculated the longitudinal chromatic aberration to be about 10mm. The average of our tested values is 14.3mm. This is a little higher than the simulated value. However, this still shows that there is significant longitudinal chromatic aberration and that the liquid lenses cannot be used as the single lens in a system. This data also helps us consider our Code V model of the liquid lens as accurate.

Finally, the distortion test was completed using a MATLAB program which used 15 pictures of a checkerboard pattern to calculate distortion. The distortion results are shown below:

$$\text{Distortion \%} = -0.04173\%$$
$$\text{Radial distortion} = 0.54586$$
$$\text{Tangential Distortion} = \begin{pmatrix} 0.03374 \\ 0.05452 \end{pmatrix}$$

The low amount of distortion again helps to prove that the liquid lens can be used with another lens and it will not reduce image quality.

2.2 TEMPERATURE SENSING

NASA is continually interested in knowing as much as possible about the environment that they are exploring. This is to ensure mission success, safety of the astronauts, and instrumentation life span. This specific iteration of the RISA camera NASA was interested with adding the ability of monitoring the ambient temperature that the camera was in as well as the temperature inside of the camera. There were three designs that were considered for this task. The design requirements for the temperature sensor were that it could record temperatures in the range or -55°C to 125°C. Also, the temperature sensor will have to meet MIL-PRF-38535 for Class V radiation hardness.

Three temperature sensors were considered for this application: TMP100, LM75, and AD590S. A table was created based on weight of importance for the requirement as well as a weight of how well the part meets each requirement. Based on the design requirements the TMP100 was determined to meet all of NASA's needs.

To read and report the temperature NASA requires MATLAB as an interface. The MATLAB code had to be very specific for this temperature sensor. The MATLAB code performs all of the I^2C communications to the camera and its peripherals. Also, MATLAB performed the task of configuring the TMP100 for the specific task that operator requests, converting the temperature hexadecimal value to an understandable decimal value, and report the real time temperatures in a plot for visual reference.

Temperature testing was conducted in a partially controlled environment. Dry ice was used to decrease the temperature and a heat gun was used to increase the temperature. During the testing it was concluded that the TMP100 was a suitable device. The temperature sensor was able to read temperatures accurately at temperatures below -60°C. There was a temperature sensors ability to report temperature ended at 128°C. This inability to report temperatures above 128°C was related to the available hexadecimal values that the sensor utilized. By default the sensor reports temperature using three hexadecimal values or sixteen bits of data. Also, to report negative temperature values the temperature sensor implements 2's complement for the binary representation of the temperature.

2.3 INTER-INTEGRATED CIRCUIT (I^2C)

The previous iteration of the NASA RISA imager utilized a Philips I^2C integrated circuit controller. The Phillips chip is operated through the ground side MATLAB software and acts as the I^2C master device. The I^2C master is the virtual police officer directing communications traffic of all the peripherals on the camera. For wiring simplicity, the imager's optical CMOS sensor, temperature sensor communicate with the ground side MATLAB software on a single 1-bit data line. Thus, only one device may use this "highway" at a time and others must wait until they are told by the master that it is safe to go. The Phillips I^2C controller does this in one prepackaged integrated circuit. However, this integrated circuit is not available in a radiation hardened or tolerant equivalent package and due to the harsh space environment that the camera must be able to withstand, NASA determined that the proper course of action is to remove the chip entirely.

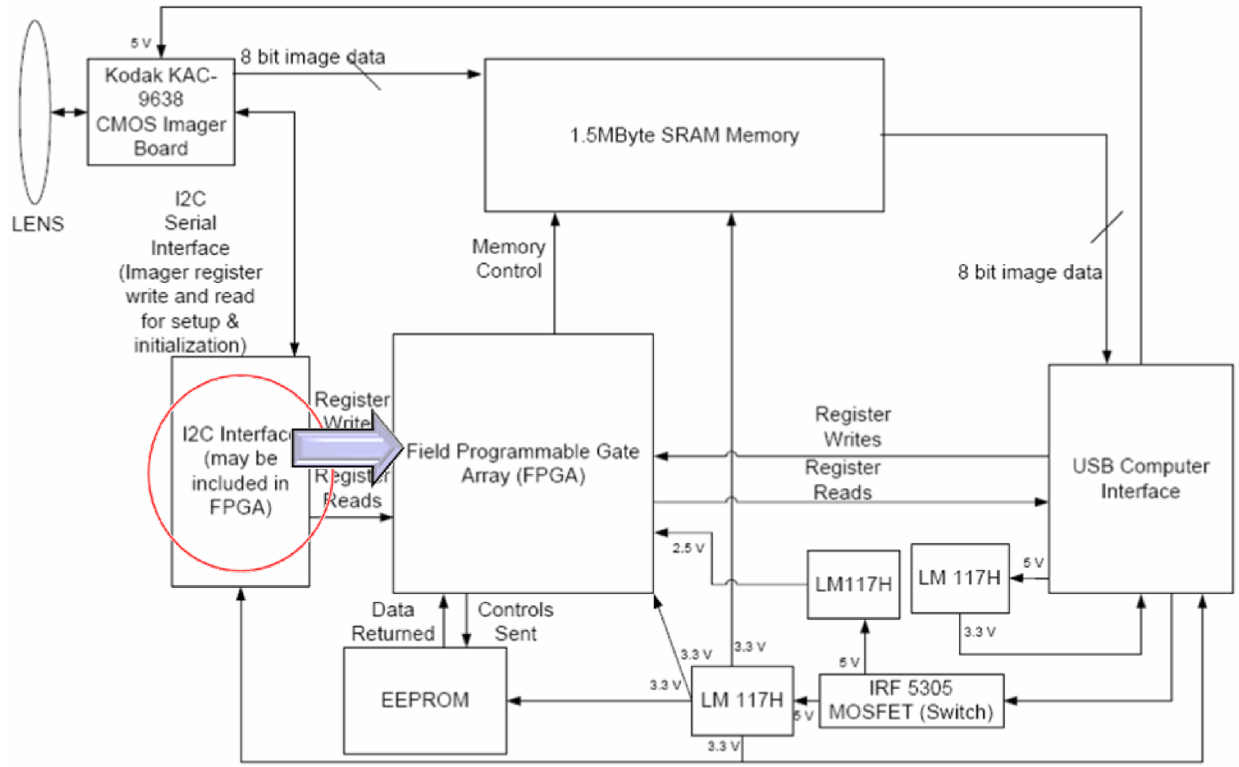

Figure 6. Circuit Layout of the Previous Iteration RISA imager. The I^2C controller circled in red is to be integrated into the FPGA as synthesized VHDL.

The I^2C functionality that this chip provides is an integral component to the workings of the entire camera. Substitute communications architecture could not be realized without significant redesign of the entire camera. Therefore the design choice is to replicate the Phillips master controller functionality in the hardware design language VHDL. Because the Phillip's I^2C standard is a widely used de facto standard, there exists intellectual property cores—hereto referred to as IP cores—that perform the master control that the RISA imager needs. An IP core is a previously written hardware description software module that provides a well defined logical operation. IP cores have been developed for many different tasks and for reuse in many different projects, and are independently verified by their users to perform their operation as advertised. Therefore, an IP core provides a specific operation, such as I^2C master control, that is reliable for its portion of the overall system.

In the selection of the best IP core to use with the RISA system, considerations and requirements had to be properly met. Firstly, the I^2C Master Controller IP core selected must be written in VHDL. The reason for this is to maintain consistency with the rest of the system which is also written in VHDL, and to conform to the 1984 Military Standard 454, which mandates the supply of a comprehensive VHDL description with every ASIC delivered to the Department of Defense, of which NASA is a contractor to. The IP core also had to be an open core, meaning it was freely available without any licensing fees. The IP core had to exactly conform to the Phillips I^2C communications standard for master control of the I^2C communications bus. Finally, the IP core had to provide a method of handshaking or status reporting in order to keep the parent MATLAB code in sync with the VHDL state machines at all times.

The selected I^2C IP core was found free for use at [1]. This Simple_I^2C master controller provides byte-level data transfer through the use of Start, Stop, Read, Write, Acknowledge and nReset control signals, while supporting handshaking with the MATLAB ground software by reporting the I^2C slave acknowledge condition after successful writes to the slave. The control signals required by the Simple_I^2C master controller are included in the third byte of the four byte frame that the RISA imager uses as the imager control and data transfers. The existing MATLAB ground software already followed this convention and therefore only slight modification was needed in the transition to the new IP core. Therefore, the Simple_I^2C master controller was selected as the IP core of choice for meeting the functional requirement of complete radiation hardness for all electrical components.

In implementing the I^2C IP core VHDL alongside the existing RISA VHDL, the RISA state machine was modified to add wait states to ensure proper timing as well as generate the proper control signals for the I^2C IP core. A status register was added to store the handshaking signals produced by the I^2C slave device and the Simple_I^2C IP core.

2.3.1 INTER-INTEGRATED CIRCUIT (I^2C) TESTING

To verify the operation of the camera had not been compromised in any way, Xilinx 8.2i simulation software was used to behaviorally test the VHDL, ensuring correct logical operation. A test bench was written that generates the proper stimuli to the described hardware so the resulting behavior can be analyzed. Specifically, a test bench was written for the Simple_I^2C IP core to ensure proper operation. This test bench verified the correct control of the SCL clock and SDA data lines of the I^2C bus by the Simple_I^2C IP core. Once the VHDL was behaviorally verified, it was synthesized by the Xilinx software for programming on the Virtex FPGA.

Hardware modifications to the wire-wrapped circuit board were made before final operational testing of the IP core could commence. The serial data (SDA) and serial clock (SCL) lines of the previous design were controlled by the Phillips I^2C Master Controller IC and therefore were not connected to any of the pins on the FPGA. The connection locations between the FPGA and the existing SCL and SDA lines had to be decided upon and implemented. Xilinx was allowed to pick the pins it deemed best for the SDA and SCL lines, while all other lines were kept locked down. This ensured that the minimum area circuit on the FPGA was found by the Xilinx placement and routing algorithms. If we had specified the closest pins to where we needed to route our wires, for example, this may have added additional area and routing to the resulting circuit on the FPGA, taking up more area in the FPGA and yielding a less optimum design. Once Xilinx picked the most optimum pins, they were locked down in the VHDL and wire-wrapped connections were made between the physical pins and the SDA and SCL lines.

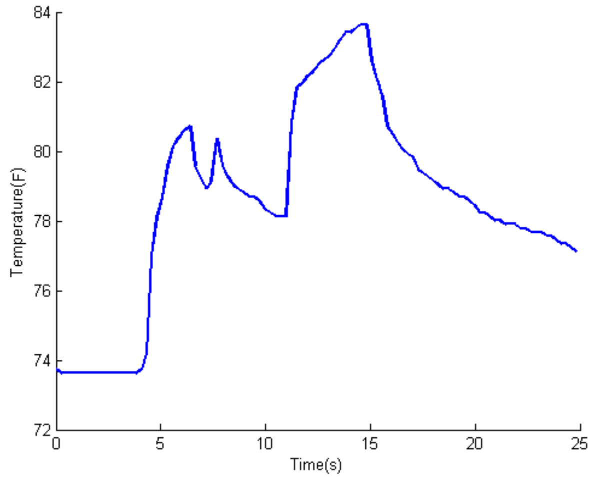

Figure 7. Real-Time Temperature Plot using the Simple_I^{2}C IP Core for Communication with the TMP100 Temperature Sensor

Initial real-world testing was at first unsuccessful, and it was found that the timing of writing to the DLP-USB245M FIFO was not in sync to the availability of the data in flip flops on the FPGA. The I^{2}C state machine had to be modified to include extra delay states to ensure the data was available during the proper time that the FIFO requested it. Once this modification was made it was possible to read successfully from the I^{2}C status register residing on the FPGA through the DLP-USB245M using MATLAB to issue the 4-byte command frames. This status register was used as a testing aid, as bits were assigned within the 8-bit register to be any internal signal that we would like to monitor. The innovation of using the I^{2}C status register as a window to view internal signals eased seeing what states we were currently in and what the value of specific internal signals were at crucial times.

The RISA system is therefore able to perform any I^{2}C communication with any I^{2}C capable slave device. This is demonstrated in the successful repeated polling of the TMP100 temperature sensor that was also added to the design. In Figure 7, positive slopes were caused by either blowing on or touching the TMP100 temperature sensor. Negative slopes were caused by blowing cool air on the TMP100 temperature sensor or letting ambient cooling take place. Room temperature at the time of testing was just less than 74 degrees Fahrenheit. The I^{2}C procedures needed to produce this plot are: send a start condition with TMP100 address, write the configuration register address into the TMP100 pointer register, write the configuration byte into the TMP100 configuration register, write the temperature register address into the TMP100 pointer register, and read a high byte and a low byte from which each temperature reading is calculated in the MATLAB ground software. This proves that any slave may be contacted on the I^{2}C bus and can be both read from and written to. The final product is a totally radiation hardened circuit board, acceptable for use in the space environment.

3 CONCLUSION

Overall, it was discovered that the Varioptic liquid lenses were not a viable solution for a lens system when they are used as a stand-alone objective. This is due to the fact that there are significant aberrations in the system as well as an extremely large focal ratio yielding very light on the image plane. However, when this lens is in combination with another lens it has been shown and tested that the image quality does not decrease significantly. The liquid lenses also provide the unique ability to be able to create a variable focus system without any moving parts in the system. The liquid lenses are very beneficial and are a viable component in a lens system, especially due to their small size for this particular application.

The software portion of the RISA imager comprises all VHDL code used to program the FPGA and all MATLAB code used to interface to the TMP100 temperature sensor. The newly modified VHDL has been shown to successfully interface with the TMP100 in providing a continuous real-time temperature reading across the I^2C bus. This successful communication is accomplished with the previously used Phillips I^2C IC physically removed from the system, which shows that the RISA system is fully operational while boasting 100% radiation hardened electrical components. The VHDL state machines that operate other RISA imager functionality were unaffected by the new additions to the VHDL and operate as before. New MATLAB code was written that outlines the new required 4-byte frame read and write format for I^2C transfers and successfully sends the commands required by the new Simple_I^2C IP core to interface with the TMP100 temperature sensor.

4 ACKNOWLEDGEMENTS

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