NASA REMOTE IMAGING SYSTEM ACQUISITION (RISA) MULTISPECTRAL IMAGER DEVELOPMENT UPDATES

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ABSTRACT

The NASA Remote Imaging System Acquisition (RISA) project is a prototype camera intended to be used by future NASA astronauts. NASA has commissioned the development of this engineering camera to support new mission objectives and perform multiple functions. These objectives require the final prototype to be radiation hardened, multispectral, completely wireless in data transmission and communication, and take high quality still images. This year's team was able to successfully develop an optical system that uses a liquid lens element for focus adjustment. The electrical system uses an Overo Fire computer-on-module (COM) developed by Gumstix. The OMAP processor onboard handles all communication with a monochromatic CMOS sensor, liquid lens control circuitry, pixel data acquisition and processing, and wireless communication with a host computer.

Keywords: NASA, multispectral, liquid lens, computer-on-module, IEEE 802.11.

1. INTRODUCTION

The NASA RISA project is a prototype camera intended to be used for planetary surface exploration and onboard NASA space vehicles. Due to new mission requirements associated with future space vehicles, less physical volume is available for cargo compared to the Space Shuttle. As a result, NASA has commissioned the development of a general-use camera, able to perform multiple functions and support new mission objectives. These objectives require the final prototype to be radiation hardened, multispectral, completely wireless, and take both high quality video and still images. The 2011/2012 RISA Team at the University of Arizona focused on many of the key requirements related to each subsystem, but did not intend to create the final camera system. Instead, the team built on work completed by previous teams and improved upon these designs to create a camera with an improved optical and electrical design. The mechanical structure has also been redesigned to accommodate the changes in the optical and electrical design.

2. SYSTEM REQUIREMENTS

The project was broken up into three distinct subsystems: optical, electrical, and mechanical. Requirements were written for each subsystem and are listed in Table 1. In general, requirements focus on optical design criteria, electrical system performance, and mechanical interfaces.

Table 1. *Key System Requirements.*

#	Requirement Description	Priority
1	The camera system shall have zero moving components.	Must
2	The camera shall meet all optical performance requirements for a minimum of two years in the harsh space environment.	Desired
3	The optical system shall operate within a spectral range of 400 nm to 1100 nm.	Must
4	Optical distortion shall be less than 1% from linear for the assembled system.	Must
5	The optical design shall include the use of a removable VariSpec electrically tunable multispectral filter (VIS-10-HC-20).	Desired
6	The system shall be capable of displaying still imagery and video at 0.5 frames per second minimum on an external computer (5 fps desired).	Must
7	The system shall communicate wirelessly to an external computer within a 100 m radius (200 m desired).	Must
8	All electronics shall have the option to communicate with an external computer via USB interchangeably with the wireless system.	Must
9	The liquid lens shall have complete onboard I^2C control.	Must
10	The camera shall be built to interface with multiple optical instruments through a C-mount.	Must
11	Liquid lens control wires shall be internal.	Desired

3. RISA HARDWARE DESIGN OVERVIEW

3.1 HIGH LEVEL DESIGN

Within the optical, electrical, and mechanical subsystems, there are a variety of key components, as outlined in Figure 1. For the optical system, one custom lens design has been implemented using common glasses with radiation-hardened equivalents. For this design, a liquid lens is used for focus adjustment. The selected lens design accommodates an electrically-tunable filter with a 15° full field of view (FFOV). The electrical subsystem is designed using a Gumstix Overo Fire board to interface with a Micron-sensor CMOS/FPGA board, henceforth referred to as the "SC2M8". The Gumstix board is able to relay image data from the camera via Wi-Fi or USB in addition to providing power for liquid lens control. Software has been written to control the Gumstix COM and allow it to interface with the SC2M8 and other elements.

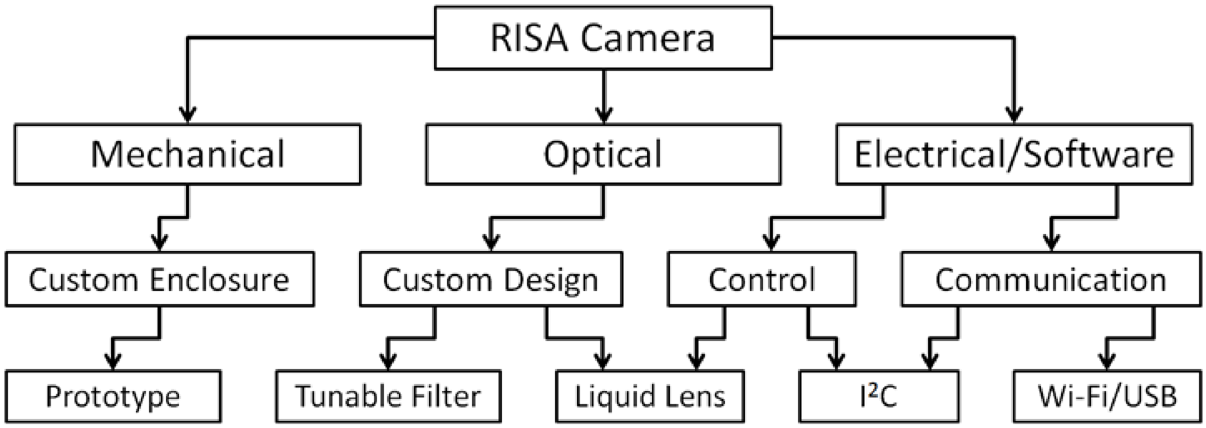

Figure 1. *RISA Camera High Level Design Subsystems.*

The mechanical system is built to hold the optical and electrical components. The camera enclosure was machined from 6061-T6 aluminum and has a Type III hard anodized coating. The lens barrel was also machined out of 6061-T6 aluminum and black anodized (Type II). The lens barrel required very tight tolerances to keep the optical elements in place. The electronic boards have been mounted on stand-offs and placed within the enclosure for protection.

3.2 OPTICAL SUBSYSTEM DESIGN

The optical design for this year's RISA prototype was designed using several known parameters. First, an electrically tunable filter was expected to be used with this optical system. The tunable filter used in this design is made by CRi and is a VariSpec VIS-10-HC-20[1]. This filter is unique in that it can create a very narrow band pass filter (about 10 nm) through the entire range of 400 nm - 720 nm. The clear aperture of the filter is 20 mm and it has a total optical path length of about 50 mm. The acceptance angle of the filter limits the possible full field of view to 15°. The use of a Varioptic ARCTIC 314 liquid lens for focus adjustment was also expected to be used in this design. Using these known parameters, a design baseline was established, leading to the finalized optical design which is pictured in Figure 2.

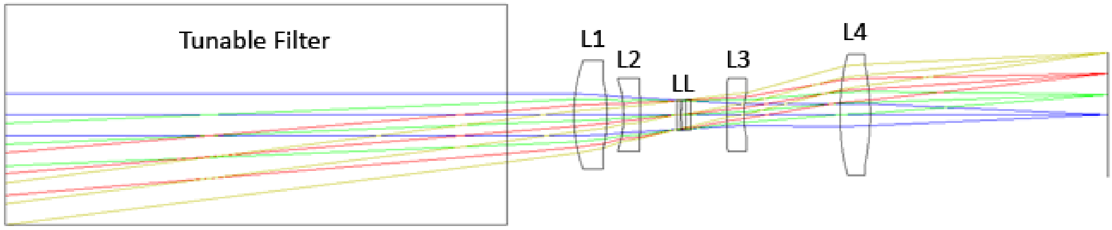

Figure 2. *2011/2012 RISA Optical Design.*

This optical design was developed while looking at the possibility of using off the shelf lenses in combination with custom elements. As a result, lens 4 (L4) is an off-the-shelf element from Edmund Optics. Unfortunately, the tolerances on the other elements were too tight, preventing off-the-shelf elements from being used. Since the liquid lens is used for focus adjustment, it is placed in the design as the system's aperture stop. In the liquid lens' default position (no voltage applied), the lens design is setup to focus slightly beyond infinity. Applying a voltage to the liquid lens (up to 60 V_{rms}) will allow the optical power to positively increase, allowing focus from infinity to about 10 cm in front of the camera to be achieved. One desired requirement for the optical system involved radiation-hardening the optical components. Early development looked at the options and decided against it due to the long lead time for radiation-hardened glass. However, the final design did use the common equivalents for radiation hardened glasses.

3.3 ELECTRICAL SUBSYSTEM DESIGN

The electrical subsystem for the RISA camera is required to have wireless communication with a host computer, USB communication with the SC2M8, I^2C communication with the liquid lens controller, and an optional USB connection directly between the CMOS sensor board and the host computer. Figure 3 illustrates these design requirements.

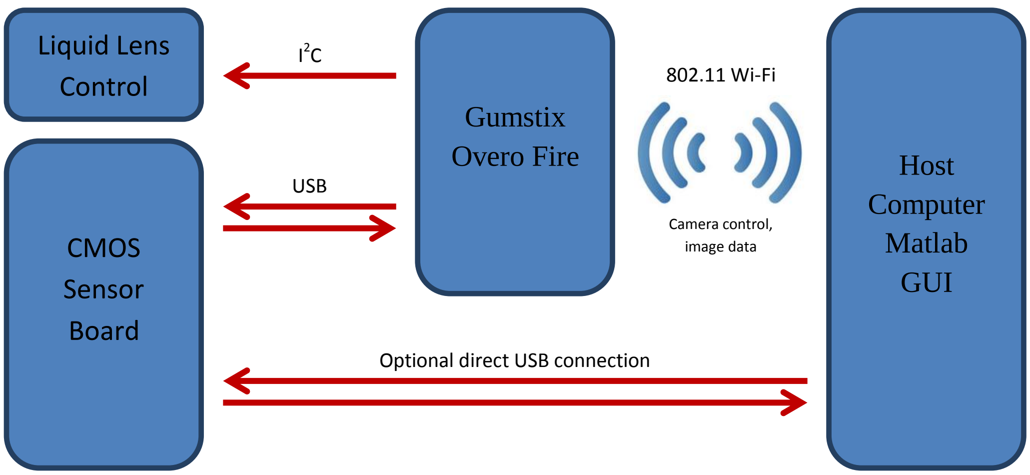

Figure 3. *Electrical System Block Diagram.*

Wireless communication between the SC2M8 and a host computer is done using the Gumstix Overo Fire computer-on-module (COM). Electronic control of the liquid lens is handled by the DriveBoard60 liquid lens control board by Varioptic. This board acts as a slave device on one of the Overo Fire's I^2C busses. The CMOS sensor board includes a USB/serial converter allowing it to connect to a USB host port on the Overo Fire where it communicates as a serial device. Inside the RISA imager the circuit boards are organized into the "Electronics Stack," shown in Figure 4. The top layer of the stack houses the Overo Fire COM mounted to the Gumstix Tobi breakout board. The middle layer is the I^2C bus where all devices on the I^2C bus are mounted. Signals from the Overo Fire come in to the 4 pin connector on the left side of the board. The lowest layer of the stack is the power regulation circuitry. This aspect of the system was not a required aspect of this year's project, but it was included for future development.

The RISA team was supplied with a CMOS sensor and accompanying circuitry that had been previously developed for use on the RISA camera. This module is called the SC2M8. The SC2M8 contains a Micron MT9M001 CMOS sensor, memory modules, serial/USB adapter, and an FPGA to facilitate communication between these components.

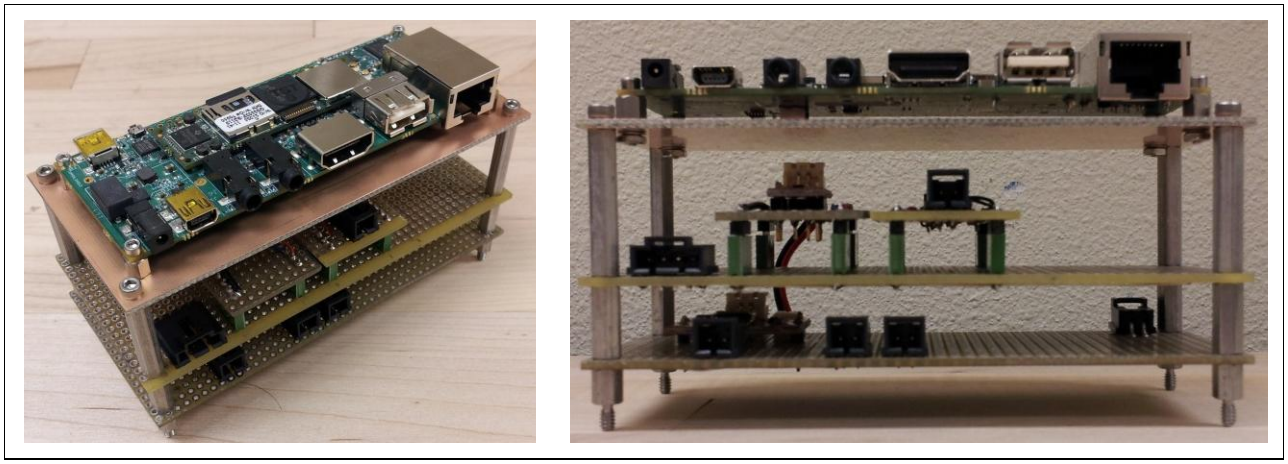

Figure 4. *Electronics Stack for the RISA Camera.*

The Overo Fire, produced by Gumstix, is a computer-on-module designed around the Texas Instruments OMAP3530 processor[2]. It includes a Wi-Fi module, power regulation chip, and connectors to access the capabilities of the OMAP3530. The Overo Fire module is mounted to a Tobi breakout board (also produced by Gumsix) that gives easy access to USB, a serial console port, and I^2C. The OMAP3530 is an extremely powerful processor that can be programmed to run a variety of embedded operating systems, including Angstrom, Android, Windows CE, or any other custom build of Linux designed for use with that processor. The RISA imager employs an Angstrom console image prebuilt by Gumstix for use with their products. The key components of this operating system that the RISA imager uses are Wi-Fi for communication with the host computer, drivers for the FTDI USB/serial module on the SC2M8, and kernel drivers for easy access to the I^2C bus.

Adjusting the focus on the embedded liquid lens requires applying an AC signal to the edge of the liquid lens. Varioptic makes a small circuit board called the DriveBoard60 that reads digital input over I^2C and adjusts the AC signal applied to the lens. There are two main components on the DriveBoard60: a digital-to-analog converter (DAC) and a liquid lens driver IC. The DAC is the LTC1663 and can output a voltage between 0 and 2.5V based on a digital input on the I^2C bus. The liquid lens driver IC is the DLL3A made by the Durel Division of the Rogers Corporation. This IC takes the analog output from the DAC and boosts it to a high voltage AC signal that shapes the liquid lens for focus adjustment. This output can range from around 13 V_{AC} to around 72 V_{AC}. Thus, a digital input to the DAC will result in an adjustable signal output to the liquid lens. Programs written in C running on the Overo Fire communicate with the I^2C bus and allow the user to change the liquid lens curvature.

The I^2C protocol dictates the use of 2 wires for data transfer: serial clock (SCL) and serial data (SDA). These two wires, along with ground (GND) and a +5V rail are all accessible on a header on the Tobi. Wires were soldered to the header pins corresponding to these signals, which terminate in a 4-pin connector that plugs in to the I^2C layer of the electronics stack. The I^2C communication protocol dictates that each device on the bus has an individual address. Programs communicating with a certain device on the bus must first transmit the address of the desired device before reading/writing data. This procedure simplifies wiring because all devices can be located on the same bus. For the RISA electronics, the only device on the bus is the

DriveBoard60 liquid lens controller, but the hardware architecture is easily scalable if other I^2C devices are to be included in future designs. There is extra space on the I^2C layer of the electronics stack that could accommodate additional devices.

Since the liquid lens is buried inside the lens barrel, a method had to be devised to get the control signal to it. The team chose to use a flex cable sold by Varioptic that sandwiched the lens between two circular traces on a flexible printed circuit. The wires are routed away from the lens, through a plastic sleeve and terminate at a pair of concentric copper rings around the C mount. A pair of spring contacts mounted to the enclosure press against the copper rings as the lens barrel is screwed on. Figure 5 shows the concentric copper rings on the lens barrel and the corresponding spring contacts on the enclosure. These spring contacts are embedded to prevent shorting from any other C-mount lens that may be attached.

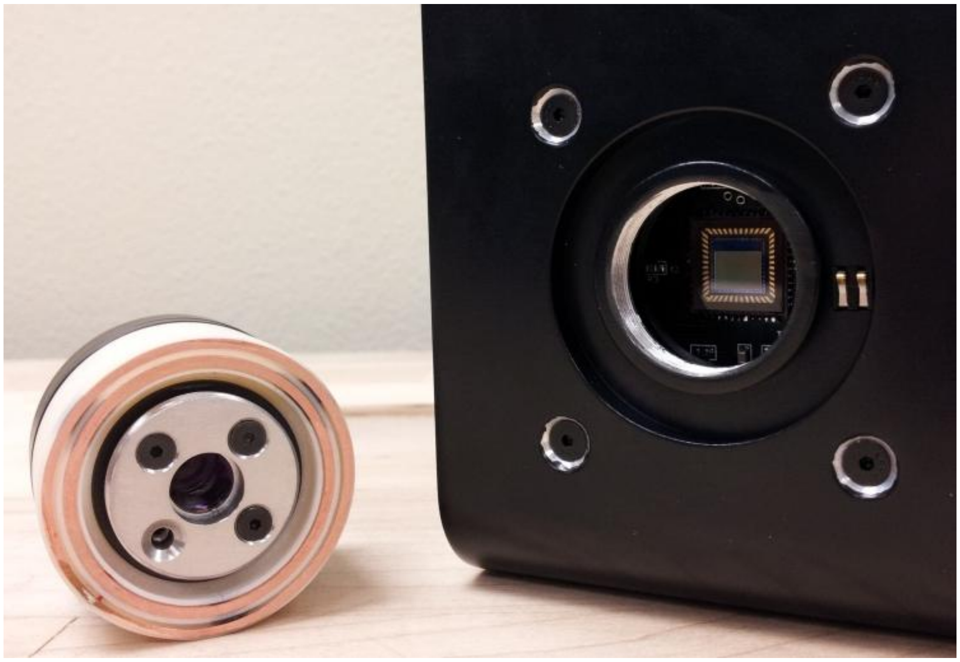

Figure 5. *Lens Barrel and Enclosure Showing Liquid Lens Electrical Contact Points.*

The output of the DriveBoard60 is connected to the spring contacts inside the enclosure. Once the lens barrel is attached to the enclosure, the copper rings press against the spring contacts causing the liquid lens to be electrically connected to the DriveBoard60. This configuration allows full focus control for the optical system.

3.4 MECHANICAL SUBSYSTEM DESIGN

The camera enclosure was machined out of aluminum and provided the interfaces for the electrical and optical subsystem. The lens barrel assembly (pictured in Figure 6) is composed of two aluminum lens barrel components (A, B), front and rear stainless steel threads (C, D), aluminum retainer rings (R1, R2), a plastic sleeve (E), and steel fasteners. Adhesive was used in place of retainer rings for some of the lenses due to space and tolerance limitations. All aluminum components were black anodized. Figure 7 shows the assembled camera system with the custom enclosure and lens barrel assembly.

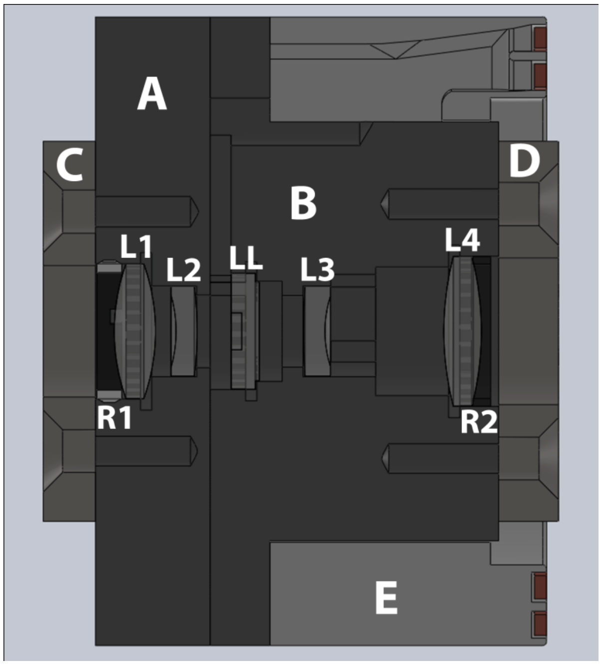

Figure 6. *Lens Barrel Annotated Design.*

Figure 7. *Integrated RISA Camera with Anodized Enclosure.*

4. SOFTWARE DEVELOPMENT

To provide the user with a relatively simple interface with the RISA camera, a MATLAB GUI was created. The MATLAB GUI allows the user to connect with the RISA imager, control camera functions like setting the exposure and changing lens focus, and acquire images.

The MATLAB GUI uses four different programs on the Overo Fire to interact with the camera. The first program is *SC2M8_set_registers*. In this program, the user can set the exposure setting, where "exposure" is an integer between 0 and 16383 (0 to 3FFF) that sets the integration time register on the MT9M001. This value corresponds to an actual exposure time between 0 and around 1.7 seconds. This program looks for a device called "ttyUSB0" in the /dev directory and connects to it. The "ttyUSB0" device represents the SC2M8 attached to the USB port on the Tobi breakout board. The program then communicates with the SC2M8 to set registers.

The second program is *SC2M8_get_image_png* which connects to the SC2M8, reads an image, compress it to a PNG file, and saves it to the Overo Fire memory as an iterative filename.

The third program is *driveboard60_send_value* which is used to set the liquid lens voltage using an integer value between 0 and 1023. This program connects to the I^2C bus on the Overo Fire that the DriveBoard60 is connected to and writes a series of data bytes. The Gumstix Overo Fire kernel used includes drivers for the I^2C busses on the OMAP3530. These devices show up in the /dev directory as /dev/i2c-1 and /dev/i2c-3. I2c-2 is reserved for internal components. The DriveBoard60 is connected to i2c-3, which can be opened in the kernel like a serial device which can then be written to and read from using the read() and write() functions.

The last main program used is *read_fuel_gauge* which communicates with the Sparkfun LiPo Fuel Gauge to read the voltage and state of charge of the battery. The final design didn't end up using a battery for power, but it was tested using various setups that did use the battery. When the battery voltage is attached to the LiPo Fuel Gauge, the program will return a measured battery voltage, and a state of charge given as a percent calculated based on a proprietary formula built into the chip.

The programs on the Overo Fire were written in C and compiled for the ARM architecture using a Gnome development desktop image on a second Overo Fire COM[3]. By connecting a mouse, keyboard, and monitor to the Tobi breakout board, the Geany editor can be used for native programming. This process allows files to be compiled directly on the Overo Fire with gcc, also letting the user test to see if it works before copying it over to the Overo Fire module in the camera. One of the programs uses PNG compression algorithms, so it was important to make sure the PNG library was installed on the Overo Fire before compiling. Another option is to cross compile them from a different architecture and then copy them over, but this process was found to be more difficult than compiling them natively using the Gnome development image.

The RISA imager is configured to automatically connect to a Wi-Fi network with a static IP address. This task was accomplished by modifying the file /etc/network/interfaces on the Overo Fire COM. This file is automatically read on boot to configure network connections.

5. SYSTEM LEVEL TESTING

The Mars Desert Research Station (MDRS) is a simulated Martian habitat run by the Mars Society near Hanksville, Utah[4]. Crews of six individuals visit MDRS for two week rotations where they perform engineering or scientific research, all while simulating living on Mars. Given the future expected use of the RISA camera, the team felt that MDRS would be an ideal location to perform system level performance testing. The five individuals on the 2012 RISA team lived at the research station for two weeks in April 2012 serving on Crew 117. At the research station (pictured in Figure 8) the crew is able to use a two-story 8 m diameter habitat, a greenhouse, and a small observatory. ATVs are provided for Extra-Vehicular Activities (EVAs).

Figure 8. *Mars Desert Research Station.*

The RISA team established five project goals that would be worked on while the team was at MDRS. These goals included: multispectral imaging using the VariSpec electrically tunable filter, geological identification of unique features at MDRS, atmospheric water vapor monitoring, greenhouse plant health monitoring, and general system level functionality tests.

Healthy plants have large amounts of chlorophyll which is a strong absorber of blue and red wavelengths. However, chlorophyll is a poor-absorber of green and near infrared (NIR) light. More specifically, at NIR wavelengths, healthy plants with large quantities of chlorophyll will appear very bright because of the reflected NIR light while unhealthy plants will look dark. This phenomenon is pictured in Figure 9 using the RISA camera.

Figure 9. *NIR (left) and Visible (right) Pictures of Plants .*

If the RISA camera were to be used for greenhouse monitoring, the camera would have the ability to image plants each day, tracking plant health and giving scientists the ability to perform remote monitoring as needed. To demonstrate the camera's ability to perform different engineering-related functions, the RISA camera was also used to document water levels in the MDRS water tanks. Figure 10 clearly shows the water level present through the water tank at MDRS in this NIR image.

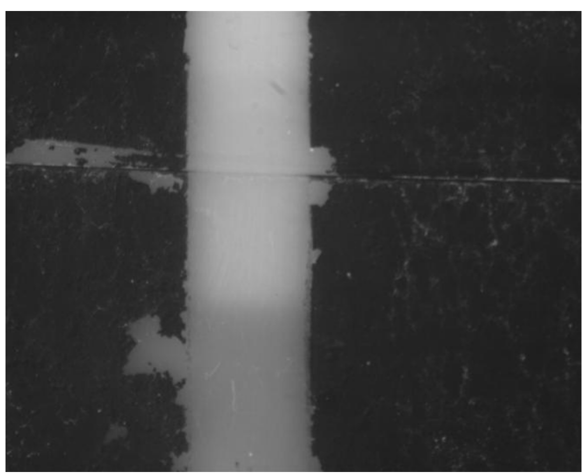

Figure 10. *NIR Image of MDRS Water Tank Level.*

6. CONCLUSION

The development that took place by this year's RISA Camera team focused on establishing a functional baseline for continued development. This plan involved creating a new optical design that met the requirements set. In addition, establishing wireless communication and control was a high priority. A mechanical enclosure was created to support the use of these components and establish interfaces between them. As described in previous sections, the RISA team has successfully developed an optical system that provides focus control using a liquid lens. This optical system meets the key performance requirements for the design. The electronics subsystem developed this year provides data transfer and component control wirelessly. A host computer using a custom MATLAB GUI is able to set sensor exposure time, change liquid lens focus, and acquire images wirelessly from the RISA camera. The camera frame rate for wireless operation did not reach the expected 0.5 fps, but the core functionality has been established.

Future development should focus on a few major topics that this year's team did not address. Further developing the electronics subsystem should be a key priority. This work would entail creating custom printed circuit boards to miniaturize components, working on improving the frame rate that has been established using the wireless system, and looking at the possibility of radiation-hardening the electrical and optical components used. In addition, a future team should spend time developing a flight enclosure that is capable of protecting all the camera components in the space environment while using a compact and lightweight form. Overall, the 2011/ 2012 RISA team at the University of Arizona has helped to further develop the RISA camera project, but understands that work is still required to further improve and finalize systems.

7. ACKNOWLEDGEMENTS

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