Design and Operation of the Planetary In-Situ Capillary Electrophoresis System (PISCES)

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The PISCES instrument is a portable, miniature, modular instrument designed to analyze organic molecular signatures of life. PISCES uses microcapillary electrophoresis (µCE) with laser-induced fluorescence detection (LIFD) to analyze fluorescently-labeled analytes prepared on a multi-layer microfluidic chip. As a modular instrument composed of five independently functioning units, each module can be easily detached from the system and used for subsystem testing in different environments, e.g. low temperature. The pneumatic module contains mechanical and electrical components necessary to control pneumatically-actuated valves for on-chip sample processing. A prototype LabVIEW program and two custom printed circuit boards (PCBs) operate the pneumatics module using an Arduino microcontroller, and a tentative design for the module's housing has been developed. The high-voltage module contains circuitry required to apply varying electrical potentials to the electrophoretic channel of the microdevice. Work is currently being done to design the circuit and PCB for this module in collaboration with our SBIR partners at Los Gatos Research. The optical electronics module contains the spectrometer, laser, and laser power supply. The mounting components for the electronics and housing for the module have been designed, assembled, and tested. The optical module contains optical components to focus the laser to a 20µm spot in the center of the electrophoretic channel.

The housing for this module has been designed and assembled with the aligned optical components inside.

I. INTRODUCTION

The Willis Lab at Jet Propulsion Laboratory focuses on the development of microdevices capable of automated, *in-situ* chemical analysis for use in planetary exploration missions.[1,2] The PISCES instrument is designed to perform such analyses on amino acids, aldehydes, carboxylic acids, and other molecular signatures of life. It is envisioned that the PISCES instrument would be used in ongoing investigations of Mars, and to explore the complex chemistry[3] of Titan, Saturn's largest moon. The greatest challenge in such investigations is distance. To overcome this barrier, instrumentation and analytical systems must be made small, simple, efficient, and automated. The PISCES instrument achieves this through a coupling of microcapillary electrophoresis (μCE) and laser-induced fluorescence detection (LIFD) on a multi-layer microfluidic chip. Microfabricated capillary electrophoresis (CE) devices, like the Multichannel Mars Organic Analyzer (McMOA) developed at University of California, Berkeley, have been shown to achieve rapid, efficient separation with minimal sample consumption and integrated sample processing[4-6] and are thus desirable for planetary exploration.

The PISCES instrument's modularity sets it apart from existing microfabricated CE devices. PISCES is divided into five modules, each of which can be easily detached from the system for subsystem testing in extreme environments mimicking the desired planetary target. By utilizing printed circuit boards in the electronics design, the size of the PISCES instrument has been miniaturized to roughly 270mm x 270 mm x 145mm—smaller than the McMOA (310mm x 320mm x 155mm). Additionally, the weight of the instrument has been reduced by having the majority of its components 3D-printed in Acrylonitrile Butadiene Styrene (ABS).

Here, the construction of the PISCES instrument thus far is described. The design and assembly of each module's software, electronics, and mechanical components are explained in detail along with their housing and mounting components. Lastly, the envisioned assembly of the entire instrument and future testing is described.

II. INSTRUMENTATION

The PISCES instrument, shown in Fig. 1, consists of five compact modules. Each module can be easily detached and reattached to the system to be used independently or with another instrument. The LIFD system is divided into two parts, the optics electronics module and the optics module. The optics electronics module contains the spectrometer, laser, and circuitry required to power the laser. The optics module contains the optical components which direct light from the laser to the chip to the spectrometer. The mechanical and electrical components required for the pneumatic and μCE systems are contained in their own separate modules. The last module contains the circuitry necessary to power all sections of the instrument. The multi-layer microfluidic chip containing the pneumatic array and electrophoretic channel is mounted to the top of the optics module and lies at the intersection of all three systems.

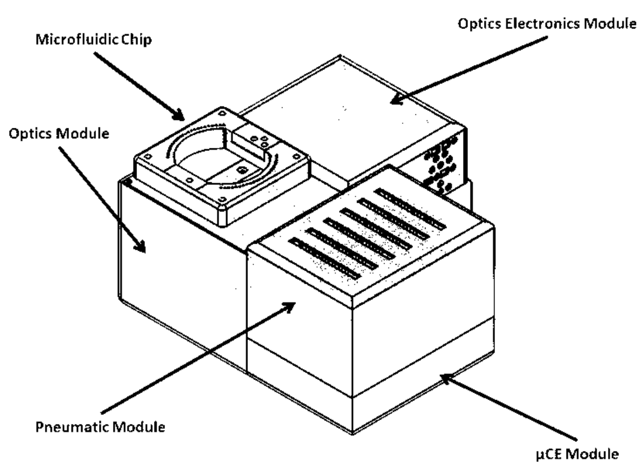

FIG. 1. The PISCES instrument divided into modules. The power supply module is excluded as its dimensions are undetermined.

A. Instrument Structure

PISCES can be divided into three main components, each having a key role in the instrument's overall purpose. These components are: (1) the pneumatic system, (2) the µCE system, and (3) the LIFD system.

The pneumatic system is the processing core of PISCES. It consists of 48 electrofluidic solenoid valves LHLA0521111H (The Lee Co., Essex CT) which open and close together in various sequences to induce movement of fluids through an array of interconnecting channels on one layer of the microfluidic chip. In this system, introduced samples are processed until they are ready to undergo separation by µCE. On the outer rim of this array are several multi-purpose reservoirs used for sample import, sample export, and for storage of dyes (to label functional groups of interest), buffers (to regulate the pH of introduced samples), standards (for purposes of calibration and comparison of experimental results), and treated/untreated samples introduced to the system.

The µCE system is the analytical core of PISCES. It consists of an electrophoretic channel integrated into a separate layer of the microfluidic chip. By generating a strong electric field across the fluidic medium in the channel, separation of a chemical mixture into components of differing mass and charge is achieved.

The LIFD system is the detection core of PISCES. The system incorporates laser optical components and a spectrometer to detect laser induced fluorescence of labeled analytes as they pass through the electrophoretic channel.

B. Pneumatic Module

The pneumatic module, shown in Fig. 2, contains the manifolds, pumps, circuitry, and software necessary to operate the solenoid valves. These valves require a low voltage pulse of current (5V or 12V depending on the model) to switch between their closed (air) and open (vacuum) states. The switch's state is determined by the polarity of current. These pulses are provided by an Arduino MEGA 2560 microcontroller. Previous devices have achieved electronic control of the solenoid valves using National Instruments Data Acquisition; however, the Arduino microcontroller achieves the same purpose while taking far less space. The digital pins on the Arduino board output TTL signals of either 0V or 5V. A separate PCB, called the H-Bridge board, contains an arrangement of Dual Full-Wave Bridge PWM Motor Drivers (Allegro Microsystems) which convert these unipolar signals to bipolar signals of either -5V/5V or -12V/12V. The final PCB serves as an interface between the solenoid valves and aforementioned circuitry. The valves mount directly to the board, and receive the bipolar signals sent from the H-Bridge board. The signals sent from the Arduino board are controlled through a LabVIEW program.

The solenoid valves are connected in rows of eight to two-port manifolds LFMX0510538BF (The Lee Co., Essex CT) which direct air and vacuum supplied by two micropumps D200S (TCS Micropumps Ltd, England). I have designed and assembled two solid, one-piece pumping manifolds (shown in Fig. 3) to direct air and vacuum from the micropumps, to all six of the solenoid manifolds. The pumping manifolds were machined out of Delrin 150 by FirstCut/ProtoLabs.

I have designed the printed circuit board that interfaces with the six banks of solenoid valves. These designs were sent to National Research Laboratories for fabrication and assembly. The board has recently been shipped and assembled with the bank of solenoid valves and their manifolds. This assembly is shown in Fig. 4. A schematic for the H-Bridge board has been sent to SaturnPCB for layout and assembly. The schematic for this circuitry was expanded in collaboration with National Research Laboratories from a pre-existing schematic designed by Los Gatos Research for an instrument similar to PISCES called the Chemical Laptop.

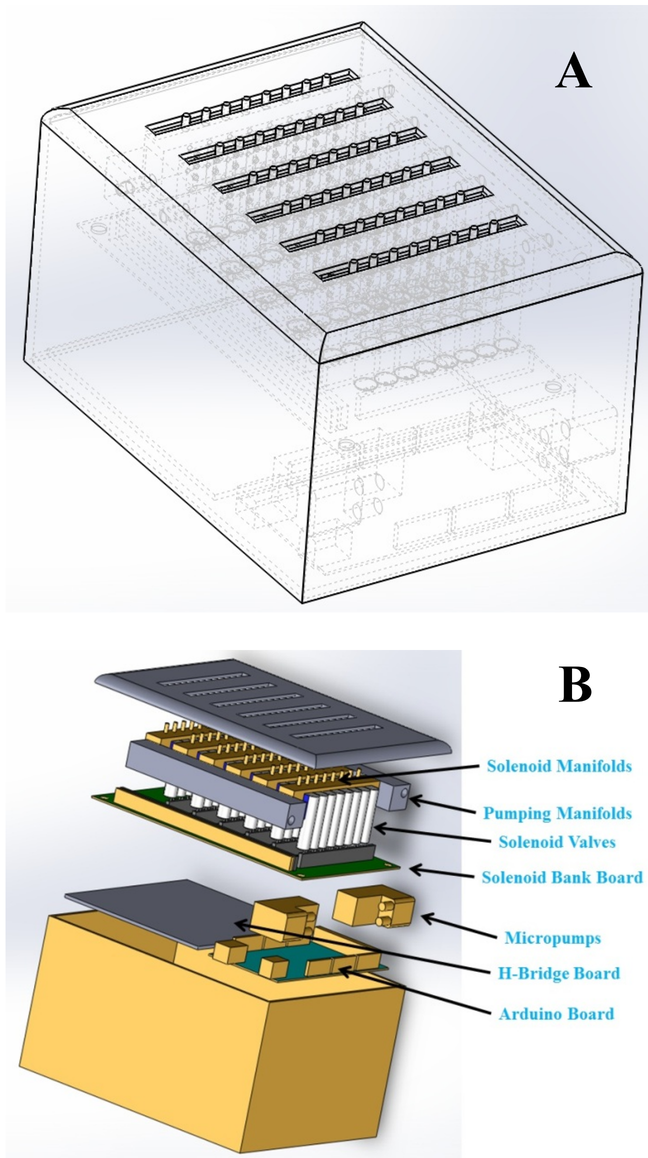

FIG. 2. (a) Incomplete design for the pneumatic module's housing. (b) Exploded view of the pneumatic module.

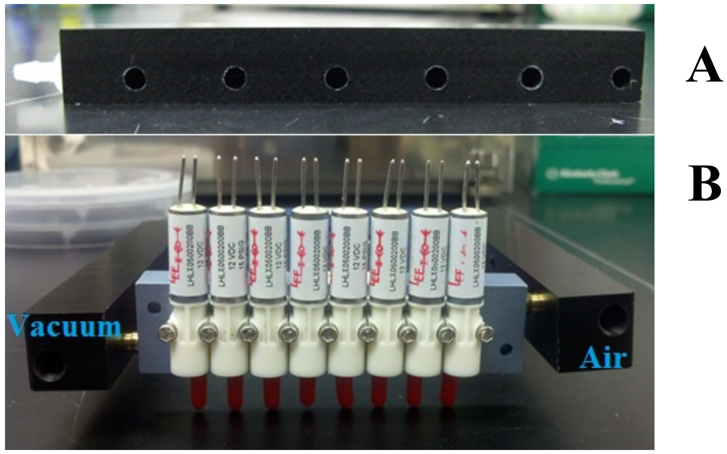

FIG. 3. (a) Side view of the pumping manifold. (b) Assembly showing the connection between the pumping manifold and solenoid manifold

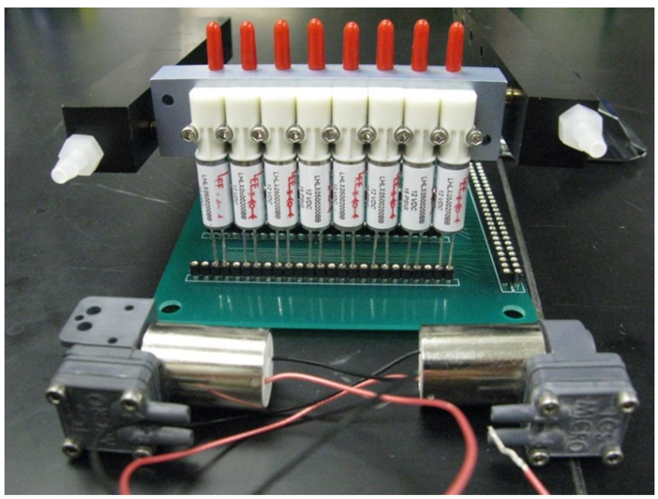

FIG. 4. Partial pneumatic system assembly showing solenoids, solenoid manifolds, pumping manifolds with barbed fittings, micropumps, and the solenoid bank circuitry.

I have designed a prototype LabVIEW program, shown in Fig. 5, to send TTL pulses from the Arduino microcontroller to the solenoid valves. The program is designed to allow for manual and automated control of the solenoid valves. Since the H-Bridge board essential to the pneumatic system is still in the assembly stage, I tested the program using an array of twelve LEDs in place of the valves. Since both the solenoid valves and LEDs require 5V to switch states, I was able to treat the "on" state of the LED as the "open" state of the valve and the "off" state as the “closed” state. By using LabVIEW to interface with the Arduino board, I was able to achieve real-time, manual control of the LED array. It should then be possible to use this program to achieve the same control of the solenoid array once the rest of the electrical components has been shipped and assembled. Currently, I am exploring methods of achieving automated control of the pneumatic array with this program.

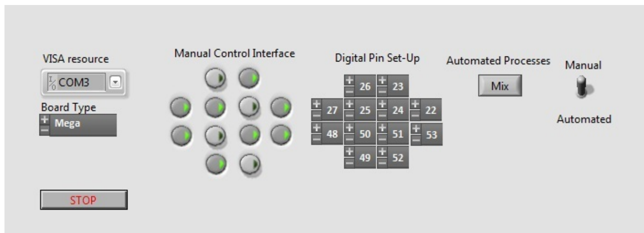

FIG. 5. Interface for a prototype LabVIEW program capable of controlling the pneumatic system

I have started a prototype design for the housing of this module, shown in Fig. 2(a). When finished, the design will be 3D-printed in ABS by the JPL Machine Shop. The design will include mounts for the circuit boards and pumps, vents to promote air flow through the system, and an easily removable top with gaps for the tubing connecting the pneumatic module to the pneumatic layer of the microfluidic chip. Once the dimensions for the inner components of the module are finalized, the housing will be designed so that it fits easily and elegantly with the rest of the PISCES system.

C. µCE Module

The µCE module contains four electrodes which connect to different points of the electrophoretic channel, and a printed circuit board integrating the necessary high voltage power supplies and relays necessary to drive electrophoresis on our microfluidic chips. The electric potentials applied through the electrodes are controlled and monitored through a LabVIEW program.

I have prepared and sent a schematic for the µCE module's circuitry to Advanced Designs Inc. for layout and fabrication. This schematic was adapted from a pre-existing schematic for the µCE system on the Chemical Laptop. However, this schematic contained a few design errors and parts unnecessary for the purposes of PISCES. The main issue with the circuitry was that it sent bipolar signals to an Arduino board only able to handle unipolar currents. I corrected this issue by introducing a bipolar to unipolar converter with a summing amplifier at every junction between the high voltage power supplies and the analog input pins on the Arduino board. The pre-existing schematic was also designed to be used with an Arduino MEGA 2560 microcontroller. I modified the schematic by re-routing all connections to the smaller Arduino UNO microcontroller after noticing that its number of analog and digital pins was sufficient enough for the purposes of PISCES. Lastly, the 3kV EMCO GP30 high voltage power supplies were replaced with smaller 3kV EMCO QH30N high voltage power supplies. The housing and software for this module have yet to be designed.

D. Optics Electronics Module

The optics electronics module contains the electronic components associated with the optics module: an Ocean Optics USB 2000+ Spectrometer, a 405 nm 20 mW laser (Power Technology Inc., Little Rock AR), and a circuit board to supply power to the laser. Two fiber optic cables connect the laser and spectrometer to the optical pathway in the optics module. The spectrometer is powered by an external USB input, and operated by a LabVIEW program utilizing the Ocean Optics Omnidriver software package.

The circuit board that powers the laser was taken from a Power Technology Inc. Class 3B Laser Diode Control Unit (LDCU). I modified the board to reduce its size and weight by removing a key switch safety interlock and the housing for the laser's 9-pin male connector. This enabled me to design a smaller housing for the LDCU also accommodating the laser and spectrometer. After modifying the LDCU circuit board, I experienced issues powering the device. After close inspection of the board, it seemed that a fuse was blown in the device. Once a replacement fuse has been shipped, experiments will be performed with the LIFD system.

I have already designed and assembled a prototype for the housing and mounting components of this module (shown in Fig. 6). After assembly, I found that with several minor adjustments, the housing could be made even smaller. I have since redesigned the housing and sent the updated parts out for fabrication . The ABS parts were sent to the JPL Machine Shop to be 3D-printed, and the aluminum parts were sent to FirstCut/ProtoLabs to be machined. This updated housing has been partially assembled as shown in Fig. 7.

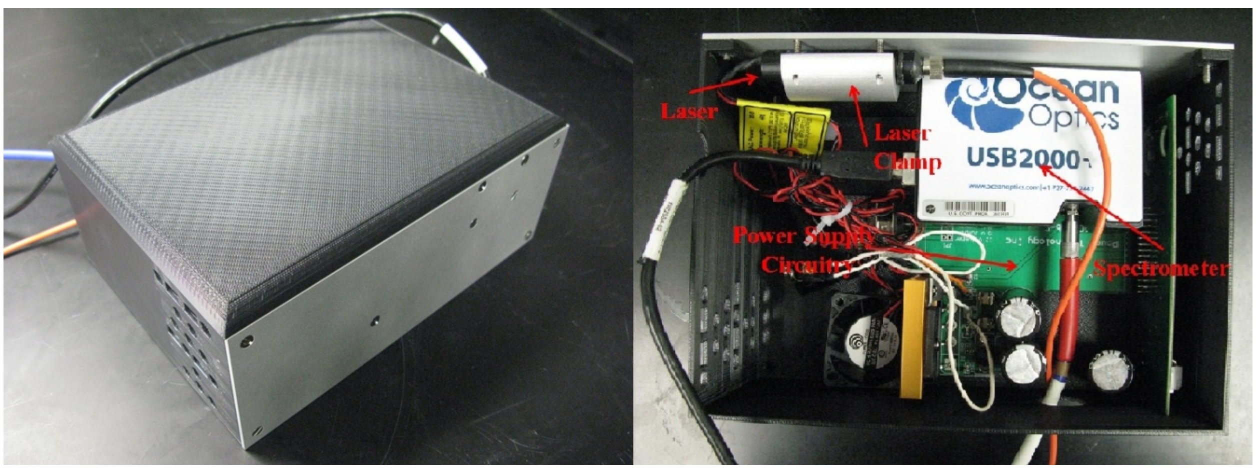

FIG. 6. Assembly showing the optics electronics module v.1

The backing wall of the module serves as a mounting surface for the optical components. This wall is made from aluminum to dissipate the heat generated by these components as well as to support their weight. The laser is mounted to the wall by a two-piece aluminum clamp. The first version of the laser clamp had a rounded bottom piece and was mounted parallel to the backing wall. To minimize the height and width of the module, I modified the clamp by flattening the bottom piece, adding a small circular groove to the top piece, and mounting it perpendicular to the backing wall. The clamp is made of aluminum to dissipate the heat generated by the laser. The spectrometer is mounted to the backing wall and is supported by a raised ledge on the bottom of the module. Every other wall in the module is made of ABS and will be 3D-printed at the JPL Machine Shop. There are vents on either side of the module to redirect the heat generated by the LDCU circuitry, and there are holes drilled for the fiber optics and USB cables entering and exiting the module. There are two additional holes drilled on one side of the module for a remote interlock connector and power connector for the LDCU. The housing for the module is designed so that it can be easily mounted on the back of the optics module.

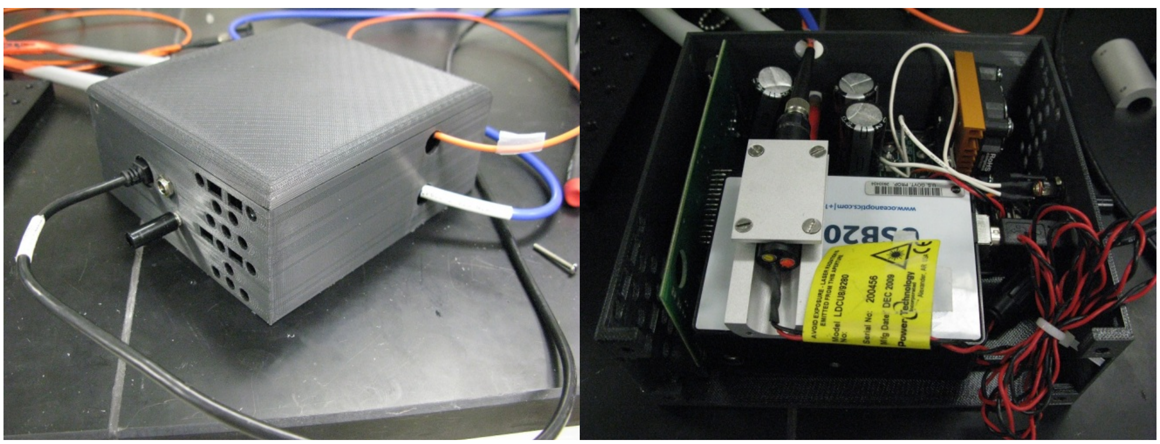

FIG. 7. Updated assembly of the optics electronics module

E. Optics Module

The optics module contains a series of optical components that direct the light from the laser to a microfluidic chip mounted to the top of the module. The optical components had been assembled and aligned prior to my arrival. The light from the laser and fluorescent dyes both pass through a Nikon Plan Fluor 20X objective lens aligned directly under the chip. The fluorescent light passes through a dichroic filter before entering the spectrometer.

I am currently working on a prototype design for the housing of this module (shown in Fig. 8). The entire housing, apart from the top, will be 3D-printed in ABS at the JPL Machine

Shop. The top will be made of thick aluminum, as it will be used to mount all the optical components inside. One tapped hole will be used as a mount for the optical components. The top will also serve as the optical stage and mounting surface for the microfluidic chip. The top contains a 30mm diameter hole for the objective, and two grooves for the two types of chips commonly used in our laboratory. The round groove is for our multi-layer chips and the rectangular groove is for a chip containing only an electrophoretic channel. The grooves are designed to place each chip's electrophoretic channel at the objective's optimum focal point. There are four tapped holes to mount the pneumatic manifold to the top of the module. The manifold delivers air and vacuum to drilled ports on the chip and also serves as a clamping mechanism for the chip. Four tapped holes on the outside of the top will be used to firmly attach it to the rest of the module. The top is supported by two 1/8" thick ABS sidewalls. The back of the module has an open top with a grooved cut around the perimeter which serves as a mounting surface for the optics electronics module. It is desirable to leave this section open, as it leaves space for the long fiber optics from the optics electronics module to coil around. This open space makes it easy to assemble and disassemble the two modules.

With this module being the largest in the system and containing the microfluidic chip and pneumatic manifold, it serves as the "hub" for the PISCES instrument. All other modules will mount to it and all electrical, optical, and pneumatic connections from the other systems will flow through its empty spaces. The finished module will include several holes so that the wiring and tubing between the mounted modules can be made internal for a more streamlined design.

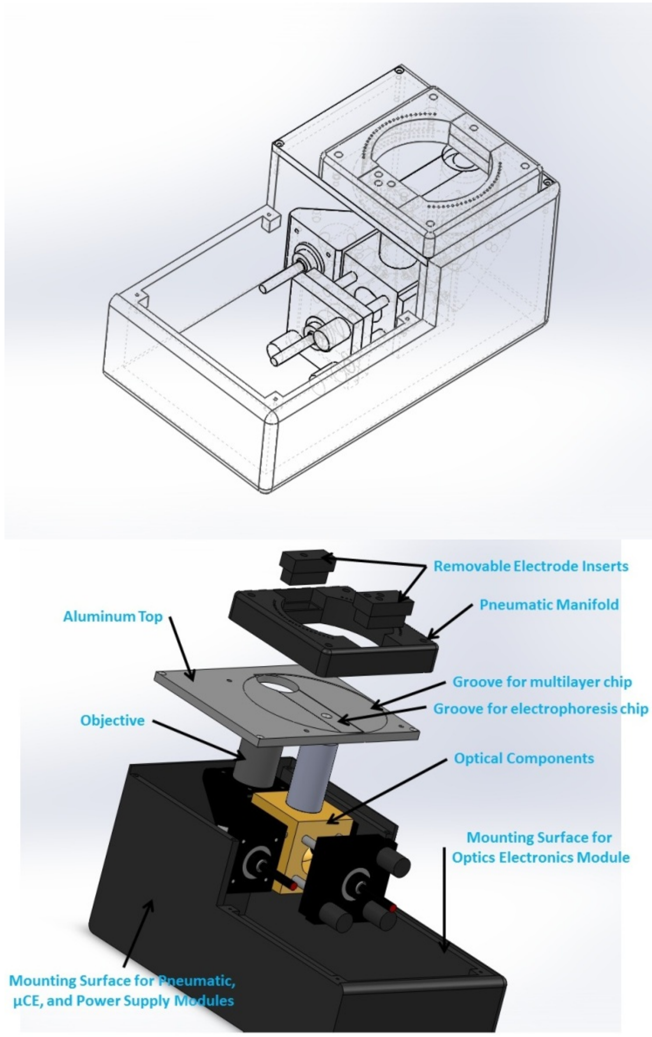

FIG. 8. Assembly and exploded view of the current design for the optics module

F. Power Supply Module

The circuitry and housing for this module have yet to be developed. In the future, a printed circuit board will be designed to supply the necessary voltages to every system in PISCES. The circuit board will be designed for use with an external power supply, or an internal battery. The housing will be designed with holes for its input and output cables.

G. Control Program

All three subsystems in PISCES are controlled by an integrated LabVIEW program. The program for the µCE and LIFD systems will be adapted from existing programs created by the Willis Lab. Slight alterations will be made to the programs to interface with the Arduino microcontrollers in place of the National Instruments Data Acquisition (DAQ) Cards used in previous instruments. Additionally, it is envisioned that an XBee Wireless module will be used in conjunction with the Arduino boards to achieve wireless control of the instrument. A program to control the pneumatic system will be built from the ground up. As explained previously, I have developed a prototype for this program that operates the 48 electrofluidic solenoid valves using the Arduino MEGA 2560 microcontroller. The program incorporates the Arduino Interface for LabVIEW software package developed by National Instruments. The program includes indicators for the VISA resource and board type, and interfaces for manual and automated control of the Arduino. The manual control interface contains an array of Boolean input buttons arranged to mimic the pattern of valves on the microfluidic chip. A Boolean input of "true" opens the valve, and a Boolean input of "false" closes the valve. Aside this array is a duplicate arrangement of numeric indicators assigning a digital pin to each valve represented by the Boolean array. The automated control interface includes a series of buttons specific to an on-chip process. In the future, we will investigate the use of higher-level programming languages to achieve a more efficient method for automated control of the pneumatics.

III. TESTING

Since many of the mechanical and electrical components for PISCES have yet to be shipped and assembled, only a minimal amount of testing has been done. As explained previously, the program to control the pneumatics has succeeded in achieving real-time manual and automated control of 5V LEDs in place of 5V solenoid valves. Additionally, control of the spectrometer has been achieved using Ocean Optics' Omnidriver software package in conjunction with LabVIEW. After all the parts have arrived and the system has been fully assembled, each module will be tested individually in environments mimicking the desired planetary targets. The modules will be tested in a cold room to simulate the temperature of Titan, and the Atacama Desert in Chile to simulate the atmosphere of Mars. Vibration tests will be performed to simulate the forces of space flight, departure, and landing.

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