TOPICAL: INSTRUMENTATION TO INVESTIGATE FIELD-DRIVEN COLLOIDAL MATTER IN MICROGRAVITY

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by

Stuart J. Williams, Ph.D.
Department of Mechanical Engineering
University of Louisville, Louisville, KY 40292
stuart.williams@louisville.edu, 502-852-6340

Co-authors (listed alphabetically):

Julia Aebersold*, Ph.D.,* Manager, Micro/Nano Technology Center
University of Louisville, Louisville, KY

Richard Boling, Vice President
Techshot, Inc., Greenville, IN

Robert W Cohn*, Ph.D.,* Electrical & Computer Engineering Department
University of Louisville, Louisville, KY

Andy Kurk*, M.Eng.,* Program Manager
Techshot, Inc., Greenville, IN

Thomas Roussel, Jr. *Ph.D.,* Bioengineering Department
University of Louisville, Louisville, KY

Kevin M. Walsh*, Ph.D.,* Associate Dean, Electrical & Computer Engineering Department
University of Louisville, Louisville, KY

Gerold Willing*, Ph.D.,* Interim Chair, Chemical Engineering Department
University of Louisville, Louisville, KY

1. Overview & Motivation

Insight into the fundamental mechanisms of colloid assembly provides the foundation for scaled-up manufacture of highly specialized, particle-based (i.e. nanoparticles, granular, etc.) materials. There has been extensive research on colloid assembly techniques on earth, but *many of the fundamental insights into the governing physics are masked by gravitational forces*, which severely limits otherwise high-impact investigations of these three-dimensional constructs. Thus, studies on the ISS would inarguably provide a significant advantage for discovering fundamental physical mechanisms of colloid assembly, with critical insights into how colloids can be optimally assembled on earth. Further, the ISS microgravity environment enables the consideration of unique experiments such as the evolution of 3D colloid morphology with time, also known as "4D" investigations. Such colloid assembly is *field driven*, meaning that well controlled external forces (hydrodynamic, optical, thermal, electric, magnetic, acoustic, etc.) are required.

Thus, *there is a need for modular instrumentation on the ISS that can facilitate multidisciplinary research and enable such discoveries in colloid science*. Our vision for the proposed instrumentation is inherently *multiscaled* (Figure 1), from the *macroscale* assembly of hardware, the *mesoscale* handling of liquid samples, the *microscale* fabrication of specialized fluidic chips and sensors, and the *nanoscale* characterization of colloids. As such, this collection of instrumentation requires a multidisciplinary team that can address each facet and, thus, requires a variety of specialized expertise.

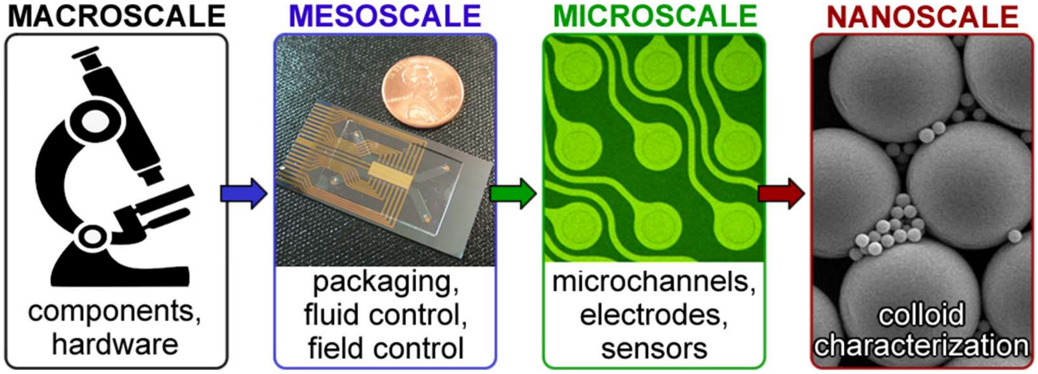

***Figure 1**. Multiscale instrumentation is needed to address multidisciplinary colloid research on the ISS.*

2. Background: Colloid Science & NASA

Advanced, specialized materials with superior physical properties resulting from significant surface area-to-volume ratios are now possible due to advancements in the field of nanofabrication. Suspended micro- and nanoparticles have been used to synthesize these novel structures, but the physical mechanisms governing colloid aggregation and stability are not completely understood. Therefore, insight into colloid self-assembly mechanisms is a key enabler of further nanomanufacturing advancement. ISS provides a unique environment to investigate scaled-up fundamental colloidal physics without gravity-induced inaccuracies. Microgravity colloidal research onboard the ISS thus enables fundamental discoveries in colloidal science that will ultimately benefit advanced materials, sensors, and products.

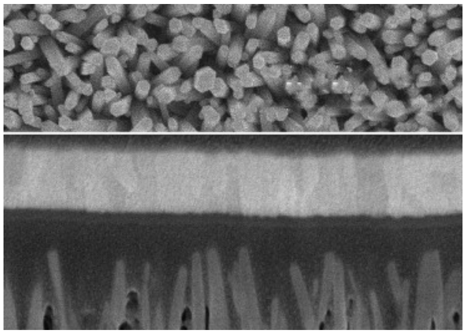

***Figure 2**. Scanning Electron Microscope image of a solar cell containing nanowires and quantum dots. From [1].*

NASA has a long history of leading colloid research including over 40 experiments through its Binary Colloidal Alloy Tests (BCAT) and ongoing Advanced Colloids Experiments (ACE). NASA also participated in the "Grand Challenges in Soft Matter and Opportunities for Microgravity Research" workshop at the American Physical Society March Meeting in 2020 and developed a roadmap for future research directions [2]. Advancements in colloid research directly impact the ongoing mission of NASA (Table 1) and introduce to new materials that will enable advanced solar energy harvesters, mechanically robust materials, inexpensive electronic displays, and analytical instrumentation for both space-related and terrestrial activities. A few of the many applications of colloid-based nanomaterials include:

- Quantum dot solar cells (Figure 2) with enhanced efficiencies, tunable absorption, sensitivity to diffused light, and flexibility [1, 3].
- "Nanofluids" with unusually high thermal conductivity used for advanced heat transfer applications [4].
- Colloidal carbon films used for electromagnetic radiation shielding [5].
- Graphene enhanced of propellant combustion [6].
- Immunoassay sensors with increased sensitivity, reaction kinetics, and reduced analysis time [7].

Table 1: Impact on NASA Technology Taxonomy

Technology Area	**Impact**
Propulsion Systems (TX1)	Colloidal packed-bed propellants would lead to simplified storage, transfer and handling. Nanotechnology materials may enable increased combustion efficiency, better reaction rate control, and reduced fuel mass. Novel materials will lead to more powerful solar arrays and advanced Solar Electric Propulsion spacecraft.
Aerospace Power & Energy Storage (TX3)	High surface area materials with inherently higher surface reactivity, will significantly enhance the performance of solar arrays, batteries, and fuel cells. Colloid-based materials may lead the way for higher efficiency, lower mass, and smaller energy systems as well as enabling novel energy harvesting.
Human Health, Life Support & Habitation Systems (TX6)	Packed colloidal structures offer enhanced optical and environmental sensing, chemical detection, air/water filtration, and radiation shielding.
Sensors and Instruments (TX8)	Colloidal structures enhance sensor sensitivity with targeted applications while providing improved durability and operational capability in extreme conditions. Nanoelectronic components are inherently radiation resistant. Colloidal aggregations with features on the order of the wavelength of light enable tuned optical response.
Materials, Structures, Mechanical Systems & Manufacturing (TX12)	Insights into colloid self-assembled materials enables the development of scalable nanomanufacturing methods with controlled structure, morphology and quality. Carbon or graphene-based materials yield superior mechanical, thermal, and electronic properties for revolutionary lightweight, multifunctional structures. Specialized, nano-textured surfaces enable superhydrophobic surfaces for self-cleaning.
Thermal Management Systems (TX14)	Nanomaterials with high bulk thermal conductivity may lead to applications in lightweight radiators and heat exchangers for remote vehicles as well as thermal management for circuits and spacecraft busses. Proper design of nanostructured materials enables reductions in system weight and, ultimately, mission cost.

3. Proposed Instrumentation

There are significant space constraints on the ISS, such that any proposed instrumentation must provide substantial scientific value to multiple investigators. Simultaneously, the instrumentation must be highly adaptable to meet the unique needs of each principal investigator (PI). There are many different types of colloidal solutions (protein crystals, gels, foams, etc.) and there are just as many unique methods of controlling these samples. Most colloid studies rely on optical observations. Although microscopy has been available on the ISS for years, existing and prior instrumentation has not been extensively versatile*, thereby severely limiting the breadth and depth of prior colloid experiments on the ISS*.

Instrumentation requirements include: (i) high-resolution microscopy, (ii) modules for different "field" actuation schemes, and (iii) adaptability to enable a variety of colloidal experiments. These characteristics are reflected in the framework of the proposed instrumentation (Fig. 3, left). First, there is a centralized unit to control all aspects of the instrumentation, including communication and data acquisition. Next, fluorescent microscopy is incorporated to visualize colloids. The microscope and general instrumentation hardware is fixed and will be used by all experimenters (Fig. 3, black). "Field Modules" (Fig. 3, red) will be implemented for a particular series of experiments to induce the necessary forces (electric, magnetic, etc.). Last, the colloid sample would be precisely controlled using a series of microfluidic components (Fig. 3, blue). Thus, the sample would be controlled by the microfluidic components, actuated by the Field Module, and visualized by the microscope. A preliminary microscopy setup that incorporates some of these features has been developed by TechShot, Inc. (Fig. 3, right).

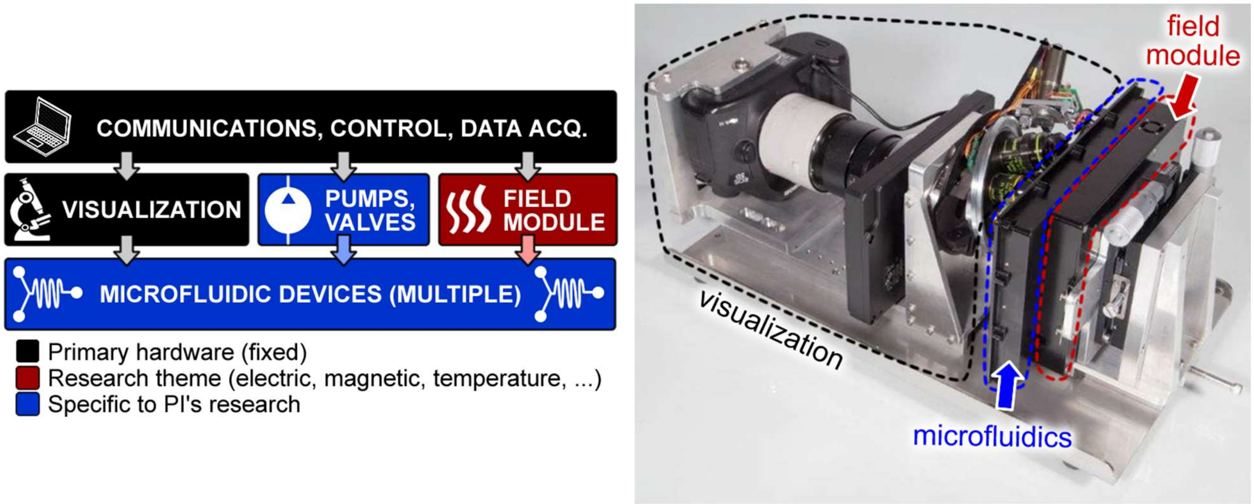

***Figure 3**. (left) Outline of the colloids instrumentation. (right) Proof-of-concept of this configuration was demonstrated by TechShot's Mic-E system.*

Visualization, Microscopy: There is a long history of microscopy on the ISS, and the infrastructure for the visualization component of this instrumentation is well established. For example, the Light Microscopy Module (LMM) has been used extensively for ACE, though it is scheduled to be removed late 2021. One significant feature of LMM that was particularly advantageous for ISS colloid research was its *fluorescent confocality,* enabling 3D scans of fluorescent particle agglomerations – this characteristic should be incorporated in future instrumentation for proper

4D colloid investigations. Although visualization is critical, the system has to be flexible to allow for multidisciplinary research; thus, the incorporation of various Field Modules and microfluidic components are necessary.

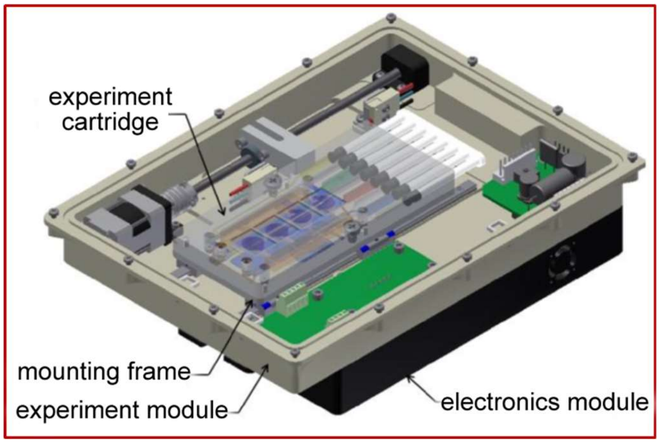

Figure 4. *Example of a microfluidics experiment coupled with an electronics module (Techshot, Inc.).*

Field Modules: One key aspect of the proposed instrumentation features interchangeable modules that apply different actuation schemes to the microfluidic chip. Table 2 lists the most common field-driven methods [8, 9], associated module hardware, and examples of enabled studies. The modules can be developed and implemented independent of each other. To optimize instrument use on the ISS, all PI's utilizing a particular module would be scheduled consecutively. An example of an electronics module is shown in Figure 4. One significant feature is the exchangeability of the experiment cartridge allowing multiple microfluidic experiment platforms to use the same module.

Table 2: Examples of Field Modules for the proposed instrumentation

Module	Hardware	Example of Enabled Studies [ref.]
Electric field	Waveform generator, DC/AC fields	3D colloid aggregations using dielectrophoresis [10]
Optical	Laser diode, Fresnel or high NA lens	Colloid crystallization using light propagation [11]
Magnetic	Electromagnet, rare earth magnet	Tunable, reversible, and reconfigurable assembly [12]
Acoustic	Piezoelectric actuators	Rapid, highly ordered assembly of colloids [13]
Thermal	Resistive heaters, thermoelectric coolers	Temperature controlled hydrophobic attractions [14]

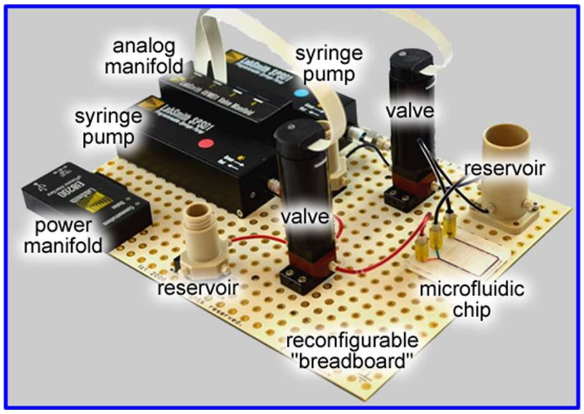

Figure 5. *Example of modular fluidic components, LabSmith (Livermore, CA).*

Microfluidics: Our vision for the microfluidic portion of this instrumentation would be an adaptation of LabSmith's "breadboard" system (Figure 5). Here, each PI would mount and arrange off-the-shelf microfluidic components as needed for their study. These components include syringe pumps, valves, reservoirs, filters, sensors (pressure, temperature), and similar components. All of these components would be mounted to a specialized "breadboard" which simultaneously provides electrical connections for power, monitoring, and control. This "plug-and-play" design provides extensive flexibility for a PI to design their platform to yield the best science. Another advantage is that the microfluidic system can be independently developed and extensively tested by each PI prior to transferring their system to payload managers. Further, LabSmith's components can be controlled using their software (μProcess) or LabVIEW, which facilitates remote and/or autonomous operation.

Microfluidic Devices: At the heart of each experiment is a microfluidic chip specifically designed for each PI. These chips will also be mounted on the microfluidic breadboard (Fig. 5) which would require modification to provide optical access. It is highly likely that more than one microfluidic device will be mounted on the microfluidic stage to allow multiple studies on the same platform. Further, each microfluidic device typically consumes small liquid volumes (≤ microliters) which enables a milliliter-sized colloid sample to be distributed across multiple microfluidic chips. The inherent miniaturized nature of microfluidics leads to small liquid volumes, meaning waste can be easily contained within a reservoir and capillary action (i.e. surface tension) would prevent the sample from escaping in microgravity. Further, due to its small footprint liquid containment measures can be implemented trivially.

The microfluidic chip would be connected to the modular fluid components. In addition, microfluidic chip features would be integrated with the respective Field Module. For example, microelectrodes (Fig. 6, top) would be connected to the generated electric field of the electric module. These microfluidic chips would be constructed out of materials that meet the stringent requirements for ISS experimentation. For example, the University of Louisville's Micro/Nano Technology Center created specialize rectangular glass capillary chambers for some ACE experiments (Fig. 6, bottom). Most of the microfluidic components would be constructed from glass and/or silicon, though polymers might be used as appropriate (their gas permeable properties cannot be ignored). Long, capillary-like geometries (Fig. 6, bottom) allow multiple samples to be simultaneously viewed within the optical window of the visualization system. Further, these capillary-like systems mimic "electric bottle" systems that have been previously used for colloid experiments [15].

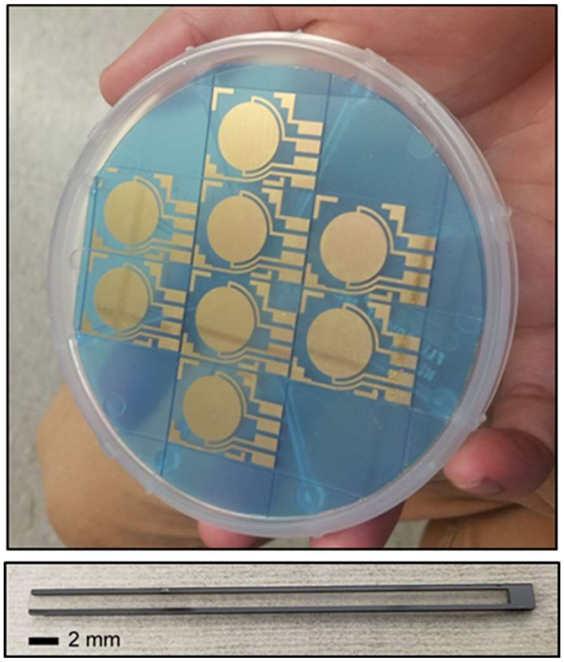

***Figure 6**. (top) Microelectrodes fabricated on a glass substrate for microfluidic electrokinetic colloid experiments. (bottom) Example of a specialized rectangular glass capillary for ACE experiments.*

4. Concluding Remarks

A modular, versatile microscopy instrument is a critical need to enable advanced, significant scientific discoveries in colloid science in the unique environment of microgravity. Current ISS microscopes do not have these features, and a multidisciplinary team is needed to address the multiscale nature of the instrument. Last, this instrumentation is *not restricted to colloids research*; due to its inherent versatility, it will impact and enhance a variety of other ISS research. Examples include, but are not limited to, (i) electrohydrodynamic manipulation of two-phase flows, (ii) stimulating and monitoring tissue-on-a-chip systems, (iii) visualizing electrostatic interactions of dust, or (iv) studying field-driven additive manufacturing.

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