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Optical Microsensor for Counting Food Substance Particles in Lab-on-a-chips

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***Abstract*—Integrated optical detection is considered to be an important operation in lab-on-a-chips. This paper presents an optical fiber-based micro-sensor that is capable of detecting food substance particles in a lab-on-a-chip. The system consists of a microcontroller and associated circuitry, a laser emitter, a laser receiver, fiber optic cables, a microfluidics chip, and the food substance samples to be tested. When the particles flow through the microfluidic channel in the chip, the receiver's output voltage varies due to the particles blocking the passage of the laser ray. The changes in the collected signals are analyzed to count the number of particles. Experiments are conducted on several food substance samples including talcum powder, ground ginger, and soy sauce. The experimental results are presented and discussed.**

***Keywords*—Lab-on-a-chip, microfluidic, optical detection, optical fiber, microsensor, food substance particles**

I. INTRODUCTION

Lab-on-a-chips are integrated microelectromechanical devices that implement biological and chemical processes. They offer great possibilities in such applications as clinical point-of-care diagnostics, food and environmental analysis, genomics, proteomics, and drug discovery and delivery [1]. They present great advantages including reduction of the analytical testing cost and time.

Lab-on-a-chips carry out sampling, pretreatment, separation, reaction, detection, and data analysis. Among these tasks, detection is a vital operation that senses and identifies analytes [2]. Whilst an accurate and fast detection would be desirable, often this is not achieved because detection is carried out off-chip and faces limits related to small sample volumes that need to be examined. Also, sensors are sometimes large and bulky, making their integration with lab-on-a-chips challenging.

In recent years, attempts have been made to efficiently integrate various detection devices with microfluidics lab-on-a-chips. Several detection methods are being investigated including optical, magnetic, capacitive, and electrochemical. Among these methods, optical detection [3] is a common approach due to its accessibility, and the simplicity of the microfluidics detector interface. Optical detection methods include optical fiber, surface plasmon resonance, total internal reflection fluorescence, absorbance, and luminescence. Some of these technologies already exist in larger devices that are used in laboratory procedures.

Surface Plasmon Resonance (SPR) is defined as an excitation of the electron plasma of a thin metal layer covering the surface of the waveguide [4]. This can be used as a sensor because it works by using materials that have different refractive indexes denoting the type of cell that is present. Merwe [5] states that SPR is good for evaluation of macromolecules, equilibrium and kinetic measurements and protein analysis. On the other hand, he believes that SPR is not good for high throughput assays, concentration assays and the study of small analytes.

Total Internal Reflection Fluorescence (TIRF) is similar to SPR, in that light travelling from one material to another with different refractive indexes. When it hits the material, the light does not propagate as well through the lower refractive index material. It only goes through a few hundred nanometers where it starts to decay, thus exciting the fluorophores in that material or cell. A high signal to noise ratio can be produced, allowing single molecule analysis. The sensors measure the fluorescence of the cell.

Dittrich and Manz [6] have identified that for a quality fluorescence signal, it is necessary that the sample has fluorophores with large absorption coefficients and quantum yields. Also, a reasonable stability to photobleaching is desirable. But fluorescence is very sensitive to climate changes. Dinh [7] has developed a bio-chip that is capable of DNA gene probe detection. The chip includes photosensors, amplifiers, discriminators and logic circuitry on a single chip. It uses fluorescence to highlight the HIV virus. Using VLSI technology, all sensors and circuitry are integrated with the chip.

Near Field Scanning (NFS) consists of an optical fiber that has been extruded and its outside is coated with a uniform layer of silver. Its uncoated tip is silanized and bonded to the anti-BPT antibody. The nanobiosensor showed increased sensitivity and response time, attributed to the small tip area [8]. The coating allows a probe to be constructed that would otherwise be outside the diffraction limit.

Boron Diffused Resistor (BDR) operates as particles passing a detector blocking an IR source reaching it changing its resistance. The resistance can be measured. The measurement of resistance can be directly linked to types of particles, as different particles and materials have different properties. The system would need to be calibrated and should

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store a record of the different properties if it is to be used for several types of diagnosis.

There are devices that use CCD sensors to analyze sample information. Boteler et al. [9] proposed using a CCD and an array of white LEDs. Light shines down through cells passing along the viewing channel in the disposable chip and onto the CCD array. The LED unit contains 24 micro LEDs.

Optical fibers are predominantly used for cell counting. When the light beam is cut, a cell has passed through the detector. Using optical fibers for flow cell detection has shown successful results. Kyungpook University researchers [10] conducted an experiment to test 125 micron optical fibers with a wavelength of 640nm as cell detectors. They detected particles with diameters of 10, 20 and 25 microns with a velocity up to 5.5mm/s with the 20 micron particles. The outcome of the experiment has shown that it is incapable of using single mode fiber.

Technology that adds to the attraction of optical sensing includes polydimethylsiloxane (PDMS) material that the micro channels are etched into. As stated by Psaltis et al. [2] the optical transparency and good optical quality of PDMS has been demonstrated in applications such as soft lithographic fabrication of blazed gratings and solid immersion lenses. When the devices use glass, there are gaps of air between the fiber and the channel, which causes a major light loss. Therefore the gaps are filled in with PDMS. PDMS is used between the end of the fiber and the microchannel to make a difference to the light scattering throughout the material.

Wrocalaw and Warsaw University researchers have joined efforts to make advancements in the optical detection using a low temperature cofired ceramic microfluidic device. They use a mixing y-shape and a creatinine solution to aid the transmittance measurements. They had trouble with the amount of light from the source.

This paper presents an optical micro-sensor system that is capable of detecting food substance particles as they flow through a microfluidic channel. Optical fiber is integrated onto the microfluidics chip. The system consists of a microcontroller and associated circuitry, a laser emitter, a laser receiver, optical fiber cables, a microfluidics chip, and the samples to be tested.

The paper is organised as follows. Section II gives a brief overview of optical fibbers. Section III describes the developed system. Section IV explains the experimental results. Section V discusses the outcome of the experiments. Finally, the concluding remarks are given in Section VI.

II. Optical Fibers

Optical fiber is a popular communication medium. The most popular type of optical fiber is 62.5/125µm. Optical fiber is predominantly used in network communications. There are two types of optical fiber: multimode and single mode. The difference between multimode and single mode is that a multimode fiber has a number of paths in which a light ray may travel. A single mode has a light ray in one direction only. Multimode fibers usually have a core diameter of 50-62.5µm compared to single mode which is around 8-10µm. There are two main fiber materials: glass and plastic. The materials can be doped to increase refractive index and increase performance. Plastic Optical Fibers (POF) are limited to larger diameters because of attenuation. Another factor for single mode fibers is dispersion. The amount of dispersion varies with the wavelength. Therefore, certain wavelengths are better suited to certain types of fiber. For example, the wavelength with the least amount of dispersion for single mode fibers is in the range of 1310nm.

The fiber that can be used for microfluidic optical sensing is multimode 62.5/125µm. Golonka [11] used the common 62.5/125µm multimode fiber. Nguyen [12] initially used only an IR emitter, but decided that the resolution can be improved by using smaller capillary and replacing the IR with fiber optic. The fiber used was 10µm single mode fiber. This improved the resolution by tenfold. Xiang [13] used different fibers for the input and the output. 50/125µm was used for the input etched to 47µm. 100/110µm was used for the sensor etched in acid to 76µm. Polydimethylsiloxane was used to fill the ends of the channels once the fibers were inserted.

Some of the existing experiments have greater thought on the sensing hardware than others, as there were not reasons for specific emitter hardware and wavelength choices. Obviously for fluorescence detection, the sensor and emitter have to be matched to the particle criteria, but for flow analysis and particle counting there is no importance on the light frequency used, so long as the wavelength is within the limit of the fiber optic cable used. Table I shows the comparison of a number of existing optical fiber-based detection approaches.

TABLE I.
Comparison of Some Optical Fiber-Based Detection Methods

Work	Sensor	Sensor Range	Emitter	Emitter Range
Golonka [11]	UV fiberoptic micro detector and a photomultiplier	510nm	Custom made multi diode light source & a Red LED	Unknown
Srinivasan [14]	Photodiode (TSL257 – TI)	320-1100nm	Green LED	510nm
Kim [10]	Photodiode S2386-8K	320-1100nm	Laser light source	Unknown
Xiang [13]	Si-PIN detector	Unknown	Red Si-PIN laser	640nm
Nguyen [12]	Honeywell SDP8436 IR Phototransistor	880nm	Honeywell SEP8736 IR Emitter	880nm

After reviewing the existing work, a few concepts have become evident. First, the emitter and sensor matching is important to reduce interference. The sensor should ideally have a small range that it detects in. For the emitter, a LED is cheaper, uses much less power, and requires less equipment. A Laser emitter offers high power and small wavelength variation compared to the LED. The most popular fiber type was the multimode in the 62.5/125µm diameter. The single mode fiber was hard to align. Etching the fiber and removing the core cladding can lead to better resolution and greater sensitivity.

PDMS filling of the area surrounding the fiber is vital as it reduces light leakage and increases the sensitivity.

III. Proposed System

The proposed system consists of the electronics for operating the light emitters and receivers, the fiber optic cable, the microfluidics chip, and the food substance samples to be tested. The block diagram description of the system is shown in Figure 1. It gives an insight into how the data flows between the system's main components.

The light from the emitter travels through the fiber optic cable to the microfluidics channel. The beam of light runs perpendicular to the channel to a receiving fiber. The receiving fiber is connected to a photodiode which incorporates a light/current to a voltage circuit. Thus, it delivers an output voltage that is proportional to the amount of light received. The sensor output voltage is fed into an A/D port of a microcontroller which converts the analogue value to a numerical value. A reference signal used to define what change in voltage drop is needed before a particle is registered. Calculations are performed using the reference and sensor output to determine if a particle has passed through the beam of light. The microcontroller is connected to a LCD which is used to display the results to the operator. The calculations are performed constantly and it is updated to the screen several times per second.

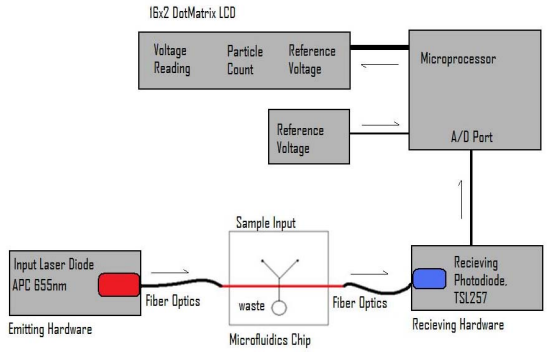

Figure 1. Block diagram description of the proposed system.

A. *Microfluidics*

The microfluidics chips that we designed are simple. Basically there is one cross design which is used for particle analysis and another which uses a pair of sensing systems at a known distance apart. As the distance apart is known, the time taken to pass between the two can be monitored thus enabling velocity calculations to be made. As the velocity and dimensions of the micro channel are known, the volume of the liquid can be monitored enabling nanolitre volume analysis.

The design of the microfluidics incorporates four microfluidics chips as displayed in Figure 2. Starting top left and moving clockwise, the first design has three sets of emitter and detector allowing for velocity measurements. It has reservoirs for input and output of the sample and 100µm wide channel. The channels running horizontal are used for aligning the fiber optics that lay in the channel. The horizontal lines do not cross the channel running vertically. There is 100µm gap between the end of the fiber and the channel. The second and third chips are used primarily for particle analysis. The difference being that one chip has reservoirs. The last design on the bottom can be used to test the effects that the angle may have on the particle, and if more pairs of fibers were used (several spaced i.e. 30degrees apart) a 2D representation of the particle could be produced. All lines are 100µm wide and 100µm deep, the chip itself is approximately 5mm thick. Due to the fabrication restrictions 100µm was the smallest viable option.

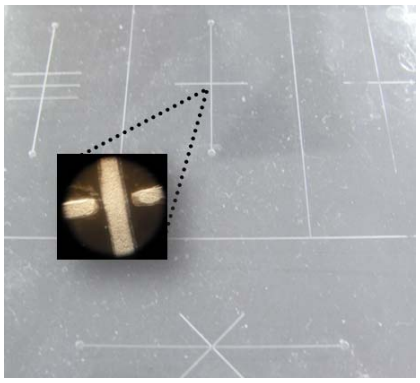

Figure 2. Manufactured microfluidics chips.

The microfluidics chips are made of PDMS that is very flexible and can be cut easily using a scalpel. Small imperfections can be seen in the substance. This is due to the master not being totally clean or the PDMS chip not pulling away from the master successfully. This was not seen as a major problem but care needs to be taken during preparation and development.

The PDMS slab is cut into individual butterfly shape. We leave around 5mm either side of the channel to ensure the chip will not break easily and so there is enough PDMS to secure the fibers to. Then, the stainless steel tubing is used to create holes in the PDMS chip for the input and output tubing. The input and output tubing are inserted. The fiber optics are prepared by cutting to length, and then carefully cut off the jacket then the clear cladding. We leave 5mm of exposed fiber core. A fiber optics cutter is used if possible otherwise a pair of scissors can be used to cut the fiber. The fibers are inserted into the guide channels under a microscope gently and slowly. Once the core reaches the end of the guide channel, tape or blue tack is used to hold in place. Epoxy resin is used to secure the fiber optics to the outside of the PDMS chip (see Figure 3).

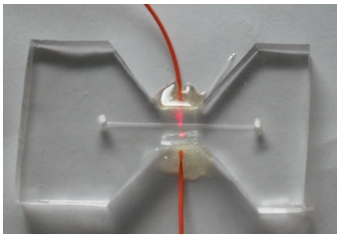

Figure 3. Manufactured microfluidics chip equipped with the optical fiber medium.

B. *Electronics*

An APC 10mW 655nm fully integrated Laser Diode was used as the emitter. An oscillation damper using two 100uF Ceramic capacitors is used to stabilize the laser frequency.

A TAOS TSL257 light to voltage converter was used as the receiver. It features noise protection and high power supply rejection while maintaining high sensitivity. In the LF package the TSL257 contains a monolithic silicon IC with integrated photodiode, OP Amp and feedback components all in a 4.6mm^2 package.

A microcontroller was used to handle the computation and conversation of the results. The processor used is a 68HC11. The evaluation board contains all hardware for port and power connections. The assembler used was ASM11C84 with the code written in assembly language and programmed into the EEPROM of the chip. The main idea of incorporating a microcontroller is to read in the results from the output of the photodiode (receiver) and to convert them into a useable form which is easier for the operator to interpret. The microprocessor also reads in a reference voltage which is determined by the user. As both inputs are analogue, they need to be converted to digital. Therefore the two signals are passed into analogue to digital ports of the microprocessor. Once converted to digital signals, a particle count can be calculated using the two signals. The microprocessor uses a LCD display to convey the results to the operator. The LCD is the QP5518 16×2 character display which includes a LED lit backlight. Figure 4 shows the electronics components used in the system.

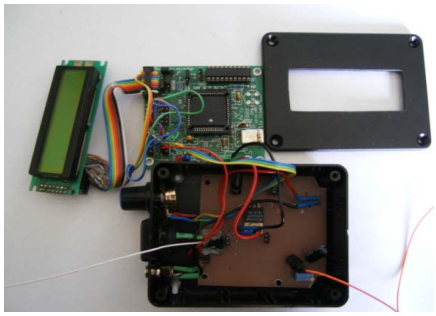

Figure 4. Manufactured electronics.

IV. Experimental Results

In order to determine if the microfluidics system is able to detect particles and what solutions it is able to detect particles in, a set of experiments were conducted. The experimental procedure is as follows:

- Use the input tube and draw deionised water into it.
- Insert into the input hole of the microfluidics chip.
- Let gravity feed water through the channel.
- Once the water has pooled at the output reservoir the channel has been wetted and is ready to test solutions.
- Prepare a sample for testing; first if the sample is a solid it needs to be suspended in the deionised water also the liquid samples may need to be diluted depending on the consistency and particles.
- Get a small amount of solid sample and place onto the glass slide. Use the scalpel to chop the solid to ensure the clumps are broken up.
- Put a small amount (the size of a match head) of solid into a container and add 50ml deionised water. Shake/stir the sample to mix.
- When the sample is suspended evenly it needs to be quickly put into the microfluidics system. If too much time elapses the solid will settle on the bottom.
- Pull out the input tubing and draw the suspended sample into the tube. Re-insert into the microfluidics system.
- Now the sample will start to flow through the channel.
- The voltage reading that shows if the particles are flowing through the channel is recorded.
- Remove the input tubing, flush with deionised water, draw deionised water into the tubing and allow to flow through the micro-channel to clean.
- Once the micro channel and components have been cleaned via flushing the system can be re-used.

The food substance samples tested are listed in Table II. Figure 5 shows the complete system that is running a test. On display from left to right, the following parameters are shown: output voltage, particle count, and reference voltage.

TABLE II.
SAMPLES USED IN TESTS

Sample	Particle Size
Ground Coffee	5-400µm
Talcum Powder	1-50µm
Ground Ginger	25-40µm
Soy Sauce	5-1000µm
Paprika	20-300µm
Mustard Powder	6-10µm
Chicken Stock	50-1000µm
Food Dye	Unknown

The sample images shown in Figure 6 represent the recording of the output voltage of the receiver. When the voltage drops, it is due to a particle or clump of particles passing through the light beam of the sensor. They are counted in the developed codes by setting a threshold to represent the number of particles that pass through the channel. The figures use 0.4ms time/div, the voltages are on the right axis in blue

V. Discussions

It was observed that the output voltage of the receiver was varied according to how the chip was assembled. This is due to the alignment being different and mainly how the fiber optic cable was cut at the end, whether it was a good dissection of the cable or when the fiber was cut if it had fractured/chipped. The initial voltage when only deionised water was in the channel did vary. This was due to different chips being used. Some chips had been used more than several times. Primarily it would be ideal if the microfluidics chips were a one use disposable device thus reducing the effect of channel wear. Some samples had particle sizes of a large variation in size. This resulted in problems as they were seen to block the channel or the reservoir and cease channel flow (see Figure 7).

Therefore the method of using a scalpel to separate particles reduces the effects.

In preparation, when suspending the sample in deionised water, it is essential to work quickly so the particles don't settle. If they do, the possibility of clumping increases. It will result in many particles being read as one large particle.

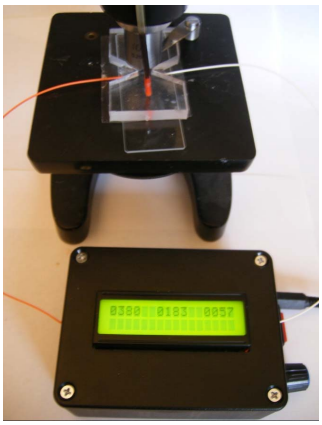

Figure 5. Complete system running a test.

There were several hurdles that were found during the manufacturing and development of the microfluidics sensing system. It was identified that there was no mention of how to affix the fibers to the hardware during the literature research. As the fibers needed to be within 10 degrees perpendicular to the output and input of the emitter and receiver respectively, it was important the fibers remained well secured.

As the receiver was in a plastic housing, it has excellent adhesion properties with epoxy resin. Therefore the fibers were aligned perpendicular to the housing and secured with clear epoxy. The securing of the fibers to the emitting hardware was more complex as it needed to be a certain distance from the laser beam and also perpendicular. As the housing was brass with a hollow design. it didn't allow the fibers to be affixed to the housing. A plastic adaptor between the two was fabricated. It consisted of 3mm ID plastic tubing which sleeved onto the laser diode housing. The end of the plastic already had an enclosed end; it was drilled to allow fiber insertion. The fiber was inserted and observed for best fit. Epoxy resin was then used to secure into in place. The laser diode, adaptor and a section of the fiber optic cable were then surrounded with heat-shrink to reduce light loss and to make rigid.

The amount of light did pose a problem. All electronics were housed in a matt black plastic enclosure. It was proven to reduce light interference thus increasing system stability and versatility.

The PDMS slabs have micro-channels scribed into them, as these are micro channels and not tubes, the channels need to be enclosed so that it can be pressurized. To do so there were many different methods all of which needed complex and expensive equipment. It was a problem as the resources weren't available to enclose the chips therefore they were useless. After brainstorming, a method of enclosing the channels was discovered. The method utilizes Contact Adhesive; this material can be cut to size easily, is clear and offers excellent adhesion properties to the PDMS chips. The material is cheap and produces a good bond to the PDMS chip, although it will not hold under high pressure, it suffices for this project's scope (see Figure 8). The Contact Adhesive does not hinder the particle flow and all results using this method are positive as seen in experimental results. This method of channel enclosure wasn't mentioned in any literature found or as a patent to date.

An overall goal of the project is to eventually integrate all electronics onto the PDMS chip. From the experiments conducted, it was evident that in some microfluidics chips there is a noise in some and much less in others. Sample preparation proved to be vital as without the correct technique, the sample would settle if it wasn't suspended correctly. Also noted that to stop clumping of particles, detergent of similar could be tested to make the particles resist adhering to each other.

The gravity fed sample insertion using a tube proved to be a workable option but as the amount of fluid is constantly flowing through the channel, this means that the pressure is dropping. A method of ensuring constant pressure would result in the particles moving at the same velocity and thus increasing result repeatability and accuracy. For the food substance samples tested, there were problems with size variations of the particles. Some samples were found with particle size variations of approximately 2-2000µm. This posed a problem

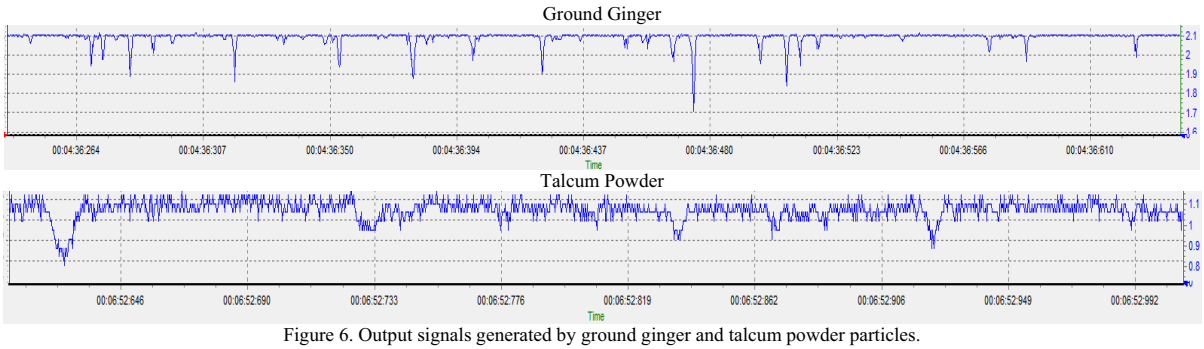

Figure 6. Output signals generated by ground ginger and talcum powder particles.

as the micro channel was only 100µm wide and deep. Therefore some samples would not be able to fit into the channel and result in channel or reservoir blockage. The samples that had a small enough particle variation flowed through the detector system. Of the samples tested Ground Ginger and Talcum Powder were the two samples which produced the best results as the particle variation was small allowing all particles to flow through the sensor system. From the results, ground ginger proved to be the most promising. An insignificant amount of noise was constant in the system and the particles could be easily identified as they had a voltage drop of up to 0.5V. The data retained from the soy sauce tests proved to be inconclusive.

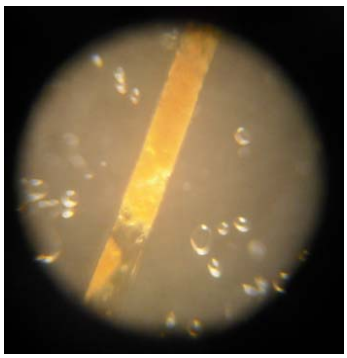

Figure 7. Channel blockage for mustard powder (x100 microscope).

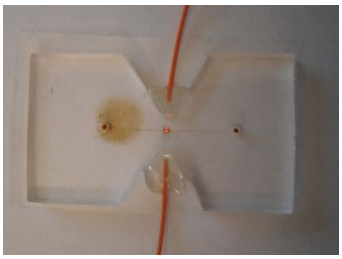

Figure 8. When a great amount of pressure is applied, the adhesive pulls away as seen in the left reservoir.

VI. CONCLUSIONS

An optical micro-sensor system capable of detecting food substance particles was presented. Optical fiber is integrated onto a microfluidics chip. The system consists of a microcontroller and associated circuitry, a laser emitter, a laser receiver, optical fiber cables, a microfluidics chip, and the samples to be tested. The hardware for detection was chosen as the TSL257 light to voltage converter and the APC 10mW laser diode. For the samples tested, there were some problems with size variations of the particles. The changes in the collected signals are analyzed to count the number of particles. Experiments were conducted on several food substance samples including talcum powder, ground ginger, and soy sauce. Some samples were found with particle size variations. This posed a problem as the micro channel was only 100µm wide and deep. Therefore some samples did not fit into the channel and result in channel or reservoir blockage. The samples that had a small enough particle variation flowed through the detector system. Of the samples tested Ground Ginger and Talcum Powder were the two samples which produced good results as the particle variation was small allowing all particles to flow through the sensor system. Not only was the aim of the project achieved, there was also much learning along the way.

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