Control of non-linear actuator of artificial muscles for the use in low-cost robotics prosthetics limbs

IOP Conf. Series: Materials Science and Engineering **257** (2017) 012073 doi:10.1088/1757-899X/257/1/012073

Control of non-linear actuator of artificial muscles for the use in low-cost robotics prosthetics limbs

Nurul Anis Atikah[4*], Leong Yeng Weng[1, 4], Adzly Anuar[2, 4], Chau Chien Fat[1, 4], Khairul Salleh Mohamed Sahari[2, 4] and Izham Zainal Abidin[3, 4]

[1]Department of Electrical and Electronics Engineering, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.
[2]Department of Mechanical Engineering, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.
[3]Department of Electrical Power Engineering, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.
[4]CAMARO Research Group, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.

[*]Corresponding author: anisatikah17@gmail.com

Abstract. Currently, the methods of actuating robotic-based prosthetic limbs are moving away from bulky actuators to more fluid materials such as artificial muscles. The main disadvantages of these artificial muscles are their high cost of manufacturing, low-force generation, cumbersome and complex controls. A recent discovery into using super coiled polymer (SCP) proved to have low manufacturing costs, high force generation, compact and simple controls. Nevertheless, the non-linear controls still exists due to the nature of heat-based actuation, which is hysteresis. This makes position control difficult. Using electrically conductive devices allows for very quick heating, but not quick cooling. This research tries to solve the problem by using peltier devices, which can effectively heat and cool the SCP, hence giving way to a more precise control. The peltier device does not actively introduce more energy to a volume of space, which the coiled heating does; instead, it acts as a heat pump. Experiments were conducted to test the feasibility of using peltier as an actuating method on different diameters of nylon fishing strings. Based on these experiments, the performance characteristics of the strings were plotted, which could be used to control the actuation of the string efficiently in the future.

1. Introduction

The efficiency of prosthetic limbs today is limited by the actuator technology such as the motor. The motor being a staple of electric to mechanical transducer increases the mass of the prosthetic limbs while at the same time requiring additional electrical energy in the form of bulky batteries to move it. This results in a limited mobility time for users attached with prosthetic limbs [1]. Hence, researcher around the world are finding ways to create a relatively low-cost, lightweight and sufficiently powerful actuator to replace the current actuator technology which will significantly benefit the users. Typical users of the prosthesis are amputees. Young amputees in particular require their prosthetic limbs to be refit once or twice every year as they continue to grow. [2] As such, costs to replace them are expensive and research has shown usage of SCP [2], can reduce the costs significantly.

Natural muscles have many desirable properties such as high power-to-weight ratios, inherent compliance and damping, fast actuation and high dynamic range [2]. Unfortunately, current robotics actuators are unable to attain similar properties especially in a slender muscle-like form factor. A recent discovery showed that artificial muscles made from nylon fishing strings are strong, tough and cheap to manufacture. In addition to that, capable of actively contracting and expanding with much larger force than real muscles[3]. This artificial muscle can be also called lightweight actuators since it does not need any supplementary component and have been proven to produce significant mechanical power when thermally cycled. The aesthetic appearance of the limb could also be more human like with smoothed and rounded contours [2]. Compared to carbon nanotubes constructed artificial muscles, the cost of artificial muscles using nylon fishing string are much lower and furthermore is able to spin rotor at 100,000 revolutions per minutes or more [3]–[5].

Researchers utilizing nylon fishing string mostly employ passive cooling and active heating, to generate fast and large force in contraction but slow stretching during the cooling phase. In order to make to process more efficient, active cooling should be employed. Based on recent literature search, active cooling were only done by scientists at UT Dallas's Alan G. MacDiarmid Nano-Tech Institute teamed with scientist from universities in Australia, South Korea, Canada, Turkey and China [4].
We have also embarked on a research project to explore the feasibility of using Peltier system that can provide compact active cooling and heating as an alternative control method to the artificial muscle actuation of SCP created. It was expected that the contractions and expansions of the artificial muscle would behave in a non-linear manner, and thus requiring experimental study to model this characteristics. Initial experiments were conducted to evaluate the performance of different diameters strings and under similar conditions.

What if there is a simpler and cheaper solution to produce artificial muscles that one day can be used for prosthetic purposes, the first discovery reported that nylon is strong, tough and low-cost nylon strings can actively contract and expand with much greater force than muscles. This new discovery on artificial muscles enabled new opportunities in medical devices among others areas that are just beginning to be explored.[4] Our own skeletal muscle, have similarities with other mammals, which can contract 20% in length and can lift a gallon of milk (3.78 L) [4]. Nylon was found to be capable of contracting in a similar fashion but able to lift a hundred times more load. This means that nylon strings can provide an alternative to conventional motors. It also opens up the possibility of more natural, simple, low-cost and compact devices. Nylon thread can contract by almost 2% in length when heated. It also increased in diameter by 5%. Surprisingly, both of these effects can be combined to make a 20% or more increase in length by producing a coil [4].

Active actuators can be driven using heating and cooling. Transforming a nylon fishing string into artificial muscle is relatively easy. The nylon fishing string need to be twisted until it forms a coil. Activation of the strings can be achieved by any means, provided it can create high temperature such as hot air, hot water, or electric current. For example, using a hot air gun will be sufficient to see the actuators react [3].An activation cycle can be produced by placing the SCP within a tube that allows hot or cool water to be alternately pumped through. A thin metal coating can be used with nylon strings where current can be applied to generate high temperature. Maximum displacement takes place when SCP is heated to just below the melting point. To attain a full displacement, a nylon based SCP needs temperature of above 180℃ [3].

2. Peltier Module

Peltier module is the key component in the proposed control circuit. A thermoelectric (TE) module or Peltier module is a semiconductor based electronic component. It can function as a small heat pump and mainly used in high end refrigerators and other cooling devices. A Peltier module acts as a heat pump when current is flowed through its terminals, where one of the sides will start to heat up and vice-versa for the other side.

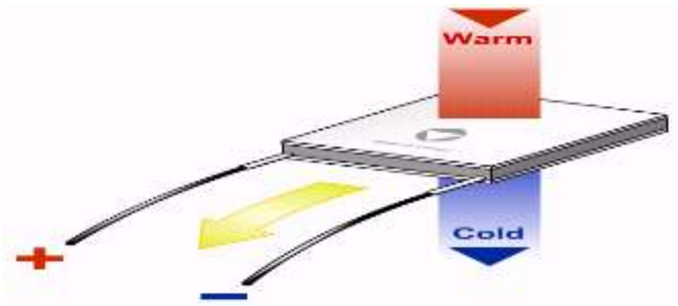

Figure 1. Peltier module[6]

A practical Peltier module, as shown in figure 1, consists of two or more elements of n and p-type doped semiconductor material. Both material are connected electrically in series and thermally parallel. These Peltier modules are mounted between two ceramics substances. The ceramics hold all structure together mechanically and electrically. These substances were insulated with individual elements from one another and from external mounting surfaces. Peltier module has variety ranges in size approximately 2.5 – 50 mm (0.1 to 2.0 inches) square and 2.5 – 5 mm (0.1 to 0.2 inches) in height. Peltier modules available in the market come in different shapes, different substrate materials, and different metallization patterns and different in mounting options [6]. Peltier module is commonly marked with some technical data presented in the form of TEC1-12709 (figure 2). [6]

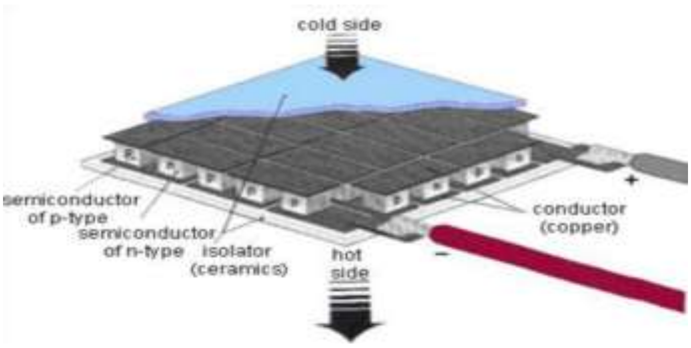

Figure 2. TEC1-12709 construction[6]

During the experiment, hot sides of the peltier module was the base in which the SCP was placed upon while immersed in thermal paste to improve heat conducting from the peltier devices to SCP.

3. Insulated Gate Bipolar Transistor (IGBT)

The Insulated Gate Bipolar Transistor (IGBT) is another important component used in these control circuit. It is a minority-carrier device with large bipolar current-carrying capability and high input impedance. Most designers consider IGBT as a device with MOS input characteristic and bipolar output characteristic that is a voltage-controlled bipolar device. IGBT also can be used in switched-mode power supply (SMPS) and other high switching repetition rates of power circuits. In this paper, the device was used to control the power supply to the Peltier module. The IGBT was connected to the peltier module which was used in this experiment.

IOP Conf. Series: Materials Science and Engineering **257** (2017) 012073 doi:10.1088/1757-899X/257/1/012073

4. Methodology

In this experiment, the nylon fishing strings were twisted using a portable drill that was attached to one end of the line while the other was attached to a 50g mass to create tension while the fishing string was being twisted. After the string was constructed to an SCP, it was stretched across a peltier module attached to a Perspex base. This base can be made up any other materials that can withstand the tension of the SCP during testing.

A Peltier system was constructed by using a 60W Peltier and IGBT, which acted as soft switch for the Peltier. The circuit was connected to two power supplies which were set at 11.2V and 7.3V respectively. The 7.3 volts was supply to turn on the IGBT while the 11.2V was used to energize the peltier. To simplify the circuit, the author's used the functionality of the power supply to control the maximum current which is to be supplied to the individual circuits. The peltier was allowed to sink 3.27 A while the turn on voltage was given a nominal current rating of 0.05A. The circuit diagram is as shown in figure 3. A thermal paste was used to ensure the temperature was evenly distributed from the peltier's hot surface to the SCP. Thermal paste was applied onto the SCP which made it a thermal interface between the peltier module and the string.

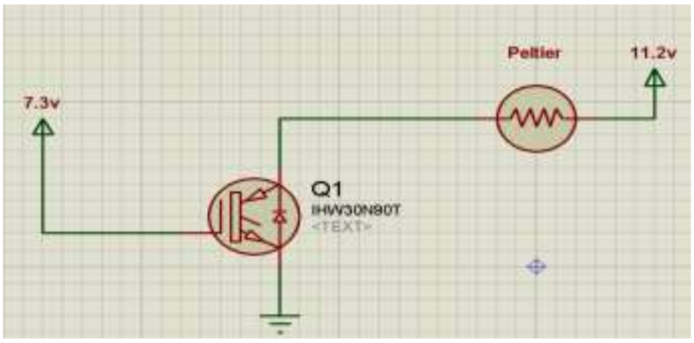

Figure 3. Circuit for IGBT and Peltier

A data acquisition device was connected a load cell rated at 3kg which was then attached to the end of the SCP to collect data during the experiment. The data acquisition device used in this experiment was the Agilent U2351A. In this research, the strings were selected from the same brand, but of varying diameter. Even thermal distribution is important to ensure different thickness of strings reacted within 10 seconds. The experimental set up to test the feasibility of using peltier module to actuate the SCP is shown as in figure 4. Data in this experiment was collected for less than 10 seconds each time and having a cool down period of 10 seconds before the next test was carried out. The forces in this experiment were collected via the load cell in voltage units. The strings with different diameters were tested in this experiment.

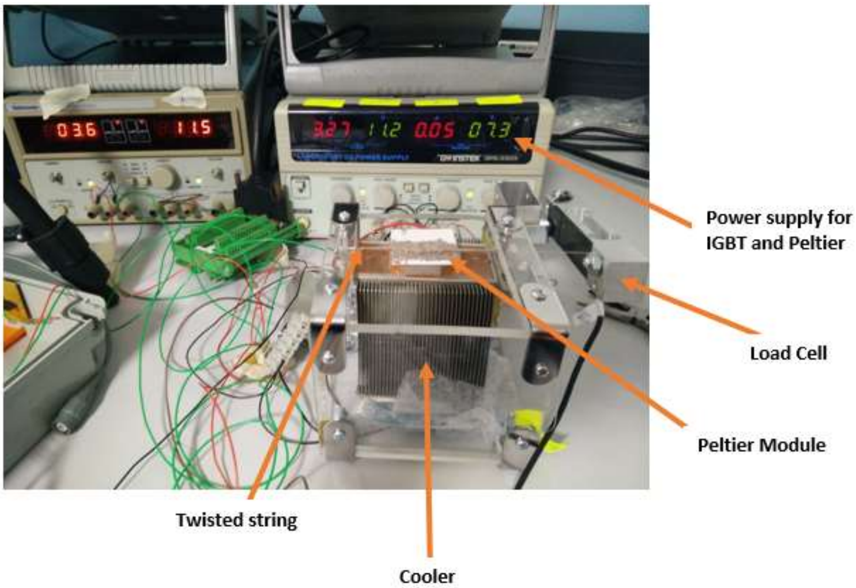

Figure 4. Experiment apparatus setup

5. Results and Discussion

Figure 5 shows the activation point (dotted lines) for the Peltier and the moment for which each of the differently sized strings reacted (solid lines) after the Peltier was turned on. On average, all of the strings took 20 -25 milliseconds to reach their respective maximum contraction force before they started to unravel. The bright red line representing string thickness of 0.55 mm had the shortest reaction time which may due to its small diameter compared to the 0.65 mm and 1.00 mm diameter string. It is thought that small diameter SPC allowed for even and faster heat transmission.

Figure 6 and figure 7 show the reaction times of strings with diameter of 0.45mm and 0.55mm respectively. As shown, smaller diameter strings reacted faster than larger diameter strings. This may due to the uneven distribution of thermal paste along the strings on the Peltier module. The uneven paste distribution could have contributed to uneven heating of the string, which may have led to slower reaction times. The 0.45 mm string had lower reaction times, this may be due to the time needed to heat up the string evenly was shorter compared to the thicker string. From the graph, equations were developed from the respective curves. These graphs were created using polynomial regression functions in Microsoft Excel. The 'y' represents the voltage in volts and the 'x' represents the time in samples from the sampling rate of 10ksa/s. The turn on voltage can be calculated at any given time in samples with the provided equation for specific curve.

Based on the points plotted on the graph, the equation for each line was produced. These equations could be used to describe the characteristics for different diameter strings. In Figure 6 and 7, the force data of each experiment were extract from the times the peltier was activated; to the times, the twisted string achieved maximum force in voltage units. We are particularly interested in this region is firstly because this is the region which effectively generates the maximum force without losing its mechanical properties such as elasticity.

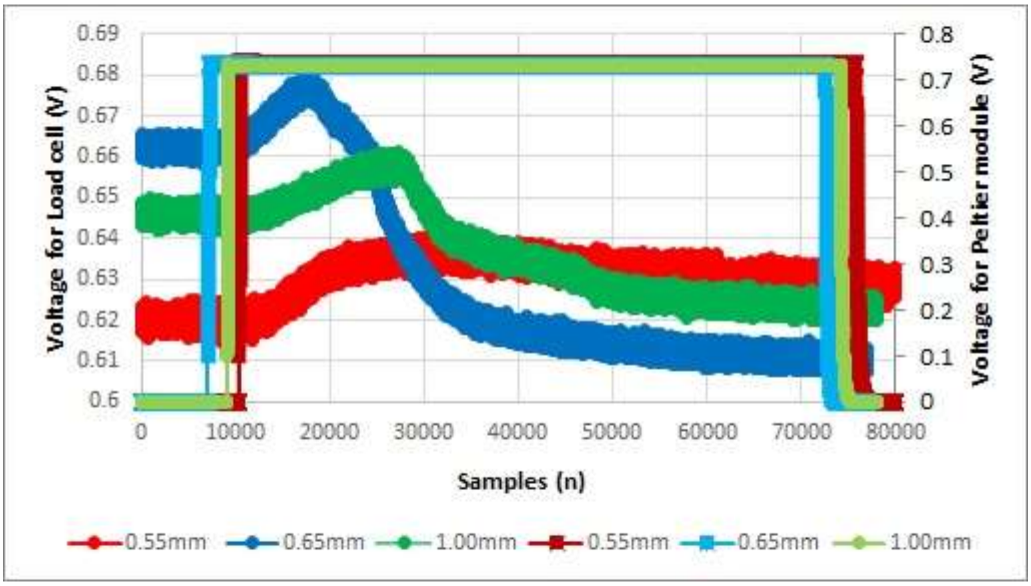

Figure 5. Activation point and characteristics of different diameter strings.

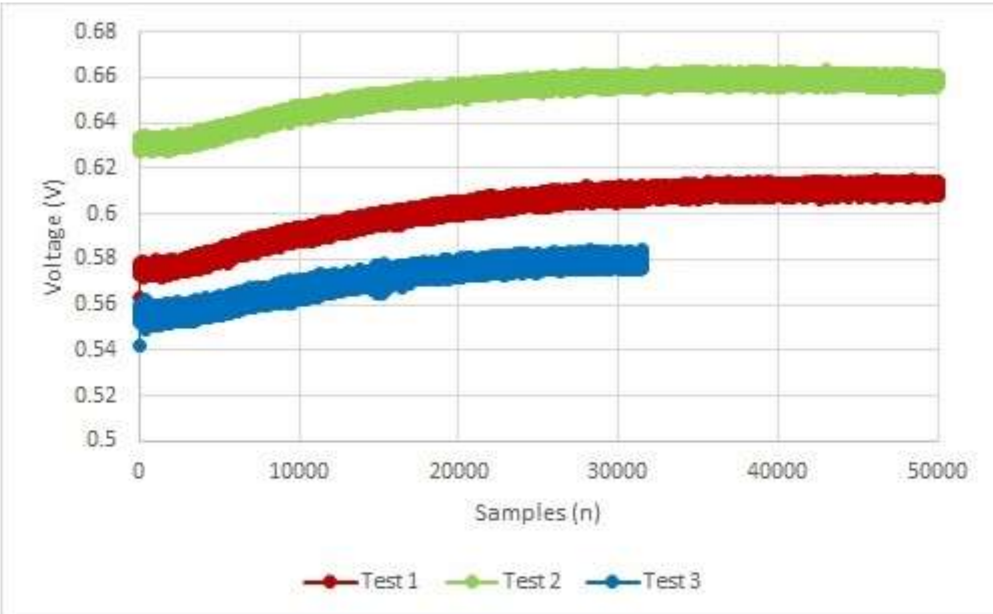

Figure 6. Reaction time for 0.45mm diameter string

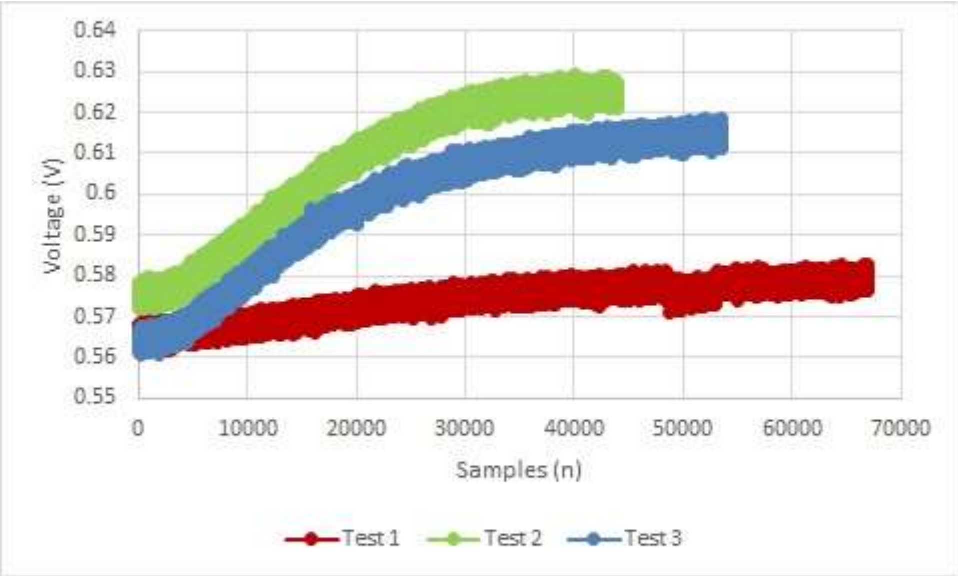

Figure 7. Reaction time for 0.55mm diameter string

In this particular case of figure 6 and 7, it can be seen that the polynomial fits yield equations with low residues of 0.9 and above. This indicates that the base polynomial fit is able to correctly characterize the strings force generation properties in voltage with reference to time.

Equation 1 Equations representing each line for each test of the 0.45 mm string

$$y = 3E\text{-}16x^3 - 4E\text{-}11x^2 + 2E\text{-}06x + 0.5725 \qquad (1a)$$
$$R^2 = 0.9887$$
$$y = 3E\text{-}16x^3 - 4E\text{-}11x^2 + 2E\text{-}06x + 0.6275 \qquad (1b)$$
$$R^2 = 0.9836$$
$$y = -7E\text{-}16x^3 + 7E\text{-}12x^2 + 1E\text{-}06x + 0.5538 \qquad (1c)$$
$$R^2 = 0.9666$$

Equation 2 Equations representing each line for each test of the 0.55 mm string

$$y = 7E\text{-}18x^3 - 4E\text{-}12x^2 + 4E\text{-}07x + 0.5644 \qquad (2a)$$
$$R^2 = 0.9233$$
$$y = -6E\text{-}16x^3 + 1E\text{-}11x^2 + 2E\text{-}06x + 0.5717 \qquad (2b)$$
$$R^2 = 0.992$$
$$y = 9E\text{-}17x^3 - 3E\text{-}11x^2 + 2E\text{-}06x + 0.5589 \qquad (2c)$$
$$R^2 = 0.9909$$

Each equation were the result of one specific diameter string being tested multiple times. Based on the residues, equation 1a and 1b, which have the highest score of reside also exhibit similar coefficients for the equation. The only difference between equation 1a and 1b is the constant, where the difference was only 0.055. As for equation 2a, 2b and 2c, the consistency was not as good as that of equation 1a, 1b and 1c. The residue value varied greatly between the three equations. Despite the equation 2b having the largest residue, the authors think the equation 2c is more likely be the actual characterisation equation for the string of 0.55mm diameter, first being that the coefficient are closer to that of equation 1a and 1b, and also the residue is the second best. Further studies need to be done, but as of now, it shows that the response of the string can be characterised experimentally.

6. Conclusions

The experiment successfully archived the objective of proving that the actuation of SCP can be produced with peltier module. Even so, it was inferred that the string would behave better if it were to be woven or bundled up so that the string can withstand the heating that were supplied by the Peltier module and also increasing the force threshold for the strings. A compact solution to allow for even heating and cooling should be found as the current solution using thermal paste does not perform well. Although other researchers have done the same experiment and resulted with only a 3ms of reaction time, but due to the different usage of material in this experiment, the data collected can be added as a resource to be further researched on. The result looks promising for further improvement and can be further expanded to ensure the artificial muscle made from nylon string works well for the young amputees.

Acknowledgments

This research is funded under UNITEN Internal Research Grant no: J510050638. The authors would like to thank those who had directly and indirectly provided insights which greatly assisted this research.

References

[1] B. Tondu, "A dynamic model of the McKibben artificial muscle contraction," *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, p. 64, 1997.
[2] M. C. Yip and G. Niemeyer, "High-Performance Robotic Muscles from Conductive Nylon Sewing Thread," *Proc. IEEE Int. Conf. Robot. Autom.*, pp. 2313–2318, 2015.
[3] C. S. Haines, N. Li, G. M. Spinks, A. E. Aliev, J. Di, and R. H. Baughman, "New twist on artificial muscles.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 113, no. 42, p. 701-708, 2016.
[4] J. D. W. Madden and S. Kianzad, "Twisted Lines : Artificial muscle and advanced instruments can be formed from nylon threads and fabric," *IEEE Pulse*, vol. 6, no. 1, pp. 32–35, 2015.
[5] U. of Hanyang, "Hybrid carbon nanotube yarn muscle," no. May, pp. 2013–2014, 2014.
[6] A. N. Nikam and J. A. Hole, "A Review on use of Peltier Effects," vol. 2, no. 2, pp. 6–12, 2014.
[7] Data Sheet, "Keysight U2300A Series USB Multifunction Data Acquisition Devices."