A Wireless Monitoring System for Measuring Flexible Tank Strain Using Fabric-Based Stretchable Conductive Sensor

Muhammad Rusydi Muhammad Razif*
Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
rusydi@uthm.edu.my

Nur Jannah Jaafar
Department of Engineering Rapid Manufacturing Connectivity Sdn Bhd
Penang, Malaysia
nurjannahbintijaafar@gmail.com

Nurul Hasyimah Mohd Mustapha
Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
gn210045@student.uthm.edu.my

Yong Tze Mi
Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
tmyong@uthm.edu.my

Nor Shahida Mohd Shah
Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia
Johor, Malaysia
shahida@uthm.edu.my

Muhamad Mohshein Hashim
My Flexitank Industries Sdn. Bhd.
Sungai Petani, Kedah, Malaysia
mohshein@myflexitank.com

Khairul Nizam Mustafa
My Flexitank Industries Sdn. Bhd.
Sungai Petani, Kedah, Malaysia
khairul@myflexitank.com

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***Abstract*— The logistics shipping industry using flexible tanks is one of the shipping industries that has grown globally. Flexible tanks are flexible containers that are usually made of polymers that can be used to transport liquids such as oil and chemicals and are usually loaded in cargo. During shipping, liquids with a large free surface area will experience sloshing due to external induced forces whether transported by land or sea. Uncontrolled sloshing is known to damage flexible tanks and cause leaks where cargo is not only wasted but can damage shipping containers, spill over other shipping containers and cause unwanted environmental pollution. This project aims to investigate the part of the tank that will provide high pressure by using a stretchable strain sensor. The project will also develop a wireless flexible tank monitoring system to continuously monitor the condition of the tank in real time. The resulting tension on the tank due to movement during shipping will be analyzed using a conductive stretchable sensor through the resistance and force data. This project will be implemented using a conductive stretchable sensor, an ESP32 microcontroller, an ESP32 camera, and a Blynk server. The sensor will be installed on a certain part of the flexible tank which is expected to produce a high strain force and then give a reading of the resulting force on that part. Based on the results, this project shows that the developed monitoring system can efficiently analyze the resistance and forces occurring in the flexible tank in real time.**

Keywords—stretchable sensor, flexible tank, wireless technology, internet of things, shipping

I. INTRODUCTION

Nowadays the demand for courier services is increasing rapidly; customers want fast and efficient delivery of the products they purchase. In addition, the transportation of food, medical products and chemicals requires more suppliers to export products to foreign countries. According to the Malaysian cargo and logistics market, the market size for the year 2024 is around USD 28.12 billion and is expected to increase to USD 38.28 billion in 2030 [1]. Demand for this logistics industry is increasing due to the increase in online shopping platforms. Due to changes in shopping habits, the logistics industry must consider long-distance delivery services [2].

There are several types of tanks for liquid transportation such as ocean tankers, flexible tanks, ISO tankers and ICB/drums. Ocean tankers are designed to carry liquid cargo in bulk which can be loaded into liquid tanks using pumps. Ocean tankers also carry various fuels and petroleum products such as gasoline, diesel fuel, fuel oil and petrochemicals with an average capacity of 500,000 to 800,000 barrels [3]. Another shipping transport tank is the intermediate bulk container. Intermediate bulk containers are reusable industrial containers used to transport and store liquid materials and bulk granules. It requires high cost packaging compared to flexible tanks [4]. It also requires special equipment for effective cleaning in addition to requiring a lot of space for storage and high storage costs.

A flexible tank is a type of flexible storage equipment that is widely used to store liquids such as water and oil. It is also known as a container that has a low tank weight, able to support a higher load and low cost [5]. One of the advantages of flexible tanks is that they can be used in remote areas and low storage costs due to the advantages of flexible tanks that can be folded. Since shipping costs using flexible tanks are cheap, suppliers always replace flexible tanks with new tanks for new materials to reduce the risk of contamination of shipping materials. Flexible tanks were first designed to be a more efficient solution to compensate for the disadvantages of other existing options.

Most flexible tanks are manufactured from nylon, rubber, plastic or polyethylene, which can be loaded into the cargo. This type of tank began to be widely used around the world in 2003 and the main application of this tank is to transport various types of liquids including oil and latex. [5]. Usually, the main products carried by flexible tanks are food products and chemical products with different densities and masses. Flexible tanks can safely transport cooking oil, juice, water and various food products. The Food and Drug

Administration (FDA) also accepts food-grade flexible tanks that are also available for domestic and international storage and transportation. Examples of food products carried by flexible tanks are soybean oil, coconut oil, palm oil and fish oil [4].

During shipping, the flexible tank cannot be completely filled in the container because the tank needs some air flow. This is because when the container moves, the surface of the flexible tank can cause the pressure on the container to increase and the additional dynamic force can cause damage to the wall of the flexible tank. According to Haidir Hamdan [6], the highest wall shear stress (WSS) occurs when the volume of material in the flexible tank is around 85% due to the 80% wall shear stress. In order to identify leakage areas on flexible tanks, supply managers have to spend a long time manually inspecting each container because there is no effective real-time monitoring system to assist them. Therefore, by introducing an IoT cloud system, it is able to save time monitoring the condition of the tank in real time. Next, by monitoring and analyzing the fluid pressure in the tank, leaks can be prevented by improving the tank design based on the analysis of tank areas at risk of leaking.

The emergence of the internet of things (IoT) which is increasingly used, gives many advantages in facilitating daily activities. Ovidiu Vermesan, *et al.* [8] describes some areas of IoT applications that can be beneficial in facing the challenges for the next decade. IoT technology can provide many opportunities in industrial sectors such as semiconductors, transportation and mobility, medical applications, communications, e-society and more. Examples of notable IoT applications are smart home security systems, autonomous farming systems, wearable health monitoring systems, environment monitoring system [9] and wireless inventory monitoring systems. There are also researchers who use IoT to monitor the condition of river water in order to anticipate the situation in the event of a flood [10].

According to Mark Weiser [11], the most profound technology is the technology that humans can assimilate to it to the point of being indistinguishable from it. After the emergence of IT and ITeS technologies, there is a significant work transformation taking place in organizations [12]. Giant companies for example use IoT technology to gain huge profits by leveraging IoT to track objects through the commodity chain and make predictions based on rapidly acquired data [13]. An example of a smart logistics industry that plans to implement IoT in the port and container industry is the port of Rotterdam in the Netherlands. The port of Rotterdam is Europe's most important shipping hub, where it handles more than 461 million tonnes of shipments and more than 140,000 ships annually [14]. The port provides employment opportunities for 90,000 citizens and the revenue from the port contributes as much as 3.3% of the Dutch GDP. The port of Rotterdam is expected to be the best example of a transport port that provides transport port facilities to Europe.

In the use of IoT systems, it will usually be connected with sensors to obtain the output that is to be monitored. Among the information that can be detected by the sensor is distance, force, temperature, light intensity, etc. and these data will be sent to other devices for record and monitoring [15]. Since IoT technology is used, the output from the sensors can be transmitted over an unlimited distance. For objects that can move or deform irregularly, stretchable sensors are ideal to use. This type of sensor has various purposes such as monitoring the movement and stretching of objects. For example, this sensor can be used on the human face to identify a person's facial expression based on the stretch of the facial muscles when the person's facial expression changes [16].

In addition to stretchable sensors used in facial expression, Hasyimah *et al.* [17] have developed a stretchable sensor based on conductive threads. The developed sensor is optimized by using spiral type coral and fabric type with a high composition of spandex material. The sensor is then tested for changes in resistance when stretched and manage to achieve the maximum elongation of 36.0 cm. Meanwhile, Maryam Ahmadvand *et al.* [18] proposed an idea to analyze the liquid in a flexible rectangular tank with horizontal cracks by using the Rayleigh-Ritz method. The method used is able to detect cracks on the surface of the tank. Based on the study, it was found that if there is a crack in the tank, the natural frequency of the tank will decrease.

In 2020, Jae Hyuk Choi, *et al.* [19] proposed a flexible strain sensor fabricated by aligned silver nanowires and integrating them with polydimethylsiloxane (PDMS). After that, the direction of alignment with the sensor is compared. Basically, the working principles of the longitudinal strain sensor and the lateral strain sensor have opposite characteristics as the resistance of the longitudinal strain sensor increases. The strain is applied to the nanowire, while the resistance of the lateral strain sensor decreases. Further, the resistance of the side sensor increases slowly as strain is applied to the silver nanowires.

Moreover, in the manufacture of strain sensors, Fatemeh *et al.* [20] proposed the idea of fabricating a screen-printed LC resonant tank-based sensor. In this sensor manufacturing project, the inductor and capacitor are interdigitated in parallel connection. Both inductors and capacitors are then able to analyze the impedance frequency. Both the inductor and the capacitor will provide wirelessly detectable dynamic pressure frequency readings based on the inductor's inductive coupling.

In 2019, O. Tangsirinaruenart *et al.* [21] proposed a stretch sensor to be used for wearable devices. This project uses a sensor made of conductive thread, consisting of silver-plated nylon 117/17 2-ply, 33 tex and 234/34 4-ply, 92 tex and this composed silver will be sewn into knitted fabrics and spandex fabrics. Based on the experiment, the electrical sensitivity and repeatability of the sensor is over 50% and the linearity of R2 is about 0.984 with hysteresis as low as 6.25%, while the gauge factor is 1.61. This study also found that conductors can increase resistance during stretching depending on the length of the conduction path and the cross-sectional area of the conductive thread [21].

II. METHODOLOGY

A. Project Workflow

The project started by implementing an IoT system to a flexible tank prototype with an experimental investigation of the flexible tank's surface tension. The tank used for the experiment is 76cm length, 30cm width and 28.7cm height. It is a real representation of a flexible tank with its size reduced by eight times. During the experiment, water was used to represent the liquid that will be delivered to the user. The resistance and force data resulting from the sloshing effect on the flexible tank are then recorded. A pilot study was conducted by fellow researchers through a tank simulation [6] and a sloshing effect detection experiment using an ultrasonic sensor [22] and this project verified the data taken by them.

In the next phase, the necessary software and hardware were identified to develop an IoT monitoring system. Basically, the system is controlled by using an ESP32 microcontroller. The system is programmed using the Arduino IDE software. For data collection, the ESP32 microcontroller is connected to the sensor and ESP32 camera. The data obtained from this system is then sent to the cloud in real time and can be observed by users using the Blynk application. By using the Blynk app, users can monitor the data collected via a smartphone.

In the next process, the system has been tested and verified to ensure that it works and can collect accurate data. After that, the monitoring system has been installed on the flexible tank. The installation process of this monitoring system begins by installing a conductive stretchable sensor on the flexible tank at the point that is expected to produce the maximum stretch based on preliminary studies through simulation [6]. This conductive stretchable sensor is a fabric-based sensor that can measure stretch by providing a resistance reading [17]. From the resistance data, force value can be obtained through the linearity of the graph and it can be calculated using equation (1), where F is the force in Newton (N) and R is the resistance in Mega ohms (MΩ). Once the stretchable sensor is installed, the obtained stretch data has been processed by the ESP32 microcontroller and verified by the ESP32 camera. The ESP32 is first programmed using the Arduino IDE software and then the functionality of the sensor has been tested. If there are any errors, troubleshooting has been done until it works as desired. Next, the ESP32 microcontroller is connected to the Blynk IoT application. Finally, all components were assembled and tested for functionality. The data from the camera is observed and the flexible tank strain readings through the sensor has been analyzed.

$$F = 0.029R^2 - 0.2438R - 82.5.05 \quad (1)$$

B. System Block Diagram

The microcontroller serves as the main driver of the system that controls all inputs and outputs. In this project, the part of the flexible tank that is expected to produce a high stretch has been installed with a conductive sensor and an ESP32 camera has been placed on the top of the tank. Conductive stretchable sensors are installed in critical parts of the tank that are likely to have higher strains due to the sloshing effect of the liquid during transport. The position of the sensor has been placed in an area that is expected to face a large stretch based on simulations performed by other researchers under the same team [6-7]. The data read by the sensor is then automatically uploaded to the Blynk server in real time and can then be accessed using the Blynk app. The function of the ESP32 camera is to monitor the condition of the flexible tank in the cargo to verify the data from the sensor. Once the sensors and cameras were installed, the tank platform has been moved using transportation simulator model Gaynes 400V to simulate the moving cargo by repeated rotary shock test movement. The data from the sensor and camera have been displayed on the Blynk application and then recorded for analysis. Figure 1 shows the system block diagram of the project.

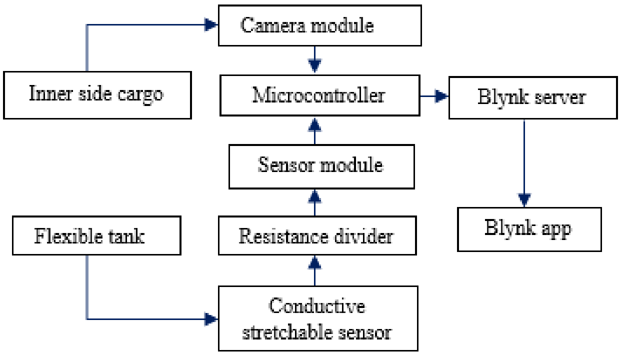

Fig. 1. System block diagram.

The hardware used in this project is a conductive stretchable sensor, an ESP32 microcontroller, an ESP32 camera, a 300 kΩ resistor, and a Blynk application. The composition of the stretchable sensor consists of conductive threads sewn onto a stretchable fabric. The resistance range of the conductive sensor is between 40 MΩ to 60 MΩ and the fabric composition consists of 15% spandex and 85% nylon and it is able to stretch up to 36.0 cm. Figure 2 shows the sensor being stretched using a hot tack tester machine to obtain a relationship between force and resistance readings. During the test, a multimeter is connected to both ends of the sensor to measure its resistance value.

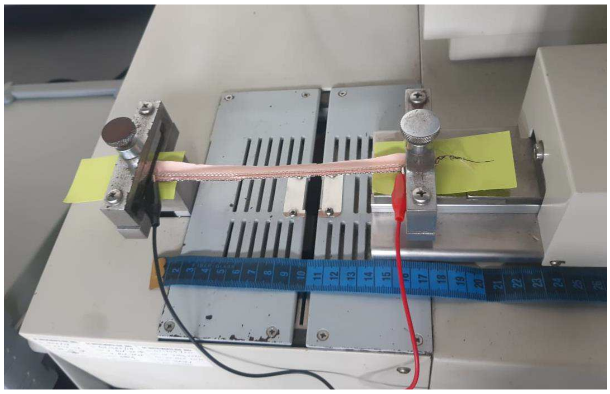

Fig. 2. A stretchable conductive sensor is subjected to a tensile force and a resistance reading is taken using a multimeter.

The setup starts with the ESP32 camera module mounted on the inside of the cargo while the conductive stretchable sensor is mounted directly on the flexible tank. After that, the stretch data is collected from the sensor and the signal is sent to the microcontroller and then displayed on the Blynk app that can be monitored by the user. The microcontroller works as a control for the system that controls all the inputs and outputs. Figure 3 shows the experimental setup of the project.

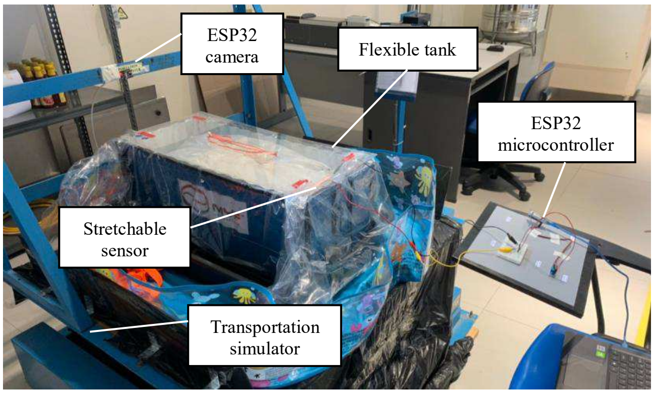

Fig. 3. The experimental setup.

III. Results and Discussion

The results of this project are obtained from the Blynk application that can be accessed through smartphones. This IoT cloud system is capable of monitoring the condition of flexible tanks wirelessly in real time. The results are divided into two parts namely resistance and force measurements and live streaming.

A. Resistance and Force measurement

Figure 4 shows a graph of force against resistance of a stretchable conductive sensor. The force data is obtained from a tensile test using a hot tack tester machine. During the test, the sensor is attached and pulled by a machine to produce a tensile force. At the same time, the ends of both sides of the sensor are connected with a multimeter to obtain a resistance reading. Based on the experimental results, the increased force will increase the resistance of the sensor. By measuring the best fit of the graph, the linear reading with the quadratic characteristic gives an R2 value of 0.887.

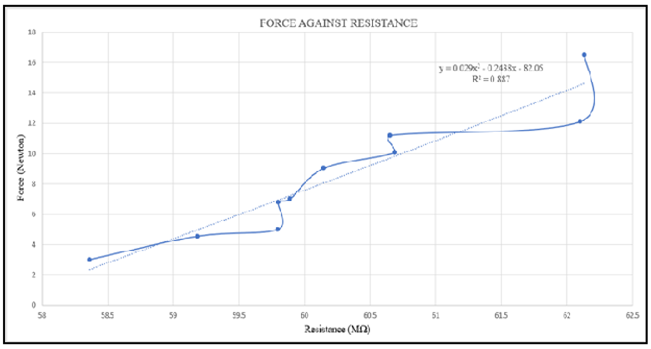

Fig. 4. The graph of resistance (MΩ) against force (N) of a conductive stretchable sensor.

To program the resistance reading in the microcontroller, the resistance value needs to be converted to digital units. For that purpose, the relationship between digital reading and resistance will be calibrated first and the results are shown in figure 5. In this figure, the graph shows that the resistance range of 40 MΩ to 60 MΩ gives a digital unit reading between 3950 and 4000. Relationship between resistance and digital unit in this range is linear with an R2 value of 0.9861. The resistance range is focused on 40 MΩ to 60 MΩ is because in this range the sensor stretches linearly, stable and consistent when subjected to tensile force.

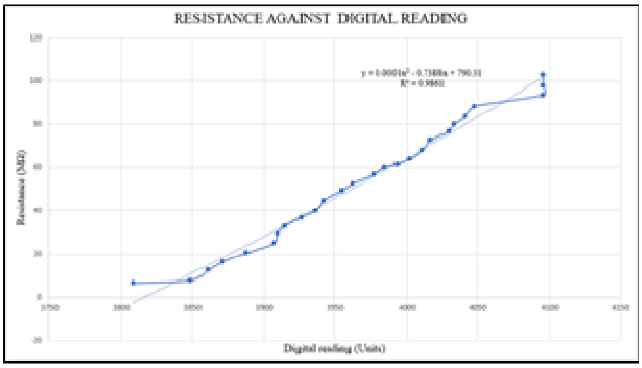

Fig. 5. The graph of resistance (MΩ) against digital readings (Units) for a conductive stretchable sensor.

Figure 6 shows the position of the stretchable sensor placed on the top of the flexible tank, where as figure 7 shows a close-up of the sensor installation on the flexible tank. Both ends of the sensor are connected to the ESP32 microcontroller using a probe that provides a resistance reading. Then the microcontroller will convert the resistance reading to the force reading using equation (1). This force reading is then uploaded to the Blynk server and the user can observe the force reading in the Blynk application in real time. Figure 8 shows the wiring connection of the electronic system. This electronic system consists of components such as ESP32 module, sensor module, resistive divider and conductive stretchable sensor. A resistance divider is needed to control the resistance and get the resistance range as desired. The power supply source to turn on the microcontroller is from a power bank or any USB port with an input voltage of 5 V.

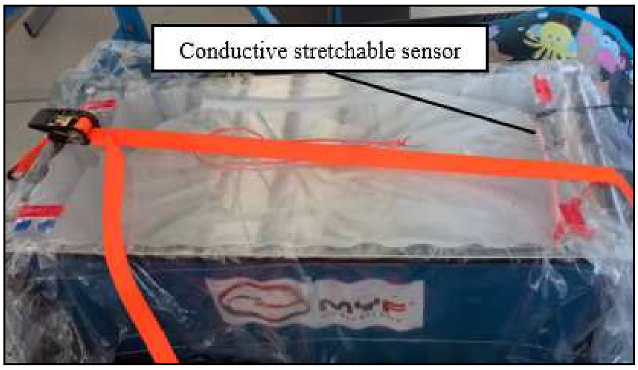

Fig. 6. The conductive stretchable sensor installation.

Fig. 7. Close up of the conductive stretchable sensor.

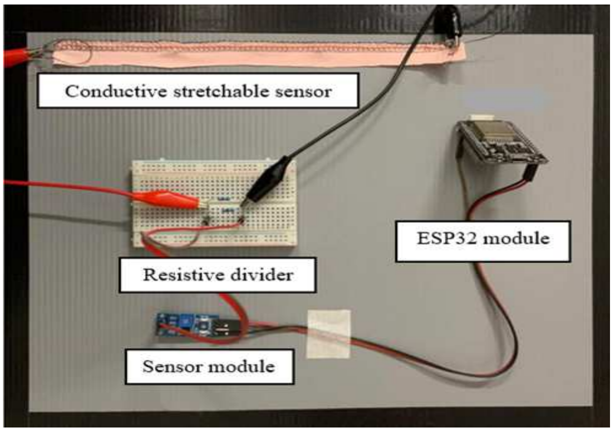

Fig. 8. The wiring connection of the system.

Figure 9 shows the resulting force and resistance readings from the conductive stretchable sensor displayed in the Blynk application. In this application, the live stream of the situation around the tank is also displayed as a result of the ESP32 camera. The diagram on the left (a) shows the initial condition of the resistance reading which is 48 MΩ which is equivalent to the resulting force of 610 mN, where as the diagram on the right (b) shows the resistance reading and the increased force when the flexible tank is shaken by the transportation simulator at a speed of 40%. At the bottom of the graph is a graph of resistance and force produced at a certain time interval.

For a clearer picture, the resistance graph and force readings that result when the transportation simulator is running are shown in Figure 10. In this graph, it can be observed that the resistance readings are between 48 MΩ and 56 MΩ where as the force readings are between 610 mN to 656 mN. It can be observed at certain intervals, the reading of the resistance and the reading of the rising force at the same time indicate the state of sloshing effect and stretching of the flexible tank is taking place. Based on the experiment on the miniature flexible tank, the maximum reading of the resulting strain is as much as 656 mN.

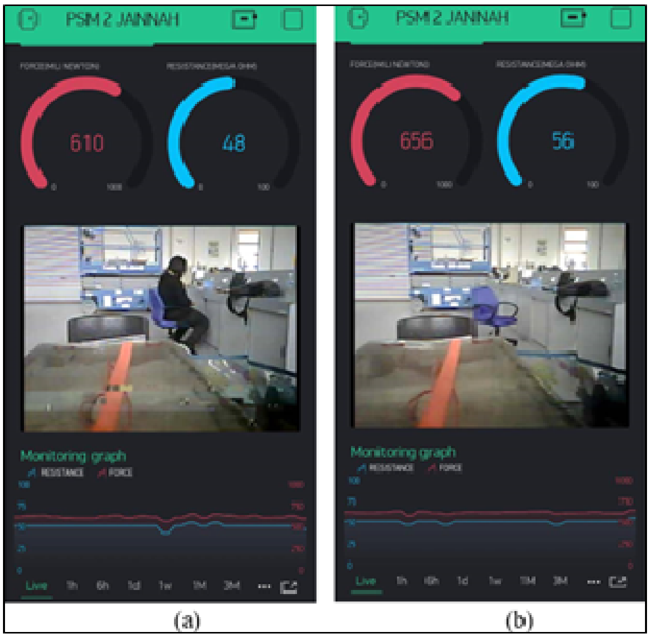

Fig. 9. Interface of Blynk app (a) before shaken and (b) during the transportation simulator run at 40%.

Fig. 10. The graph that generates from Blynk App.

B. *Live streaming*

The function of the ESP32 camera is to monitor the condition of the flexible tank in real time through the Blynk application on the smartphone. Figure 11 shows the ESP32 camera installed on the top of the flexible tank to capture an external view of the tank where as Figure 12 shows the result of a live stream on a smartphone that can show the current view of the flexible tank. Based on the figure, the ESP32 camera is suitable for use in transportation.

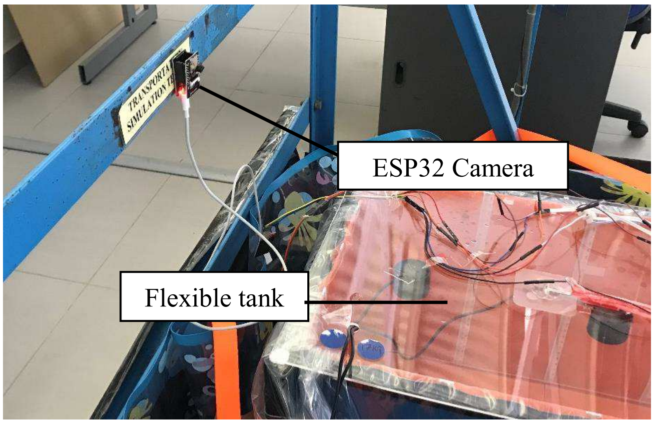

Fig. 11. ESP32 camera installed on top of the flexible tank.

Fig. 12. Live stream of the miniature flexible tank.

IV. Conclusion

In conclusion, this study found that the conductive stretchable sensor is a suitable sensor to be used to measure force and resistance on flexible tanks. The installation of a wireless flexible tank monitoring system capable of continuously monitoring the condition of the tank in real time has been successfully implemented. Additionally, the installation of conductive stretchable sensors on flexible tanks can measure resistance and force readings during testing and can monitor those readings via a smartphone through Blynk application. Based on the experiment, the resistance range is between 40 MΩ and 60 MΩ where as the resulting force on the flexible tank as a result of the 40% shaking transportation simulator is between 610 mN to 656 mN. Finally, the results of this project have the potential to be used on real size flexible tanks.

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