Proposal and Experimental Validation of Suspended and Power-Tethered Drone (SPTD) for Inspection of High Bridges

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***Abstract*—Bridges play an essential role in the economy. Any significant damage requiring close down may halt any economic activity. As such, periodic inspection and maintenance of bridges are of utmost importance. However, the traditional method of inspection using scaffolding is time-consuming and expensive. For instance, bucket trucks for high bridge inspections are costly, dangerous, and cause traffic disruption. Meanwhile, drones can be a cheap and safe alternative method for inspection. However, regular drones have limited flight time and risk falling and getting damaged if the drone malfunctions or drains power.**

This study thus proposes a suspended and power-tethered drone to address the issues of drone use. The drone emulates the bucket truck method for visual inspection. This power-tethered drone is designed to provide the unlimited flight time required for more extended and undisrupted inspection tasks. The tether will also serve as a support if the drone malfunctions. In this paper, we introduce the concept of a suspended and power-tethered drone (SPTD) and the various strategies used in this drone design, including power tether, tether control, and drone localization. Multiple experiments were performed to verify the performance of the proposed system.

***Index Terms*—Unmanned aerial vehicle, tethered-drone, bridge inspection**

I. Introduction

BRIDGES play an important role in the economy. Materials and goods are delivered from one place to another through this infrastructure. And yet, bridges of 50 years old or older are considered among aging infrastructures that frequently require periodic inspections to assess their current condition. Most of these inspections are performed via a close visual inspection conducted by a human inspector. Low-elevation bridges can be observed using scaffolding or by placing a ladder for checking underneath. In the case of high bridges with elevations of 50 m and above, the method of scaffolding can be laborious and expensive. Another method for bridge inspection is the use of a bucket truck, also known as a snooper truck, allowing inspectors to observe the bridge from underneath (e.g., concrete slab) through the bridge deck, eliminating the need to install scaffolding as shown in Fig. 1(a). However, the use of bucket trucks still has several disadvantages. For once, they are expensive pieces of equipment; also, a bucket truck consumes at least one lane that can disrupt traffic, leading to congestion and delays, especially on busy main roads. This method is also risky for any human inspector boarding the bucket, in case there

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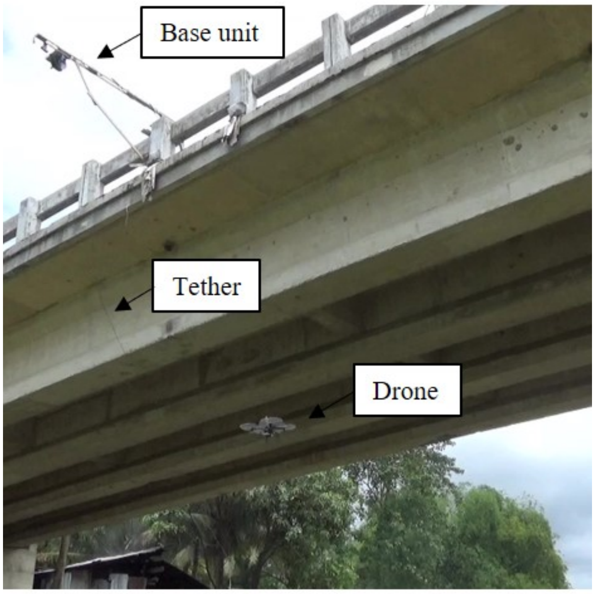

(b)

Fig. 1. (a) Bucket inspection truck and (b) suspended and power-tethered drone (SPTD) for high bridge inspection.

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is a truck failure during an inspection.

Currently, significant interests have emerged in the use of unmanned aerial vehicles (UAVs) or drones for bridge inspection. These can be utilized when visually assessing the bridge underneath and replicating the bucket truck, as shown in Fig. 1(b). Drones are inexpensive compared with bucket trucks and do not require lane closure during the inspection.

Several drones have already been utilized for the inspection of bridges: Salaan et al. [1] used a UAV with a passively rotating spherical shell to access the narrow and complex structure of a bridge. Meanwhile, Kim et al. [2] used a commercial drone and investigated aging bridges using a crack identification method. Also, Feroz and Dabous [3] compiled various remote sensing technologies integrated with UAVs for bridge assessment whereas Chan et al. [4] reviewed the use of UAVs for conducting visual bridge inspections. Jung et al. [5], on the other hand, discussed the significant challenges and solutions from a practical perspective when using UAVs for bridge inspection. And Seo et al. [6] presented a UAS-based bridge inspection method to capture various image data required for damage determination. Adding to these studies, Nohara et al. [7] also developed a drone system embedded with multiple distance sensors while Kawabata et al. [8] introduced an autonomous flight drone with a depth camera for infrastructure inspection.

Most previous works assumed that the drone is operated directly by the human operator and operated on the ground. The bridge deck above is the safest and easiest access for high-bridge inspections. Thus, flying the drone underneath the bridge can be risky because the operator is out of sight. The drone may also lose its signal when operating underneath the bridge for GPS-assisted flight. For a regular drone with exposed propellers, performing a close visual inspection is risky as the drone may collide with the bridge structure while the operator has no direct sight of the drone. If the drone malfunctions during flight, it will inevitably crash to the ground and will be deemed unusable.

This study introduces a new mechanism to address the aforementioned issues of drones for high-bridge inspection. The proposed system emulates a bucket truck using a suspended and power-tethered drone. It utilizes a tether wire to track the position of the drone (related to previous works [9][10] on tethered-drone localization) underneath the bridge. Knowing the position of the drone, the operator can fly close to the structure while maintaining a safe distance from it. With a power-tethered drone, the drone can ideally have an unlimited flight. In the case of drone malfunction, the tether can save a dead drone while hanging.

In this study, the researchers introduced the concept of suspended and power-tethered drones (SPTD). And in this paper, discussed are the methods for the proposed system, alongside the validation results that were performed through various experiments.

II. The Concept of Suspended and Powered-Tethered Drone

A. General Concept

As mentioned in Section I, the use of bucket inspection trucks is an effective method for closely inspecting the structures underneath bridges; however, owing to several issues, it is difficult to utilize them frequently. This paper introduces a simple method of using a tethered drone to emulate a bucket inspection truck for close visual inspection of bridges. It proposes a so-called suspended and power-tethered drone (SPTD).

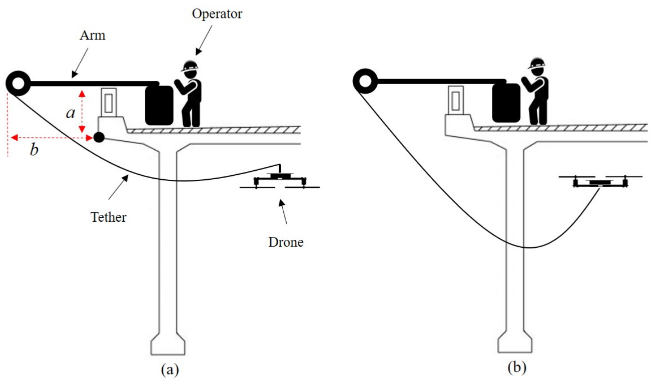

Fig. 2. Concept and configurations of suspended and power-tethered drone emulating a bucket inspection truck.

Two configurations can be implemented for suspended and tethered drones, as illustrated in Fig. 2. Fig. 2(a) shows the first configuration, where the power-tethered wire is attached to the top side of the drone. This configuration provides good positioning for the drone start-up while hanging. However, the top connection of the wire may hit the propellers, as the wire forms a catenary curve. This problem may be solved by (1) placing the propeller at the bottom side and covering it with a propeller guard at the top and (2) providing proper pull-release control for the wire.

On the other hand, Fig. 2(b) illustrates a second configuration where the power-tethered wire is attached to the bottom side of the drone, similar to the usual tethered drone [11][12][13][14]. However, this configuration may require a longer wire compared to that of the first configuration. In addition, the connection at the bottom may not be a good position for the drone during start-up. When the tethered drone is initially suspended, it usually turns upside-down. Several solutions can be used to avoid these issues. Given this, the first shown configuration was used in this study.

B. Horizontal force analysis

The most crucial factor to consider in the presence of a suspended wire is the minimization of the F_{BX} force. This is because the wire forming a catenary curve pulls the drone, and its horizontal movement is affected. Fig. 3 shows the forces acting on the suspended wire. The tether can be treated as a uniformly loaded cable with inclined chords [15]. The horizontal force F_{BX} can be calculated as

$$F_{BX} = W\frac{a^2}{2h_1} \tag{1}$$

,where a is the horizontal distance from the lowest sagging point C to B and h_1 is the vertical distance between point C and B.

Based on Eq. 1, F_{BX} decreases as the horizontal distance from the lowest sagging point C to B decreases. Ideally, it

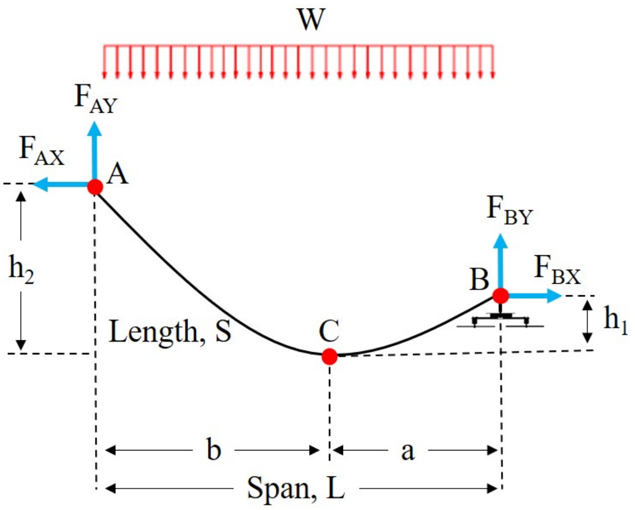

Fig. 3. Suspended wire as a uniformly loaded cable with inclined chords.

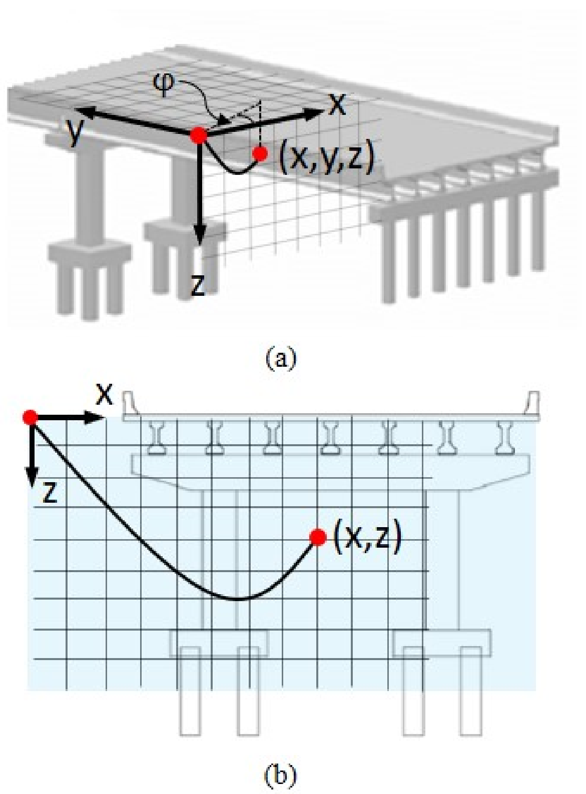

Fig. 4. (a) Representation of a suspended tether in three (3) dimensional space and (b) x-z plane showing the catenary curve of the wire.

is desirable to have a minimum value of a. However, it is important to note that as a decreases, the wire may be hit by the propeller. Thus, it is necessary to control the sagging of the wire to minimize the F_{BX} while avoiding the propeller. This is the basis of the control strategy. Controlling the tether is also important to maintain the catenary form and prevent inconsistencies for localization purposes.

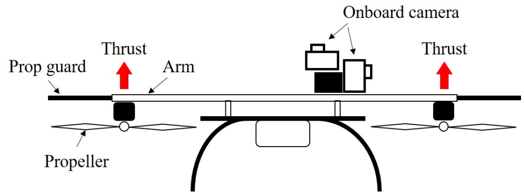

Fig. 5. Drone configuration for the SPTD where the propellers are placed at the bottom side of the arm.

C. Localization of suspended and tethered-drone using neural network

The localization of a tethered drone for bridge inspection is essential during the inspection process. It provides information about the position of the drone to avoid any hit with the bridge structure and provides the locations of any abnormalities (e.g. cracks) in the structure relative to the drone's position. Tethered-drone localization has also been employed by several researchers [9] [10], but with a tethered wire attached to the ground. This research, on the other hand, introduces a new localization setup.

Consider a bridge in three-dimensional space as illustrated in Fig. 4(a), where the position denoted as x, y, and z of the drone can be estimated based on the position, weight, and length of the wire. In the $x - z$ plane, as shown in Fig. 4, (b), the positions x and z can be estimated using the length and weight of the wire. However, it is challenging to solve catenary equations, which are likely to be considered transcendental functions. [17]. To determine the positions x and z given the length and weight of the wire, the researcher opted to gather data and then train a neural network to model the relationship between the position and the length and weight of the wire.

In this study, a neural network was used. It offers several advantages to this application, such as requiring less formal statistical training, implicitly detecting complex nonlinear relationships between dependent and independent variables, and detecting all possible interactions between the predictor variables [16].

Meanwhile, the proposed system assumes that it is possible to determine the drone's location in the y-direction on the bridge, taking the drone lying on the x-z plane. In this case, position y has been put aside to be implemented for future research.

III. DESIGN OF THE SPTD

The proposed system comprises of four (4) main units: the drone unit, power-tethered unit, tether control unit, and localization unit.

Fig. 5 shows the configuration of the drone for SPTD, where the propellers are positioned at the bottom side of the quadrotor arms. It is purposely installed at the bottom side to avoid hitting the wire, as it also requires the wire to be lowered to minimize the F_{BX} as discussed in Section II. The propeller guard also provides extra protection for the wire against the propeller.

For the power-tether unit, Fig. 6(a) shows the components that include the AC power source, high-voltage AC/DC rectifier, power tether, and the DC converter.Meanwhile, the system will be powered through the AC outlet, but a battery

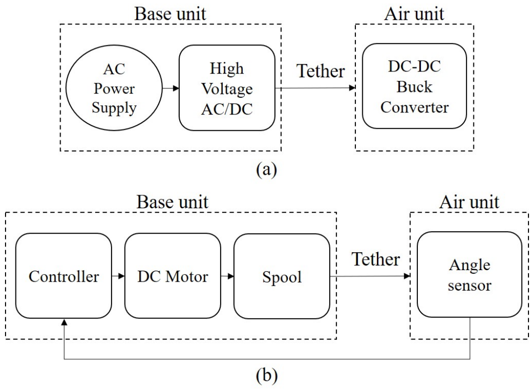

Fig. 6. Components of a power-tether unit and tether control unit.

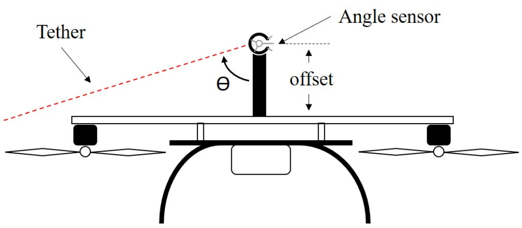

Fig. 7. Illustration of the required angle for control.

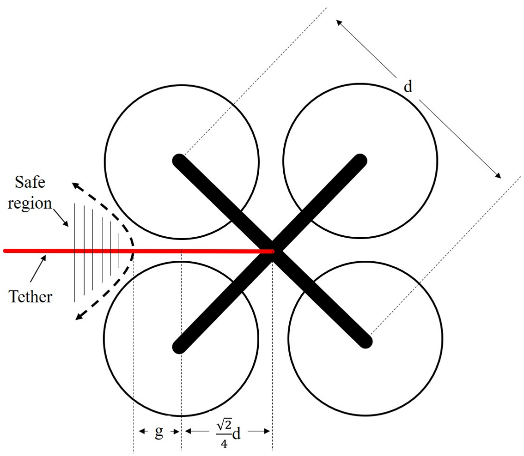

Fig. 8. Illustration of the safe region to lower the tether/wire for X-frame type quadrotor.

system will be used for the final deployment. One of the important factors to be considered for the power-tether unit is the selection of a tether (wire) that can provide sufficient power for the drone while minimizing the weight of the cable. For instance, Kiribayashi et al. [14] proposed a method for the optimal cable selection for a power-tethered drone. In this study, the strength of the wire was considered as it can additionally become the drone's support in case the power supply suddenly shuts down.

For the tether control unit, Fig. 6(b) shows the components, including the spool, the DC motor for releasing and pulling the wire, the controller, and the angle sensor. The wire needs to be controlled to minimize the F_{BX} such that it does not hit the propeller. Fig. 7 shows the equivalent angle for the control. The opposite side dimension of the angle can be computed where the propeller will not hit the tether.

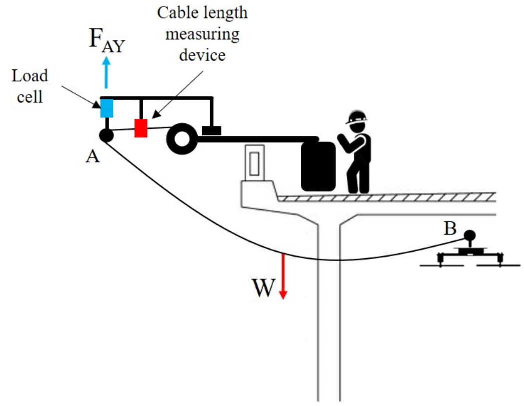

Fig. 9. Illustration of the localization components such as force sensor and wire length measuring device.

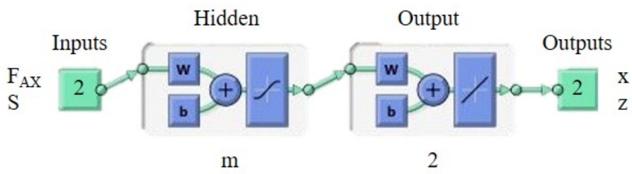

Fig. 10. Neural network model where F_{AY} and S are inputs and x and z are the target outputs.

For instance, an x-frame configuration for the quadrotor is shown in Fig. 8, which indicates that the tether can be extended inside the safe line. On the other hand, other drones may depend on the configuration and the distance between adjacent propellers. Therefore, for this study, the minimum angle that can be considered safe for the wire not to hit the propeller can be estimated as

$$\theta_{min} = \arctan\left[\frac{g + \frac{\sqrt{2}d}{4}}{offset}\right] \tag{2}$$

For motor action, the motor releases the wire when $\theta > \theta_{min}$ and pulls the wire when $\theta < \theta_{min}$.

For the localization unit, Fig. 9 illustrates the two main components needed for localization: the vertical force F_{AY} felt by the load cell and the length of the cable as estimated by using a wire length measuring device. As mentioned in Section II-C, a neural network is used to estimate the positions of x and z. Several data will be collected with the following parameters: x, z, F_{AY}, and S, where S is the length of the wire from points A to B. The data was obtained by taking sample points on the grid (as illustrated in Fig. 4(b)) for x and z and then measuring the values of F_{AY} and S using the load cell and wire length measuring device, respectively. The neural network model is shown in Fig. 10, where F_{AY} and S are the inputs to the network, and x and z are the outputs.

IV. Results and Discussion

Fig. 11 shows the entire assembly of the SPTD. Fig. 12 shows the components attached to the drone, including the DC-DC converter and the angle sensor unit. A prop guard with a net was added to the drone as extra protection for the wire to avoid hitting the propellers.

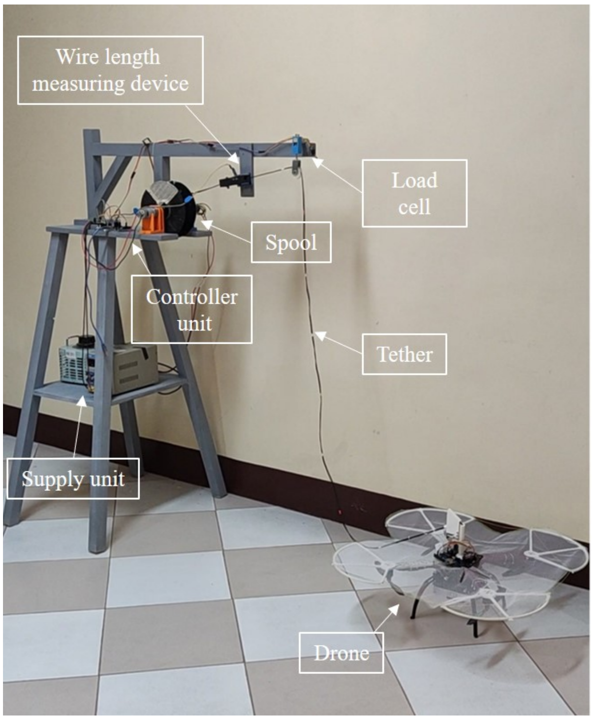

Fig. 11. Whole assembly of SPTD

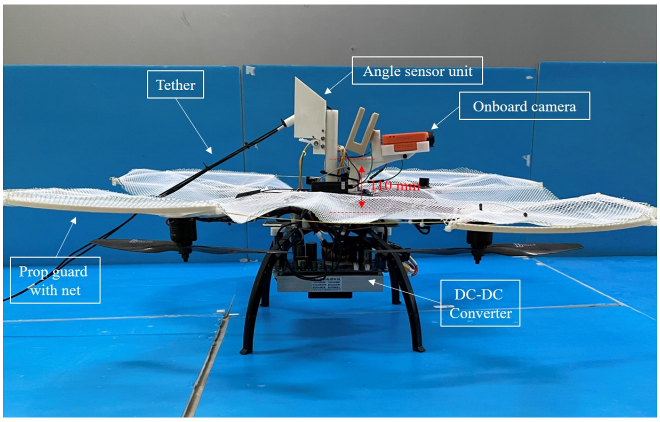

Fig. 12. Drone assembly.

The system utilizes a quadrotor with a 450-mm diameter frame, a 980-KV brushless motor, and a 10-inch propeller. The total weight of the quadrotor with the other air unit components was approximately 1570 g.

The power-tethered unit utilizes a 70V AC supply and is rectified to create a 70V DC output. A DC-DC converter installed in the air unit has a rating of 70V DC to 16V DC with a maximum power of 800 W. The wire selection was based on ampacity, weight, and strength, as mentioned in Section III. The power and voltage rating required a suitable wire for handling a 14 A electric current.

Table I presents the wire-selection evaluation. The results show that an 18 AWG wire can ideally handle the required current with minimal weight density compared to 16 and 14 AWG. However, during the drop test of a 5.6 kg load at a 1.2 m drop height, the 18 AWG wire snapped. To solve the problem, a high strength 0.5-mm nylon monoline with a weight density of 0.27 g/m was added to support the 18 AWG. As a result, the 18 AWG with the nylon held a drop

TABLE I
WIRE EVALUATION

Wire size	Ampacity (A)	Weight density (in g/m)	Drop test
20 AWG	13.87	14.1	Failed
18 AWG	22	22.8	Failed
18 AWG w/ nylon	22	23.07	Passed
16 AWG	35	38	Passed
14 AWG	55.6	56.3	Passed

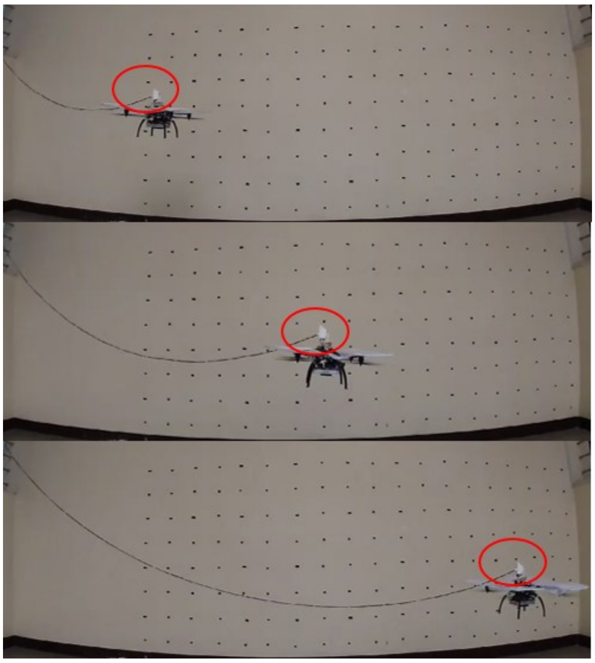

Fig. 13. Actual flight test of SPTD showing the tether angle θ remains the same given the different location of the drone.

test height of 1.2 m using the 5.6 kg load. In addition, it could hold on to a 4.28 m drop height for the 1.57 kg actual weight of the drone. Much larger diameter nylon can be used to provide a much heavier drone, but it is important to always take note of the weight added to the entire system.

For the tether control unit, the angle sensor, as shown in Fig. 12 provides feedback to the controller in the base station. This study utilized a simple angle sensor based on time-of-flight (TOF) distance measurements. It measures the vertical movement of the tether and converts the distance in terms of the angle. From Eq. 2, the θ_{min} with values for the $offset$, g, and d are 110 mm, 30, and 450 mm, respectively, will result to an angle of 59.8 °. A simple PD control was implemented with Gain K_P and K_D equal to 15 and 1.4, respectively. The reference tether angle for the controller was set as 70 °.

A flight experiment was concluded to test the reaction of the motor with respect to the measured tether angle, as shown in Fig. 13. It can be visually observed that the tether angle remains fixed despite the drone being positioned at different locations. The flight experiment was also confirmed quantitatively by the reaction of the motor (change in speed and rotational direction) based on the measured angle as

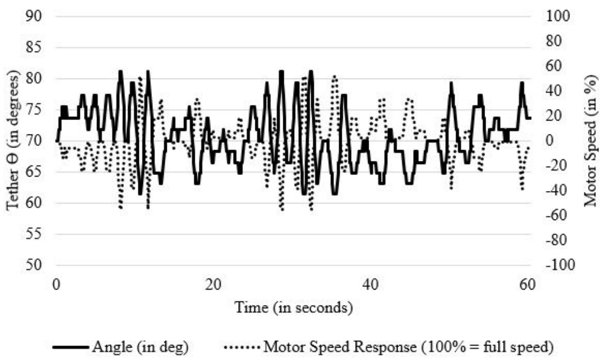

Fig. 14. Recorded measured angle and corresponding motor speed response. Negative value for the motor speed means reverse direction.

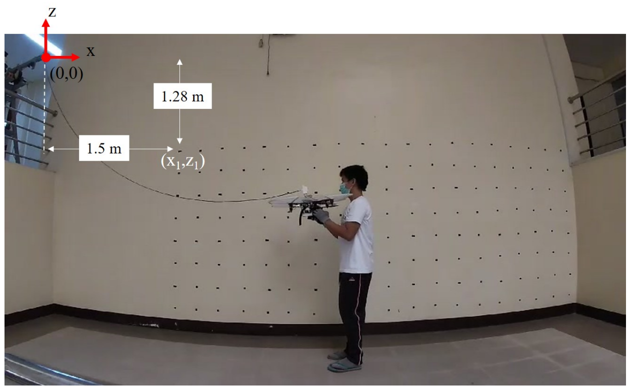

Fig. 15. Actual footage of data gathering for localization.

TABLE II
TRAINING RESULTS.

	Samples	Mean squared error (MSE)	Regression (R)
Training	96	0.0108502	0.998567
Validation	20	0	0
Testing	20	0.0834411	0.999016

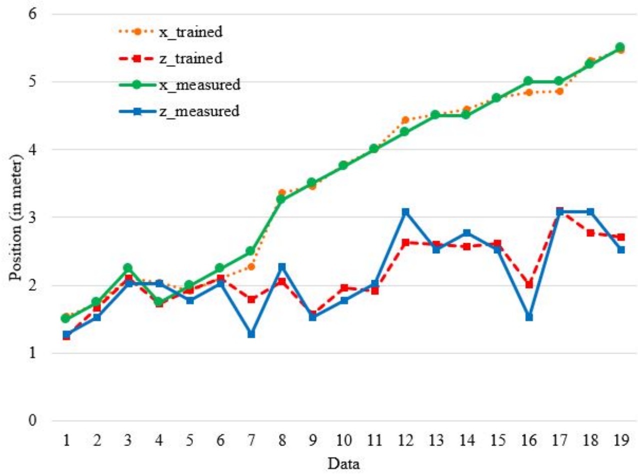

Fig. 16. Sample data showing the comparison between trained and measured data for the x and z position.

illustrated in Fig. 14. With a reference angle of 70 °, as the tether angle increases, the motor releases the wire (shown as a negative value in 14), and motor speed (in % of the motor at full-speed) changes based on how significant the change in tether angle.

For localization, the researchers initially gathered the data for the x and z positions by setting up several points on the wall, as shown in Fig. 15 and then measured the corresponding F_{AY} and S. A total of 136 data points were collected. The data are then divided into 96, 20, and 20 for training, validation, and testing, respectively.

In this study, the network utilizes Bayesian regularization as a network algorithm. The training results are listed in Table II. Fig. 16 shows a comparison between the trained and measured data for the x and z positions. The network predicted the x and z positions fairly. The predicted values can be further improved by adding more data for training and exploring different or improved network algorithms.

The system was initially tested in the laboratory as shown in Fig. 17. The flight attitude of the tethered drone is shown in Fig. 18. An actual bridge experiment is conducted to verify the performance of the system. Fig. 19 shows the setup of the bridge with the SPTD unit, the drone operator, and the system operator. The system operator controls the action of the tethered drone through the laptop. The drone operator controls the drone through the information obtained from the localization method and from the onboard camera. Fig. 20 shows the tethered drone flying underneath the bridge. Fig. 21 shows the view from the onboard camera.

Fig. 22 and 23 show the screenshots of the software application for the system. Manual and automatic control of the tether was added to the application. For the localization, the load cell and wire length were obtained and converted to the drone's x and z position using the trained localization network. Visualization underneath the bridge was also added

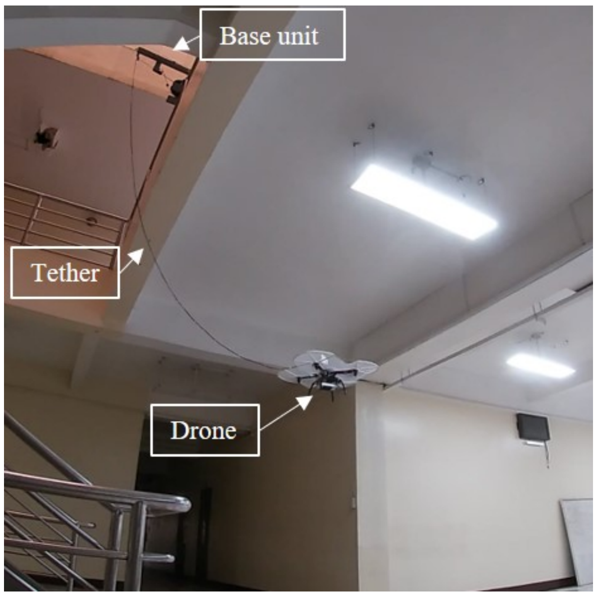

Fig. 17. Actual image of tethered drone durong laboratory-based experi-ment.

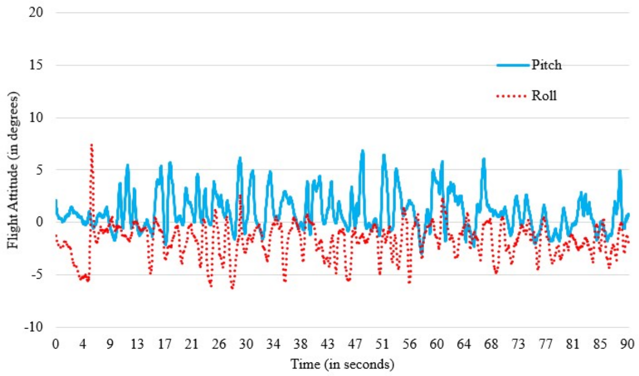

Fig. 18. Graph record of flight attitude of the tethered drone during the conducted experiment.

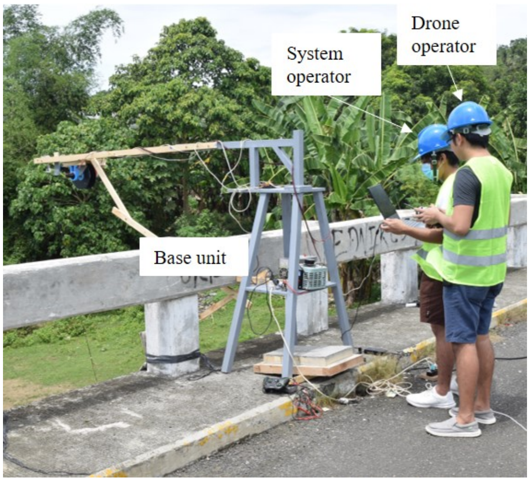

Fig. 19. Experimental setup on the bridge.

in the application to aid the drone operator during flight, providing more information about the drone's position. A distance sensor was added onboard to measure the distance between the drone and the nearest obstacle for additional protection.

Several observations for improvement were noted during the experimental validation. The current DC-DC power converter can be replaced with a high-power DC-DC converter for the power-tether unit. Also, the drone can provide more thrust to add more components needed for inspection and can have additional counters for any horizontal force acting on the wire.

However, note that increasing the power requires a larger ampacity for the tether wire, which also eventually requires a larger wire. Still, larger wires can provide better strength to hold the drone in case of any malfunction. It is also important to consider and evaluate different tether (lightweight) supports aside from adding a nylon line (e.g., braided fishing line) that can better support the primary wire providing optimal strength and weight to the device's overall functionality.

For the tether control unit, the angle sensor based on TOF measurement can be replaced with a rotary sensor (e.g., potentiometer or IMU) to provide a better angular measurement. More accurate angle data can aid the controller in providing an accurate response for the motor, thus, avoiding

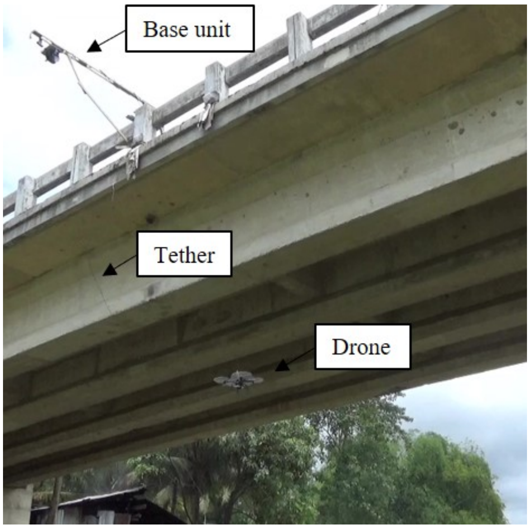

Fig. 20. Actual image of a tethered drone underneath the bridge.

Fig. 21. Onboard camera view of the drone.

excessive fluctuations on the wire. Likewise, the PID- based controller can also be improved with a better response to any sudden fluctuations in the wire, especially when the drone is set to move forward quickly. The effect of drone pitching on the tether angle as the drone moves forward can also be investigated further. A tilted rotor, as presented in previous works [18] [19] or adding horizontal rotors [20][21] can be implemented to solve the pitching problem.

For the localization unit, the position in the y-direction can be added to obtain the three-dimensional positioning of the drone. The position y can be determined by including the azimuth angle ψ as shown in Fig. 4(a). It was also noticed that the tether was in contact with the side-bottom structure during the actual flight.

The tether control unit can respond to tether conditions. However, the localization technique might be affected because the structure disrupts the force measurement felt in the load cell. One possible solution to this issue is to extend the SPTD arm further or increase the length b in Fig. 2(a).

For neural network prediction of the drone's location, it is best to add more data. More data gathered implies better understanding of the neural network on the complex

Fig. 22. Screenshot of developed software application for system's operator control and camera view.

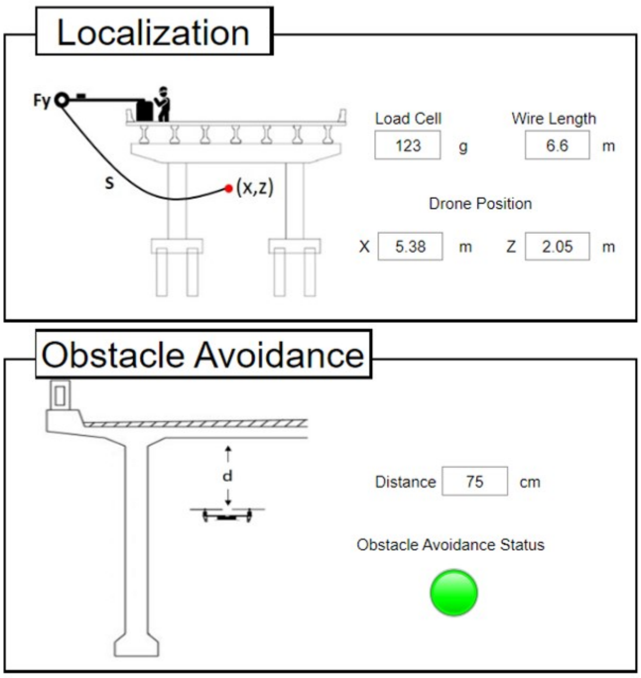

Fig. 23. Screenshot of developed software application for system's localization.

relationship between the length of the wire, the vertical force measured at the base, and the drone's position. Thus, the network could have an accurately modeled system and can provide a more accurate drone positioning.

V. Conclusions and Recommendations

In summary, this paper proposes a suspended and power-tethered drone for visual inspection of the underneath structure of a high bridge. The design emulates that of a traditional bucket inspection truck using a drone. In particular, the system utilizes an 800 W, 16V output quadrotor-type power-tethered drone. This quadrotor platform can carry a weight of 1.57 kg using the 980 KV motor and 10-inch propeller. Likewise, the designed tether control unit allows the system to maintain the tether angle, thus allowing the wire to avoid being hit by the propeller and keeping the tether in catenary form for localization purposes. The flight experiments and data confirmed the action of the tether control unit. The neural network-based localization technique fairly predicted the drone's location based on the vertical force felt by the load cell and the estimated length of the wire. Finally, an actual bridge successfully conducted a flight experiment emulating a bucket truck.

The researchers of this study intend to improve the system further based on the lessons noted from this experiment. A thorough analysis of the power and wire selection, tether control, and localization technique will be further investigated.

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