Design and Construction of An Aesthetically Pleasing Vertical Axis Wind Turbine (APVAWT) – A Case Study of Art and Engineering Collaboration in Engineering Capstone Course

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Abstract

This paper proposes an enhanced approach for the capstone design course, as a part of the undergraduate engineering curriculum, through collaboration of art and engineering by designing and building an Aesthetically Pleasing Vertical Axis Wind Turbine (APVAWT). Such collaboration brings creativity to art and engineering students through an interdisciplinary project considering both functionality and beauty for wind generation system.

In order to assist the capstone team's design and construction of an APVAWT, total eight decision gates (stakeholder requirements, system requirements, system operations, system functions, system architectures, implementation, verification and validation) are set for the project from inception to completion in order to satisfy the need of a client who asks to make an APVAWT. This process includes technical and artistic designs considering functionality, beauty, safety, economics, and ethical implications, ensuring the functionality and beauty for the completed physical unit. Through this project, students will have an enriched opportunity for an interdisciplinary design process combining engineering and arts.

1. Introduction

According to recent reports on renewable energy, although wind power technologies serve the environment significantly and play an important role in the renewable energy mix, it has been argued that they are an ugly blemish on areas of natural beauty due to their visual impact of wind turbines [1].

In addition to visual impact of wind turbines, current wind energy technology moves toward the development of efficient small-scale wind turbines for buildings and campuses in cities and rural areas together with utility-scale wind farms [2-4]. Researchers, designers, and project developers have recommended small-scale wind turbines become a potential solution to achieve energy efficient buildings with clean energy source [5].

Between the two major wind turbine architectures such as Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT), HAWT is relatively ineffective for buildings and locations near buildings, and faces local resistance due to noise as well as aesthetic, visual and public safety concerns [6]. Alternatively, VAWT has been predicted as a potential solution for small-size wind turbines that are installed at buildings and near buildings [7, 8].

Responding to that line of discussions, one of the engineering capstone teams have been working on designing and building an Aesthetically Pleasing Vertical Axis Wind Turbine (APVAWT) system with a logo of the Liberty University School of Engineering for their capstone project. To achieve the functionality and aesthetics of the APVAWT system, art design team joined for designing aesthetically pleasing outlook of wind blades and the APVAWT structure. Such interdisciplinary collaboration will be a good example to show that artists and engineers work together with an integrated approach on aesthetical, mechanical, and electrical aspects of the system.

2. Design of the LU Engineering APVAWT

The Liberty School of Engineering capstone program requires total eight decision gates such as stakeholder requirements, system requirements, system operations, system functions, system architectures, implementation, verification and validation, to assist a capstone team's design and construction. All teams should complete all eight-decision gates over two semesters from inception to completion of the project. In the next sections, all decision gates where the APVAWT capstone team has passed will be introduced to show how the engineering students of the team design and build the APVAWT system with the Liberty art students.

2.1 Decision Gate 1 – Stakeholder Requirements

The 1st decision gate is to identify and confirm stakeholder requirements that guide the capstone team in understanding what is needed to be accomplished for the project and the class. Here, stakeholders represent all entities who are involved in this project: the capstone team, the client(s), and the class instructor. Table 1 shows stakeholder requirements the team presented and is required to fulfill.

Table 1 – Stakeholder Requirements for Design and Construction of the APVAWT

Task ID	Name	Description	Rational
R.1.1	Aesthetically Pleasing	The VAWT must be aesthetically pleasing.	This turbine will be used primarily as decoration, and aesthetics are a large part of the appeal.
R.1.2	Functionality	The VAWT must rotate in the wind to provide electricity.	There is no purpose in making a wind turbine to promote renewable energy if it does not function.
R.1.3	Liberty Signature	The VAWT must have some design feature that indicates that it was created by Liberty University.	This is to spread Liberty's reputation, to indicate the role of the engineering department.
R.1.4	Design Constraints	The VAWT must operate within the provided design constraints.	The application of the VAWT is based upon these constraints, and without them, it will not fit the client's needs.
R.1.5	Collaboration with Art Team	The VAWT must be designed through collaboration with the assigned art students.	This will ensure that aesthetics and function are both in consideration during the design phase.
R.1.6	Design for Safety	The VAWT must be designed to operate safely.	The VAWT should operate safely to ensure the safety of pedestrians.
R.1.7	Design for Reliability	The VAWT must be designed so that it is reliable and lasts a specified lifespan.	This is not for the VAWT to be able to operate for more than a single test, but rather a specified lifespan.
R.1.8	Budget Limit	The prototype must be built within the provided budget.	A prototype that is designed exceeding the budget is not allowed.

2.2 Decision Gate 2 – System Requirements

The 2nd decision gate is to identify and confirm system requirements that are the foundation of the system definition, and form the basis for the architecture, design, integration, and verification. The purpose of system requirements is to transform the stakeholder-, user-oriented view of desired capabilities into a technical view of a solution that meets the operational needs of the user [9]. Table 2 shows system requirements the team presented.

Table 2 – System Requirements for Design and Construction of the APVAWT

Task ID	Name	Description	Rational
R.2.1	Enhanced Savonius, Darrieus, or H-Type model with Art Design	VAWT shall be an aesthetically pleasing model. Either the Savonious, Darrieus, or H-type model. Design is created with Art School.	The artistic features of the design will be aesthetically pleasing, based on the measure of client satisfaction. The VAWT will be one of the two models.
R.2.2	Turbine Design, Gear Box & Generator	The VAWT blades shall rotate, converting energy from mechanical to electrical, to power an external load. Must continuously produce 100-200 W of power.	The VAWT will function as intended and provide electrical energy, because it is meant to be both decorative and functional.
R.2.3	LU Logo (etched in, printed on, or shape of turbine)	There shall be a logo of the Liberty University School of Engineering on the VAWT that is etched in, printed on, or the shape of the turbine.	There shall be a logo of the Liberty University School of Engineering on the VAWT.
R.2.4	Function within Rated Wind Speed	The VAWT should be built to operate in windspeed conditions between 1 and 3 m/s.	This provides needed operating conditions, to grant context for meeting the design goals.
R.2.5	Turbine Height	The turbine height must be between 0.5 and 2.5 meters.	This height constraint provides bounds on the overall size of the VAWT.
R.2.6	Height Above Ground (On roof or standalone device)	The VAWT height including the tower shall be within 1.0-10m from the ground. The height should also ensure the system is out of reach of pedestrians for safety concerns.	The VAWT must not be within the reach of surrounding people for practical reasons.
R.2.7	Max Turbine Diameter	The maximum of VAWT diameter shall be within 0.1 to 1 m.	The range for the maximum diameter of the turbine was determined to be the right one by the clients.
R.2.8	Low Friction Gear Box and Low Frictional Resistance Generator	The VAWT will start rotating and generating power at windspeeds of 0- 1 m/s. The gear box and generator should be low friction and frictional resistance, respectively.	Given the low windspeeds in Lynchburg, a low startup windspeed is required for a wind turbine to function properly.
R.2.9	Robust Mechanical and Electrical Components	The VAWT must be able to survive windspeeds of up to 10 m/s without damage, and temperature ranges of -20 to 50 degrees Celsius.	The VAWT should be robust enough to survive extreme conditions, to facilitate outdoor use.
R.2.10	Output Voltage Control Circuit	The VAWT shall output power at a voltage range of 12-24 V.	The load would be designed to work in that range, so the output voltage must be regulated to support this.

R.2.11	Mechanical Braking	The VAWT must have a system to prevent safety issues due to high windspeeds, by applying a brake to the turbine. Activated when wind speed is above 10 m/s.	A mechanical braking system is needed in case of high winds, because otherwise the turbine could be a safety hazard.

2.3 Decision Gate 3 – System Operations

The 3rd decision gate is to identify and confirm system operation definitions based on use case studies of the stakeholder needs and resulting system requirements. Table 3 shows system operation definitions the team presented.

Table 3 – System Operations for Design and Construction of the APVAWT

Task ID	Name	Description	Rational
O.1.1	Wind Hits and Turns Turbine Blades	The wind will hit the turbine blades and cause them to start turning, then to generate electrical energy.	This affects most of the turbine design specifications, including safety parameters.
O.1.2	Gears Modify Angular Velocity	The input angular velocity from the turbine blades will be multiplied to meet the generator requirement.	The generator rotor speed has to be greater than the one from the blades.
O.1.3	Rotational Energy Turns Generator Rotor	The mechanical energy from the rotating blades will be transferred to the generator by the gears.	The generator rotor needs to rotate to convert mechanical energy into electrical energy.
O.1.4	Generate Electricity	The spinning turbine powers a robust generator, generating electricity for a useful purpose.	The VAWT needs to have a practical use, and this reflects the primary purpose of the system.
O.1.5	Light Emits Through Bulb	The turbine will use the generated electricity to power a light source to illuminate an area.	The generated electricity needs to be used somewhere, and this application ties into both the aesthetic and functional aspects of the system.
O.1.6	Promote Wind Turbine Integration into Architectural and Building Environments	The artistic design and the practical nature of the turbine will counter the common complaint of wind turbines being aesthetically displeasing.	This project is meant to create a wind turbine that promotes the aesthetics of wind power turbines, so this is a key operation.
O.1.7	Display Liberty Logo	The VAWT will have Liberty University's Logo on clear display.	One of the goals of this system is to spread Liberty's reputation, and this operation reflects that.
O.1.8	Recognize Liberty Logo	The observer will recognize the Liberty Logo on the VAWT when looking at it.	Liberty's reputation could be spread by the observer.

2.4 Decision Gate 4 – System Functions

The 4th decision gate is to identify and confirm system functions based on system operations. Table 4 shows system operation definitions the team presented.

Table 4 – System Functions for Design and Construction of the APVAWT

Task ID	Name	Description	Rational
B.1.1	Turbine Rotor rotates in wind.	The turbine rotor is the rotating part of the turbine that transforms the wind energy into mechanical motion. The turbine rotor must be both efficient and aesthetically pleasing.	To satisfy the requirement that the VAWT is functional, the turbine rotor must efficiently collect energy from the wind to deliver it to the generator.
B.1.1.1	Rotor blades capture wind.	The blades convert the kinetic energy of the wind into the rotation of the hub.	Each blade must rotate after being hit by the wind
B.1.1.2	Hub attaches blades to rotor shaft	The hub is the center of the rotor to which the rotor blades are attached.	The hub must hold the turbine blades together, in addition to connecting them to the rotor shaft.
B.1.1.3	Rotor shaft transmits rotation.	The shaft is turned by the blades and transmits the rotational motion to the generator.	The rotor shaft must transmit mechanical energy from the blades to the generator
B.1.1.4	Bearing reduces friction.	Bearing reduces friction caused by rotation.	Using the bearings will assist the efficiency requirement.
B.1.1.5	Lubricant reduces friction	The lubricant further decreases friction between the shaft and the hub at the bearings.	Lubricant must be added to reduce friction.
B.1.2	Structure provides support and aesthetics	The structure of the turbine provides both support and aesthetics to the system.	The structure must be able to support the system, while looking appealing. The structure must emphasize both beauty and function.
B.1.2.1	Tower supports turbine rotor	The tower is the stationary part that supports the rotating shaft, along with raising the blades to a useful height.	This part protects the rotating shaft from the elements, enhancing safety and efficiency.
B.1.2.2	Turbine base supports rotor and tower.	The turbine base supports the weight and the mechanical reactions of the turbine.	This stabilizes the entire structure, enhancing safety and robustness. It should be built with aesthetics in mind.
B.1.2.3	Artistic design of structure enhances aesthetics	Aesthetic design choices in the turbine components will make wind turbines more accepted and appealing.	The artistic design will ensure that the VAWT is an artistic piece that is beautiful.
B.1.3	Gear modifies angular velocity	The gears take the lower rotational speed from shaft and increase it for the generator.	The gears will multiply the rotational speed produced from the turbine rotor to aid the production of electricity from the generator.
B.1.3.1	Input gear transmits rotor motion	The rotor speed will be transmitted to generator shaft by the input gear.	The input gear must transfer the energy provided by the turbine shaft to a gear system.
B.1.3.2	Output gear increases angular speed	The output gear will increase the angular speed according to the gear ratio.	Most generators are designed to function at a specific RPM, and a proper gear ratio can be used to more closely match this value.

2.5 Decision Gate 5 – System Design

The 5th decision gate is to identify and confirm system design based on all previous decision gates. Figure 1 shows the system architecture diagram that shows all components and their connections for the APVAWT system.

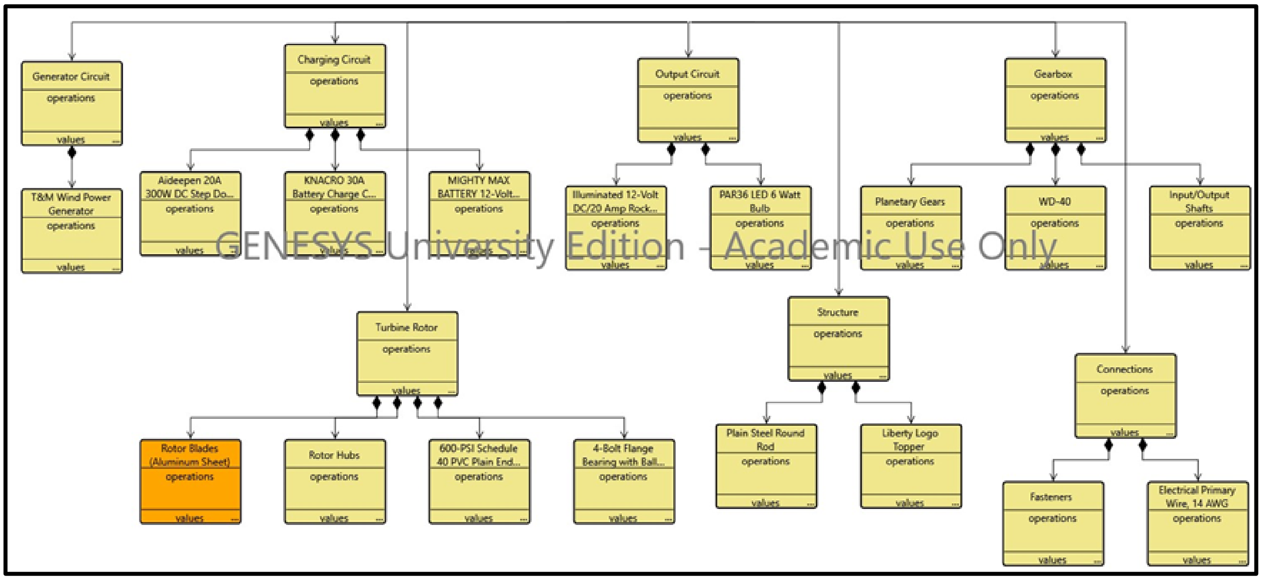

Figure 1. The system architecture diagram

According to the physics that govern vertical axis wind turbine, the Savonius blades are self-starting but have relatively low efficiency because of the opposite drag force on the side that is convex to the wind. The Darrieus blades, on the other hand, are more efficient than the Savonius; however, they are not self-starting and require a starting system. Hence, the team combined both types together so the Savonius blades will enable the system to start itself while the Darrieus blades will increase efficiency [10].

Artistic features are implemented in our system with the help of the art professor, including a flames topper that is added on top of the turbine. The team also chose to stack the Savonius blades on top of each other in a helical fashion in order to have the satisfactory visual effect. The electrical components are put out of sight for convenience and for people's safety. The top plate helps reducing corrosion, which will be caused by rain. Figure 2 shows the overall diagram of the APVAWT the team designed.

Figure 2. The APVAWT designed

3. Construction of the LU Engineering APVAWT

3.1 Decision Gate 6 – System Integration Strategy

The team has passed decision gate 6 which requires implementation strategy on building and testing of the APVAWT system. For the implement strategy, the team clearly documented 3S (Scope, Schedule, and Spending) and allocation of responsibilities to resources. Based on the implementation plan, the team has completed construction of the APVAWT by assembling the subassemblies, the turbine rotor, the gearbox, the electrical system, and the supporting structure. The detailed construction plan is shown below:

1. The turbine rotor is connected to an upper support of the structure and a lower one through a pair of bearings, one for each support.

2. Each support is a square section of a plywood to which the bearings are attached through appropriate fasteners such as screws, bolts and nuts.
3. The gears are connected at the bottom of the turbine rotor. They are attached to the center shaft of the turbine rotor and the alternator shaft according to the right meshing configuration; the rotor will transfer rotational energy to the generator, which is the main component of the electrical system.
4. The electrical system has its own housing which also serves as the turbine base.

3.2 Decision Gate 7 – System Integration and Verification

After the team completed decision gate 6, the parts for the APVAWT system have been ordered, and, the APVAWT system has been physically built and tested for its functionality. Figure 3 shows the physical APVAWT hardware the team integrated and verified for it functions.

Figure 3. The physical APVAWT integrated and verified

The functionality of the physical APVAWT has been verified in a variety of aspects. The verification items for test with their verification identification numbers are shown below:

V.1.1 – Wind turbine rotates in the wind.

V.1.2 – Rotor provides an aesthetically pleasing motion.

V.1.3 – Wind turbine generates electricity.

V.1.4 – Wind turbine contains Liberty School of Engineering signature.

V.1.5 – Wind turbine follows and meets the predefined design constraints that include wind turbine type, height, weight, diameter, operation temperature, start-up, maximum and rated wind speed, rated power, and output voltage, etc.

The team has passed decision gate 8 on system validation successfully and made a poster and a short-length (1-3 minute) video infomercial that are used to showcase the physical prototype at a poster session on April 30, 2020.
The client has been participating in determining pass/fail at each decision gate up to the current decision gate the team has passed, assessing the team's performance based on electrical, mechanical, and aesthetical perspective; it has been confirmed that the goals agreed upon among all the stakeholders of this art-engineering interdisciplinary project have been met.

Based upon the results so far, the level of satisfaction of students on this project, and their feedbacks, it is found that there is a high level of interest among students on interdisciplinary projects with non-engineering programs. Encouraged by this, the capstone course faculty is planning on expanding the scope of capstone course program by incorporating more collaborative elements between engineering and non-engineering into the course projects. Once more systematic implementation of those collaborative elements is incorporated into our capstone course, more reports on the assessment on the implementation will be made to the future ASEE conferences.

4. Conclusion

The project team consists of engineering and art students in the capstone class went through rigorous design stages following Wasson's system engineering model [11]. The capstone class of School of Engineering in Liberty University is designed to provide students with engineering design experiences close to those of real-world practices where integrated system approach and interactions with team members and clients are two of the key elements for success. Although project teams in our capstone class are interdisciplinary within the School of Engineering, this APVAWT project is the first interdisciplinary collaboration between art and engineering. The fact that the project team successfully finished all the decision gates and showed high level of interest with positive feedback on their experiences, and a study such as [12] on the impact of aesthetics on consumer products, suggest the value of interdisciplinary collaboration efforts between engineering and non-engineering students.

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