Study on a Low Starting Torque Vertical Axis Wind Turbine

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Abstract

The main objective of this paper is to analyze the effect of gear ratio on the performance of a Low Starting Torque Vertical-Axis-Wind-Turbine, to explore alternatives for generating electricity. A mathematical model was derived and analyzed which expresses the movement of the wind through orientation blades in a Wollongong-Wind-Turbine, and a series of gear ratios that yield satisfactory results were found. Based on the results form the numerical analysis, corresponding experiments were conducted and the results are satisfactory.

Key Word：Wind Vane, Bevel Gears, Gear Ratio, Wollongong, VAWT

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1. Introduction

Today's power sector emits large quantities of greenhouse gases and relies heavily on volatile carbon-based with rising prices. As such, the current system is unsustainable, both economically and environmentally. Scientists urgently warn such pollution must be sharply reduced to avert the most serious consequences of climate change.

There have been many discussions on which solution is optimal to diminish this problem, and most of scientists agree that "Renewable Energy" or "Zero Pollution Energy" is the best answer. Many countries have accelerated the ramp-up of clean, renewable electricity sources through new policies and increased private and public investment in technologies that work. These technologies already exist and have been expanding.

Renewable Energy field has several areas; one that presents largely potential and has improved in the last decades is "Wind Power". Wind power is growing at the rate of 30 percent annually, with a worldwide installed capacity of 121,000 megawatts (MW) in 2008. (1)

There are two essentially different types of wind turbines:

Impulse type wind turbines (Savonius rotors) are vertical axis wind turbines with blades covering the whole swept area and shaped to offer a high resistance to the wind coming in, in the direction of the rotation and as little as possible resistance to wind blowing to the other side of the blade.

Aerodynamic wind turbines have wing shaped blades covering a small percentage of the swept area; the wind flow along these blades generates a lift force, as with airplanes, perpendicular to the flow.

Wollongong is an impulse type of wind turbine, composed by a vertical main shaft, which has mounted on it a wind vane that holds a "free" bevel gear that controls the pitching of the blades. The gear ratio will play an important role on this mechanism, since the efficient of the turbine will depend in the most suitable gear ratio between the main shaft and the blades.

A numerical analysis have been done in this research, in order to find which gear ratio will help people to obtain the largest torque on the turbine, which will be directly used to calculate the Work made by the wind. In this manner more energy can be extracted from the wind with lower starting wind velocity

2. Conceptual Development

A Wollongong wind turbine is an impulse type Vertical Axis Wind Turbine (VAWT) whose design controls the angle of attack of the blade as it rotates. Autodesk Inventor software was used for the 3D model of the turbine.

The turbine is composed by a main shaft, which has mounted on it a wind vane that holds a "free" bevel gear, that are the responsible of give the initial position of the three turbine blades. Three blades are used, since is the quantity of blades that will not generate a large amount of negative moment on the turbine. Then the orientation of the blades is controlled by the "free" bevel gear that is connected to a small shaft placed on each turbine arm. This small shaft is also connected to a bevel gear pair on the top of each blade. By this arrangement, the blades angle can be controlled at any moment of the whole turbine revolution. The model can be appreciated at figure 1.

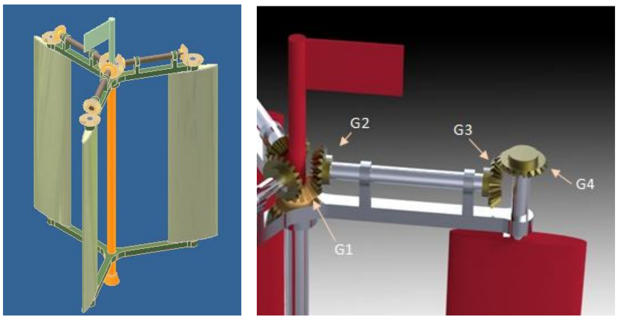


Figure 1 Wollongong Turbine and Gear Configuration

The principal idea is to obtain, by mathematical analysis, the suitable gear ratio that permits to have the blade in a perpendicular position with the incoming wind direction in the right hand side, and almost parallel position of the blade with the incoming wind direction in the left hand side, and also that this gear ratio help to produce the larger initial torque applied to the turbine, which will represent a higher Work.

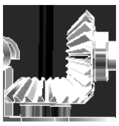
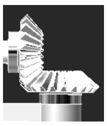
By definition the gear ratio depends on the relationship between the numbers of teeth of two pair of gears. In this case each arm of the turbine is composed by 2 pairs of gears. The relationship of these gears is expressed by equation (1),

$$G = Nt_{G1} / Nt_{G2} * Nt_{G3} / Nt_{G4} \quad (1)$$

where Nt_{Gn} is the number of teeth of each gear in the turbine configuration. It should be noticed that the speed of the blades rotation is also controlled by the gear ratios.

As an example, the gear ratio functions as a multiplication, is listed in Table 1.

Table 1. Gear Ratio Relationship

Gear Pair 1 	Gear Pair 2 	Final Gear Ratio
1:1	1:1	1:1
1:2	1:1	1:2
1:2	1:2	1:4
1:2	1:3	1:6
2:1	3:2	6:2 = 3:1

Note also that the direction of the blade's rotation is also controlled by the gear configuration (Fig. 2).

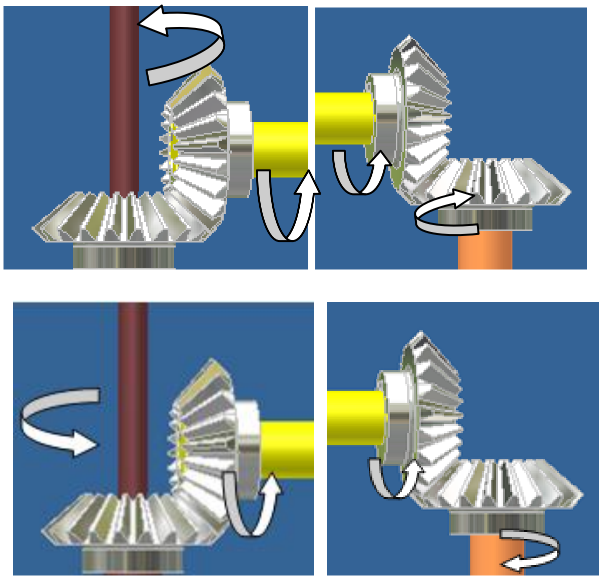


Figure 2 Gear configurations in opposite directions. Positive and Negative Configurations

On the top figure a positive configuration (both gear rotate on the same direction) is presented and at the bottom figure a negative configuration (both gear rotate on different direction).

3. Numerical Analysis

Now that the Wollongong Vertical Axis Wind Turbine function has been covered, it is possible to analyze its function more closely.

Let's establish a coordinate system based on the position of the wind vane. This is because the wind vane will always be parallel to the incoming wind under normal conditions. For these research wind will be set always blowing in the +y direction as is shown in figure 3.

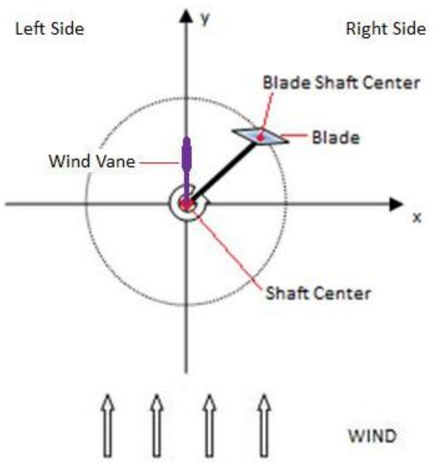


Figure 3 Established Coordinate System

To present a simple explanation, the following conditions are set:

1- Uniform wind velocity.
2- The turbine blades are designed for drag. (The lift force is negligible).
3- As the design is drag based, the force generated by the wind is proportional to the blade's projection on x axis.

Now, another important thing that has to be considered is the Angular Work done by the force of the wind. By knowing this force, then can be know how much energy can be extracted from the wind.

By definition, the work done by a force is equal to the magnitude of the force times the corresponding displacement. The angular work done by a force applied on a rotating body is related to the angular displacement of the body, the moment multiplied by the rotational angle.

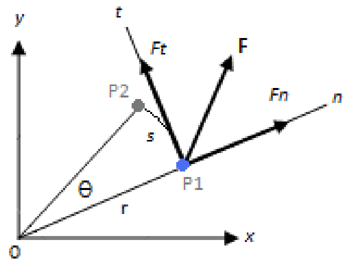


Figure 4 A particle located at P1 is displaced by an angle Θ or arc length *s* to position P2

Consider a body rotating about a fixed axis at the origin O due to an applied force F. As illustrated in figure 4, P1 and P2 represent the positions of a point in the body at times t1 and t2, respectively. In the time interval between t1 and t2, the body rotates through an arc of length s, the Force is projected in x and y axis and the torque should be applied at the origin O.[7] Thus, the Work done in that finite interval displacement is

$$W = \int_{\theta i}^{\theta f} M(\theta)\, d\theta \qquad (2)$$

Then the next target is to find the larger torque since it is directly proportional to Work.

Let's then consider the following:

A turbine arm that rotates around the origin may be described as: L ([cosΘ] î + [sinΘ] ĵ).

One term (L) describes the length of the arm, while the other ([cosΘ] î + [sinΘ] ĵ), describes its orientation. The latter, therefore, is the one that holds the most significance, then the arm's orientation is describe by equation (3).

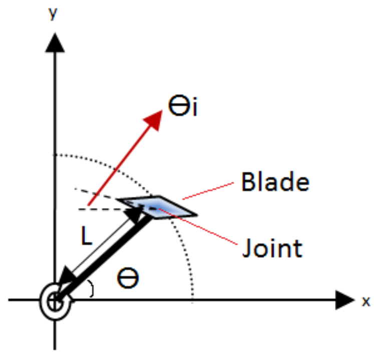


Figure 5 Arm and blades' orientations' description

$$\frac{\overline{r_{arm}}}{|r_{arm}|} = [\cos\Theta]\,\hat{\imath} + [\sin\Theta]\,\hat{\jmath} \qquad (3)$$

If a blade is then attached and aligned with the arm; and the arm rotates around O, then the blade will keep the set initial position during all arm revolution, so it has to be considered this blade's initial angle in the orientation equation. The constant orientation of the blade can be expressed in equation (4),

$$\frac{\overline{r_{blade\ constant}}}{|r_{blade\ constant}|} = [\cos(\Theta + \Theta_i)]\,\hat{\imath} + [\sin(\Theta + \Theta_i)]\,\hat{\jmath} \qquad (4)$$

But this equation has to be improved, since is not convenient to have the same blade's orientation during the total revolution of the arm, because if this happens, when the blade is passing by the left side of our set coordinate system, it will produce a large torque in the opposite direction of the turbine movement.

This is why the study of the gear ratio will be a key in the analysis. Then a relation between the blade's angle and the turbine arm angle was made. This relation is done by the gear ratio (G), where G is the number of revolutions the blade undergoes for every revolution the arm undergoes. This can therefore, be recognized as the numerical representation of the gear ratio between the arm and the blade. Note, also, that the sign of G indicates whether the blade rotates in the same sense as the arm or in the opposite sense.

Subsequently, the following equation (5) describes the orientation of the blade in the coordinate system:

$$\frac{\overline{r_{blade}}}{|r_{blade}|} = [\cos([1+G]\Theta + \Theta i)\hat{\imath} + \sin([1+G]\Theta + \Theta i)\hat{\jmath}] \qquad (5)$$

If the wind blows in the +Y direction and the blade is designed so that the arm turns because of the drag force generated by the wind, then there is going to be a relationship between the blade's projection on X axis and the force generated.

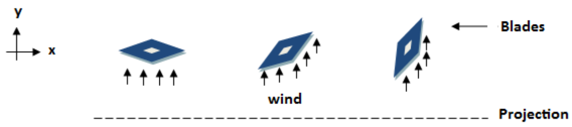


Figure 6 Projection of the wind force on X axis

Taking the previous fact into consideration: How can it be maximize the positive projection of the blade in the x axis?

This can be conveniently modeled through torque. Since the force is proportional to the x projection $(\cos([1+G]\Theta + \Theta i)\,\hat{\imath})$, the moment generated around origin O is proportional to the x projection of the arm (L*cos Θ).

Notice that the term $(\cos([1+G]\Theta + \Theta i)\,\hat{\imath})$ can be both positive and negative. This is undesirable, as the blade is constructed in a symmetrical fashion.

Therefore, this is best modeled by equation (6).

$$M(\Theta) = |\cos([1+G]\Theta + \Theta i)| \cdot L * \cos\Theta \qquad (6)$$

It now becomes a simple matter of integration through numerical methods in order to obtain a point of comparison for different gear ratios G and initial angle Θi .

The important factor is that the best way to compare the results is not from integrating from 0 to 2π, but instead from 0 to the "periodic angle" for the gear ratio, where periodic angle (Θ_c) is the angle necessary for the blade and arm to return to its original position or an equivalent.

For example if G=1/2, it takes 2 arm revolutions for the blade to complete one revolution. Therefore, at Θ = 0 and Θ = 2π, the blade would have equivalent positions, then $\Theta_c = 2\pi$.

Note that the previous case does not hold true for G=1/3. Since, at Θ = 0 and Θ = 2π the blade will not have equivalent angle with each other; this is because at Θ = 0 the blade will have an angle of 0˚, but at Θ = 2π the blade will have an angle of 2π/3. Therefore, the "periodic angle" is 6π.

Finally, for any integer value's of G (i.e. 1, -1, -2, etc.) the "period angle", is 2π, since the blade always completes its revolutions in accordance to the arm's revolution.

The "periodic angle" or Θc is therefore given by equation (7):

$$\Theta c = \begin{cases} \dfrac{2\pi}{|G|} & G = \dfrac{m}{n}, n \text{ is odd}, \{m|m \in Z\} \\ \dfrac{\pi}{|G|} & G = \dfrac{m}{n}, n \text{ is even}, \{m|m \in Z\} \\ 2\pi & \{G|G \in Z\} \end{cases} \qquad (7)$$

Once Θ_c have been determined, the work done by the wind can be quantified through the following equation (8):

$$W = \int_0^{\Theta c} M(\Theta)\,d\Theta = \int_0^{\Theta c} |\cos([1+G]\Theta + \Theta i)| * L\cos\Theta\, d\Theta \qquad (8)$$

By using LabView software from National Instruments, the numerical analysis was made for various gear ratio values, and the conclusion that G = -1/2 will give the maximum initial torque was reached; it means that the blades should rotate contrary direction of the main shaft rotation. It can be appreciate in the graph number 1. Also the rotation of the blade at G= -1/2 is described in figure 7.

Now the initial positions of the blades can be set as is shown in figure 7. The blade number one will have a starting angle of 0˚ respect the horizontal line, since in that position the swept area will have a larger contact with the incoming wind, therefore the force on the blade will be larger which is going to generate a larger torque that will represent a bigger Work.

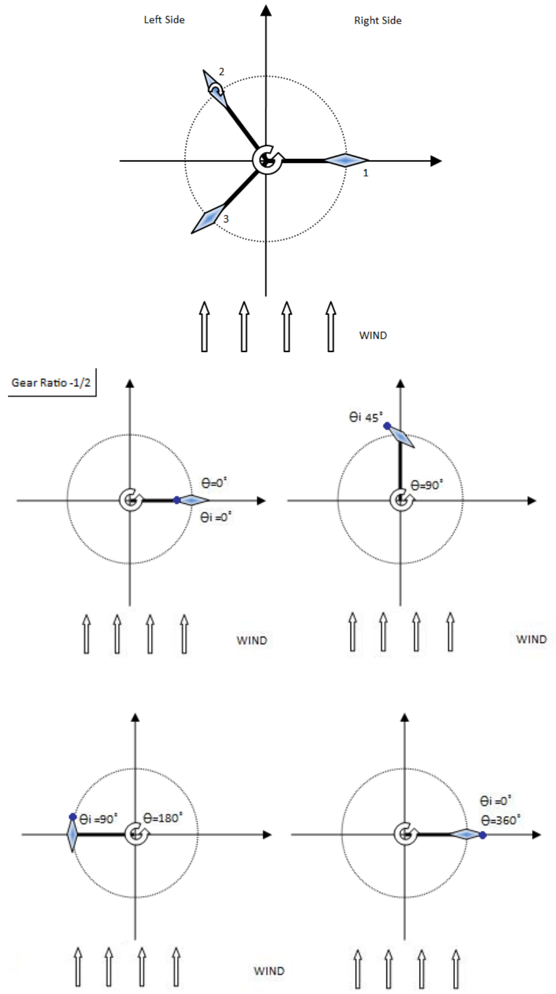


Figure 7 Blades initial position and description of the blade rotation in relation with the arm rotation

The numerical analysis led to the following results:

1. Of the various gear configurations available, only those in counter rotation provide satisfactory results.
2. Of the counter rotation gear configurations possible, only those that follow the following pattern yield non-zero values for the Net-Work generated during a period: $G = \frac{1+2n}{2+2n}$
3. Of the gear configurations that follow the previous condition, $G = \frac{-1}{2}$ generated the most work per cycle.

The analysis comes to a conclusion that G = -1/2 is indeed the most effective gear ratio for the mechanism, although there are other gear ratio that produce non-zero work within the periodical angle. This can be appreciated through the comparison of the following figures.

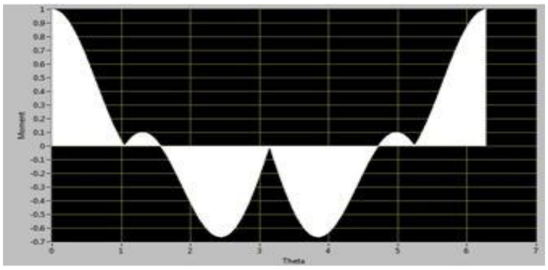


Figure 8 Moment at G = 1/2

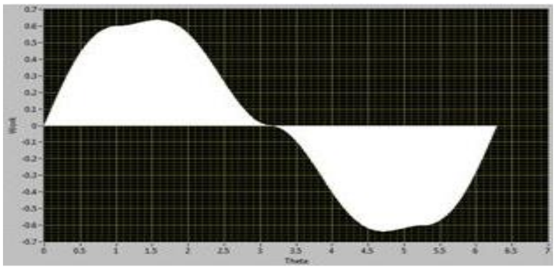


Figure 9 Wok at G = 1/2

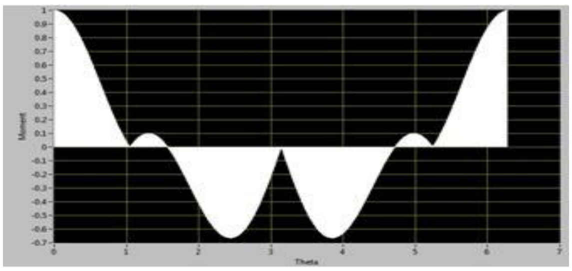


Figure 10 Moment at G= -1/3

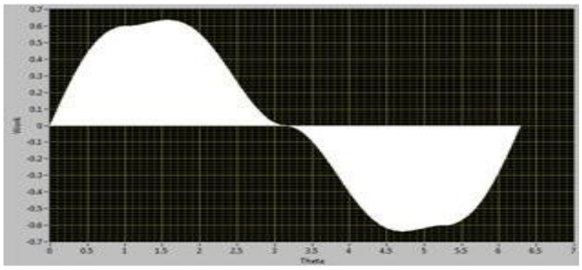


Figure 11 Wok at G= -1/3

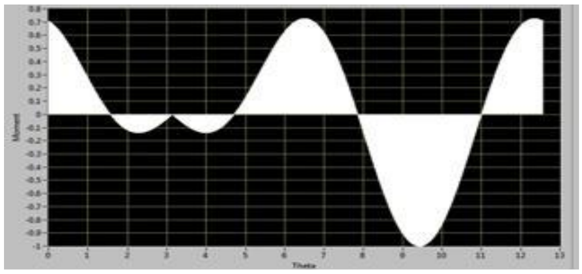


Figure 12 Moment at G = -3/4

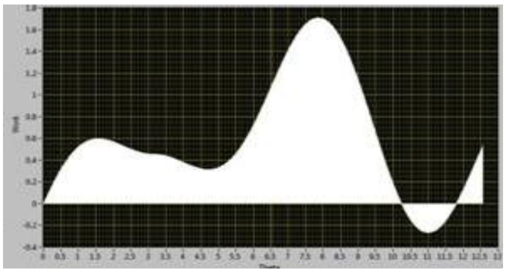


Figure 13 Wok at G = -3/4

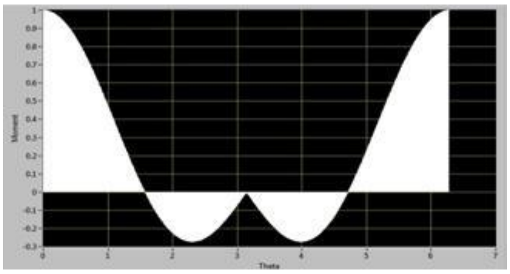


Figure 14 Moment at G = -1/2

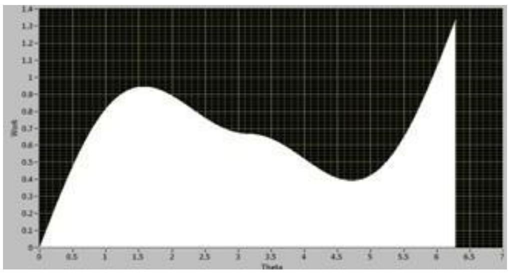


Figure 15 Wok at G = -1/2

5. Experiment Observations

In this work, the applicability of a new vertical axis wind turbine is shown in Fig 16. In this case, a gear ratio of G = -1/2, presented the best result, in which the Wollongong turbine generated the highest RPM and electric power. Besides, most of the parts were designed by Autodesk Inventor and fabricated by Rapid Prototyping machine had an excellence performance during the laboratory tests. A stand-family-fan with three speeds was used to simulate the wind.

Figure 16 Purchased Savonius Wind Turbines and Self-made Wollongong at G=-1/2, overall dimension is about 140mmx200mm

All this information could be obtained with the help of an electronic circuit who was the interface between the turbine and the computer. Finally, both turbines were tested for three different fan velocities. Two screen plot for the voltages generated are shown in the following figures.

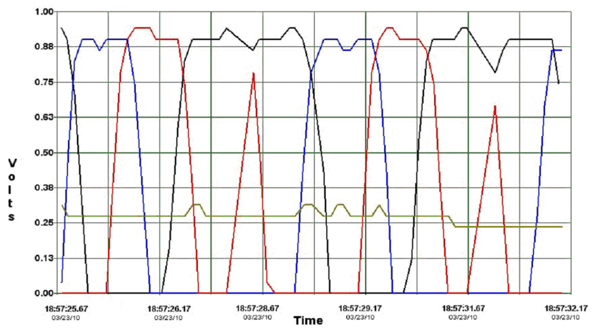


Figure 17 Screen Plot for Savonius Turbine at Wind Velocity 3 (Star Connection)

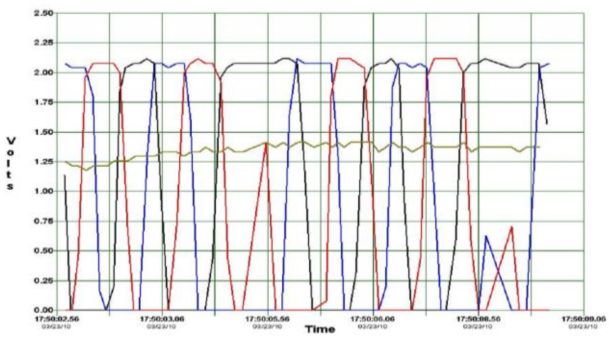


Figure 18 Screen Plot for Wollongong Turbine at Wind Velocity 3 (Star connection)

In the case of the Savonius turbine, during the first velocity, it did not generate enough torque to turn, which results in oscillation. However for the Wollongong at G=-1/2, it started to run automatically without any hesitation. It is clear from Table 2 that the new wind turbine is much better than the one purchased.

Table 2 Summary of Experimental Data (Delta connection)

Turbine Type	Wind Velocity 1		Wind Velocity 2		Wind Velocity 3	
	Turbine speed (rpm)	Voltage (mV)	Turbine speed (rpm)	Voltage (mV)	Turbine speed (rpm)	Voltage (mV)
Purchased Savonius turbine	708	0	984	180	1092	310
Self Made Wollongong turbine	1,287	430	1,439	970	2,152	1,400
Self start	Yes	No	Yes	Yes	Yes	Yes

6. Conclusions

Wollongong turbine at G=-1/2 showed a very efficient performance, from theoretical analysis as well as experiment results with quite a notorious difference.

Future work is being planed to design, fabricate and test a real life prototype, about 1000mmx2000mm, if budget permits.

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