MECH 4010 & 4015
Design Project I

CONCEPTUAL DESIGN REPORT

Strandbeest
Team #13

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1. Project Information

1.1 Project Title

Strandbeest (Dutch: strand = beach; beest = beast); a mechanical beast that inhabits the beaches of Nova Scotia.

1.2 Project Customer

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2. Conceptual Design Summary

The Strandbeest is a mechanical structure that uses the power of the wind to walk via linkages in a way that resembles an animal. The scope of this project would be to build a Strandbeest that can move using linkages and is only powered by wind.

In designing and building this mechanism, we will apply and expand on our previously acquired knowledge of dynamics of machines and many other engineering principles.

Our design will include the Jansen linkages powered by the rotating shaft of a wind turbine. We chose to use the Jansen linkage over the Klann linkage because it has a smoother motion and can be easily balanced by offsetting the legs. We chose to use a turbine instead of a sail because the turbine can transfer energy directly to the crankshaft, and with the use of gears, the right torque and speed can easily be set.

Another important aspect is finding the right materials to build the Strandbeest so that it will be light weight, strong, durable, made with recycled or reusable materials, and have low friction in the joints. Aluminum was the material chosen to be used for the linkages in the mechanism because of its high strength to weight ratio and its recyclability.

In order to validate our approach, AutoCAD and SolidWorks will be used, as well as a model of the mechanism made out of Lego. This will be useful in showing us areas which could be problematic, and we will be able to explore the options of how to fix them so that they will no longer be a problem on our full scale model.

3. Background and Context

In 1990, Dutch artist Theo Jansen became interested in creating life-like, kinematic pieces of art. He named these structures Strandbeests, which translates to “beach beast”. The name comes from its beast-like appearance and the fact that Jansen displayed his creations on the beaches of Holland and used the strong winds coming off of the North Sea to move the structure. He used linkages as the method of motion to resemble animal leg movements and powered the legs through sails or windmills. Figure 1 is one of many Jansen’s Strandbeests.

Figure 1: Theo Jansen’s Strandbeest

The scope of this project is to create a wind powered mechanical structure to move using leg-like linkages. The motivation for creating a Strandbeest comes from Dr. Andrew Warkentin’s interest to have a working model displayed to students who enroll in the Dynamics course offered at Dalhousie University. A Strandbeest model would help to facilitate learning through visualization and physical manipulation. Further motivation comes from getting to apply engineering skills that we have learned over the years and to get real group design experience.

Building a Strandbeest will engage our dynamic knowledge learned from previous years and will allow us to explore areas of wind power that we are currently unfamiliar with. It will also allow us to exercise stress analysis knowledge and explore design concepts and techniques.

4. Requirements

A list of criteria pertaining to the design and construction of the Strandbeest is detailed below.

4.1 Must walk with leg linkages on a level surface

The original Strandbeest uses linkages to walk. It is the objective to mimic the way the structure moves in a classroom setting on level surfaces.

4.2 The main source of energy must be wind power

A Strandbeest is defined to move on its own, the originals use wind power.

4.3 Should be mostly made of renewable/recyclable material

Since the beest runs on renewable energy, it is desired to build it with as much renewable/recyclable materials as possible. This way, there is no unnecessary harm to the environment.

4.4 Must walk a minimum of 10 meters when full scale

It is felt that 10 meters is an acceptable distance for the structure to move to prove it functions properly. It should also be small enough to be effectively demonstrated indoors (e.g. Classroom floor).

4.5 Easily transportable by one person

The structure must be easily transportable from classroom to classroom by one person. The customer would like it to be able to fit in a standard size laundry basket.

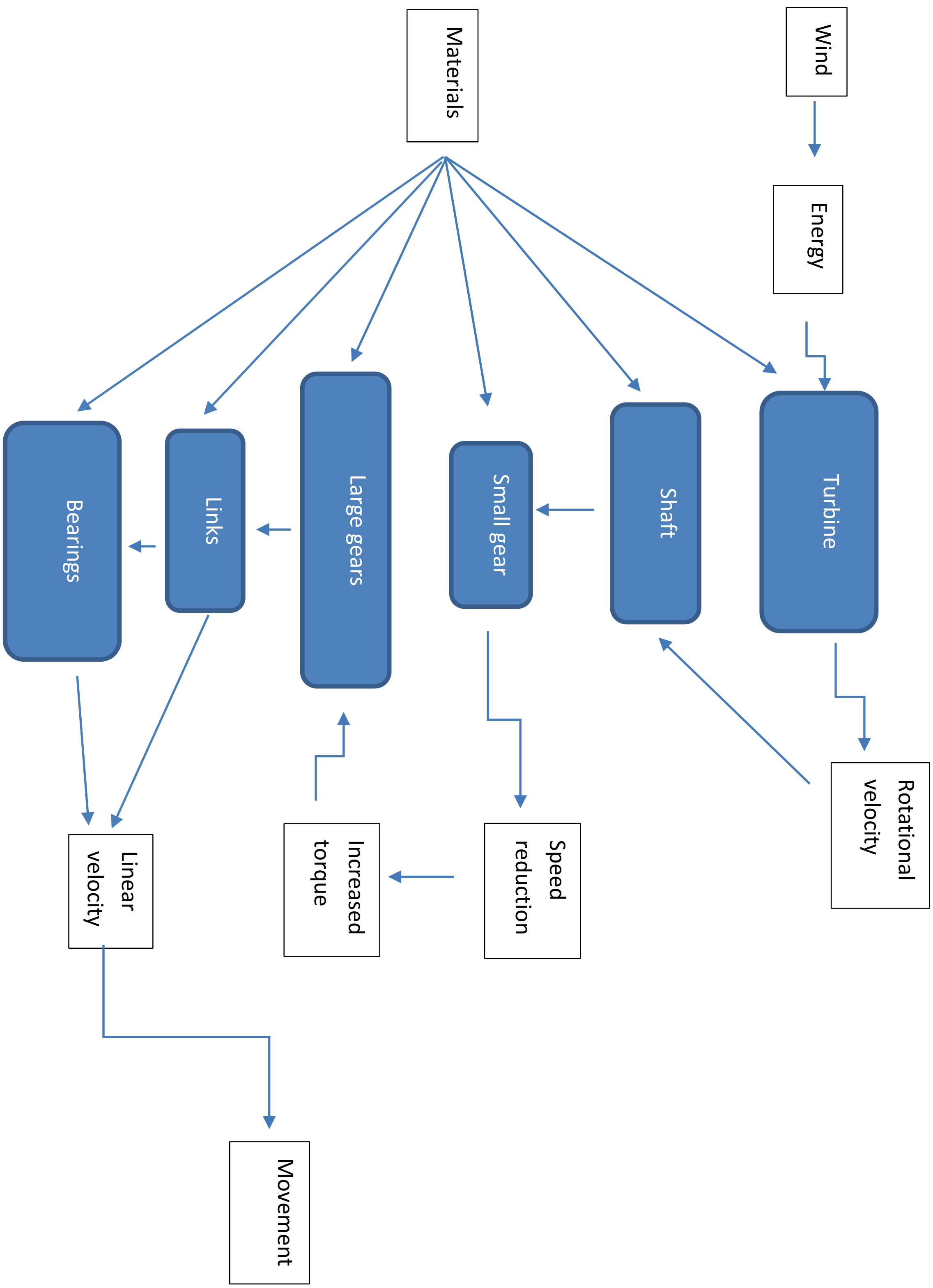
4.6 Should have elements of biomimicry

The leg linkages should operate in a way that is similar to how animals in nature move. Designing the structure after an animal is desirable.

4.7 Must be aesthetically pleasing

The original Strandbeests were made to be moving art. The structure made should follow in that idea.

5. Functional Block Diagram



6. Concept Classification Tree and Table

Figure 2 shows the concept classification tree used to divide the list of possible solutions to facilitate comparison.

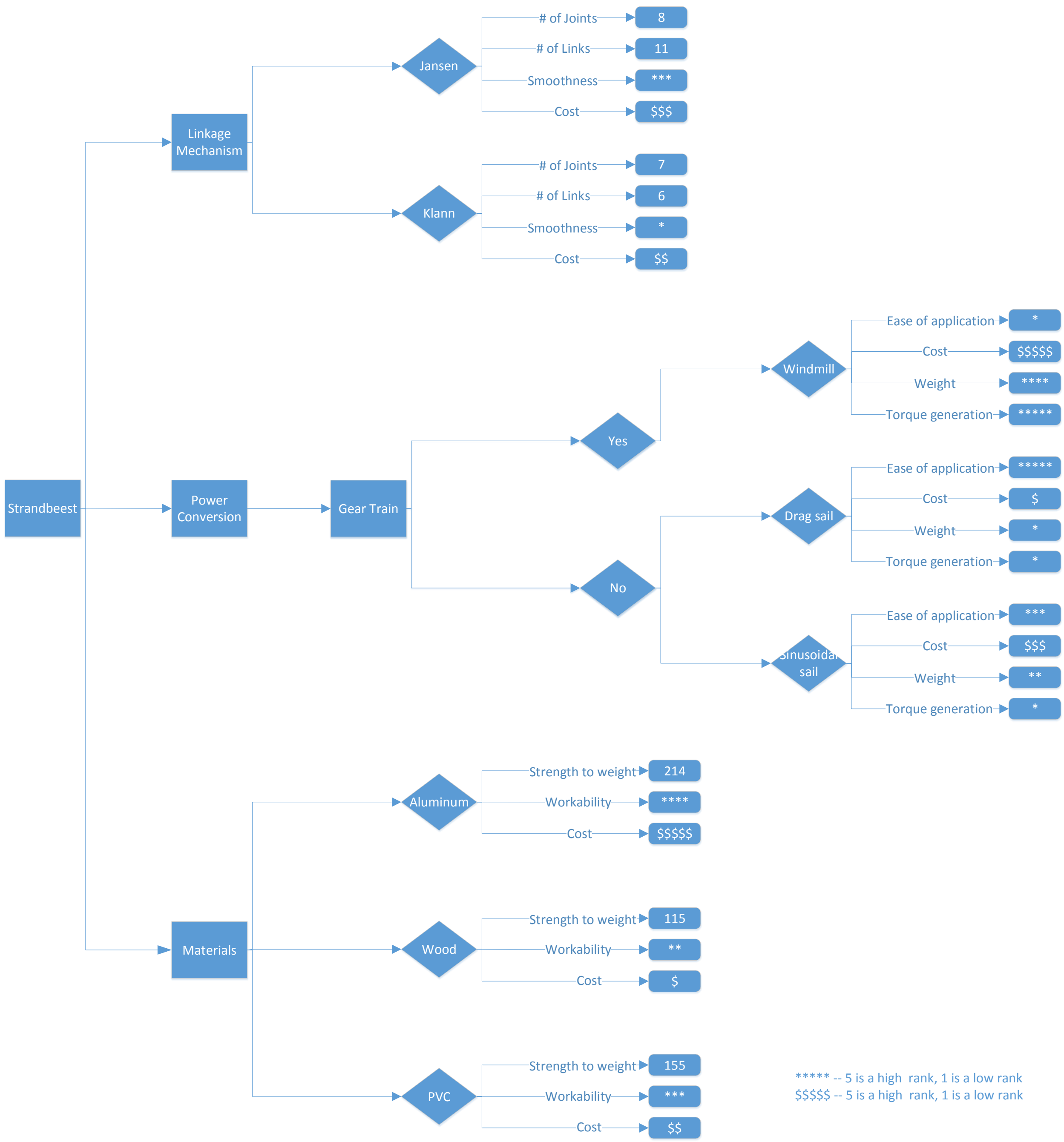


Figure 2: Classification Tree

Concept	Power η	Torque Trans.	Balance	Weight	Renew Recyc.	Simplicity	Cost	Grade
7.1	4	4	4	3	3	2	2	**76**
7.2	3	1	4	2	4	4	4	**67**
7.3	2	3	4	4	1	3	4	**67**
7.4	4	2	1	4	3	3	3	**59**
Value	5	4	5	2	2	1	3	

Each concept (as numbered in the next section) was evaluated based on various areas of the design and with the ratings for each section weighted 1-5 with five being the most desirable. These sections are wind power efficiency, torque transmission, mechanism balancing, weight, renewability/recyclability of the materials, simplicity of the design, and cost. A value factor is also given to each section of the design, which indicates the importance of the section based on a scale of 1-5 with five being the most important. The final grade was achieved by multiplying each rating by their respective value and summing all of the parts. Concept 7.1, as described in the following section was determined to be the most desirable.

7. Overview of Conceptual Solution Alternatives

The following section identifies and describes all design solution alternatives that were considered throughout the design process. It will discuss the advantage and disadvantages of each using engineering rationale. A recommended strongest design alternative will also be presented.

7.1 Aluminum Jansen Linkage with Gear Train and Windmill

This design alternative, which is recommend to be the most effective, uses a Jansen type linkage to act as the six legs. Figure 3 shows a SolidWorks model of the design. A gear train for each pair of legs will allow the drive shaft to be located away from the rotating parts of the leg and will also allow more torque to be transmitted to the legs. The drive shaft will be powered by a windmill either directly or via a gear train if additional torque is required. The majority of the strandbeest will be made out of aluminum due to its lightweight properties and its ability to be recycled.

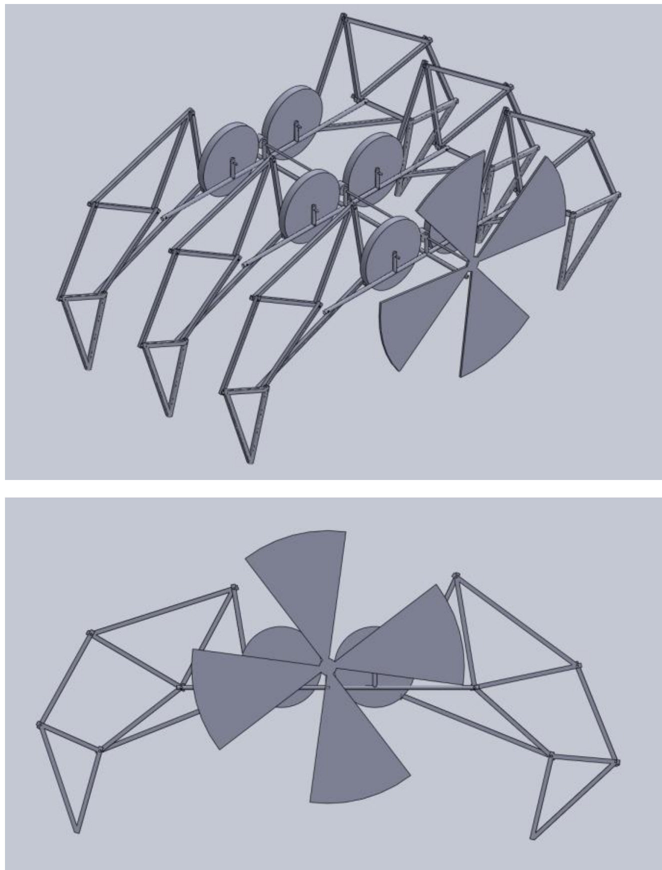


Figure 3: Recommended CAD Design

7.1.1 Leg Linkages

The Jansen linkage was chosen for this design alternative. The three legs on one side of the beest will be aligned parallel to each other, but will be offset by 60 degrees via crankshaft to provide a well-balanced mechanism. The three legs on the opposite side will mirror their partners, but will be offset by 180 degrees of rotation with respect to their individual partners. This effect will cause one leg to propel the strandbeest forward while the other is lifting up and readying for another step. However, there are tradeoffs for this type of approach just as with any design.

The advantages of using a Jansen leg are as follows:

- The smooth motion of the "foot" of the linkage and its low height variation makes the required torque input more uniform
- The three-leg offset makes the mechanism more balanced, also making the required torque input more uniform
- The information for optimum linkage lengths is readily available

The disadvantages of using a Jansen leg are as follows:

- The 11 member leg means many joints causing friction adding to the input energy required
- The 11 member leg means more material required, which adds to cost and weight

Overall, we believe that the balancing effect of the mechanism coupled with the low center of mass height variation will outweigh the disadvantages, resulting in a relatively easily powered and smooth device.

7.1.2 Windmill

A windmill was chosen to power this device since it translates wind power into rotational energy, which we then will harness for movement. There are advantages and disadvantages to this approach as well.

The advantages of using windmill power are as follows:

- The windmill shaft can be aligned with the crank shaft of the device for minimal losses in power.
- The high angular velocity of a windmill can be easily geared down to get the torque and speed required.
- It will allow us to expand our knowledge in areas of engineering in which we are currently limited.
- It can easily be powered with a hand held blow drier or a fan for class demonstrations.

The disadvantages of using a windmill are:

- The blade contours may be difficult to achieve for an effective design.
- The components needed to install the windmill would add weight to the structure.

7.1.3 Gear Train

The gear train is necessary to achieve the torque required from the windmill input, but the components could be costly and make up a large portion of the structures mass. The gears will also serve as a crank and will be connected to two of the leg linkages to set the legs into motion. Overall, gears are an efficient way of converting power and are required for this design.

7.2 Wooden Jansen Linkage with Drag Sail

This design alternative also uses a Jansen type linkage for its six legs in the same balance configuration as described above. However, it will not be shaft driven as in the previous design. A drag sail will be used to harness as much wind energy as possible and that force will push on some of the strandbeest's "feet" which will rotate their common drive shaft and cause the others to step forward. Wood was chosen for this design due to its high renewability properties as well as its ease of workability for thicker members. A thicker member was chosen because the legs will now have to withstand other forces if they are being driven from their feet.

7.2.1 Leg Linkages

The Jansen leg linkage was chosen for this design because of its ability to move its legs while being pushed. This was demonstrated through the many videos on Theo Jansen's strandbeest website. The advantages and disadvantages are the same as those listed above.

7.2.2 Drag Sail

Using a drag sail to power the beest is a simple and effective way to transfer wind energy into motion. The power is proportional to the area of the sail, which results in simple calculations for the design power input. However, there are advantages and disadvantages to drag sails.

The advantages of the drag sail are:

- The simplicity of its design.
- The low cost and weight of applying a sail to the design

The disadvantages of the drag sail are:

- The pushing force causes the friction on the feet to rotate the leg linkage in "reverse", which would cause unwanted forces in the members and the structure itself
- Class demonstrations could be difficult of the normal force applied to the structure is not enough to power the legs
- Overall, we feel like the drag sail approach is a risky approach and does not fully demonstrate our engineering skills to our design class or the possible dynamics classes in the future

7.3 PVC Jansen Linkage with Sinusoidal Sail

This design concept is much like the strandbeest Theo Jansen produces. It will have the six leg configuration as described before for balancing, but will be made out of PVC piping and a sinusoidal sail for propulsion. The sinusoidal sail uses a series of levers coming off of the crankshaft, but all offset from the next one to produce a sinusoidal shape once the single continuous sail is fitted over the levers. The concept behind this design is that the crests of the sail will catch the wind and be forced sideways, turning the crankshaft and causing another lever to be moved into the crest section where the process is repeated. If the levers are placed correctly then a smoothly rotating crankshaft will be available for power extraction. The advantages and disadvantages of the Jansen leg are the same as above so they will not be stated again. However, the sinusoidal sail has some unique advantages.

7.3.1 Sinusoidal Sail

Figure 4 shows an example of a Theo Jansen type strandbeest with a sinusoidal type sail. The bottles labeled are for energy storage.

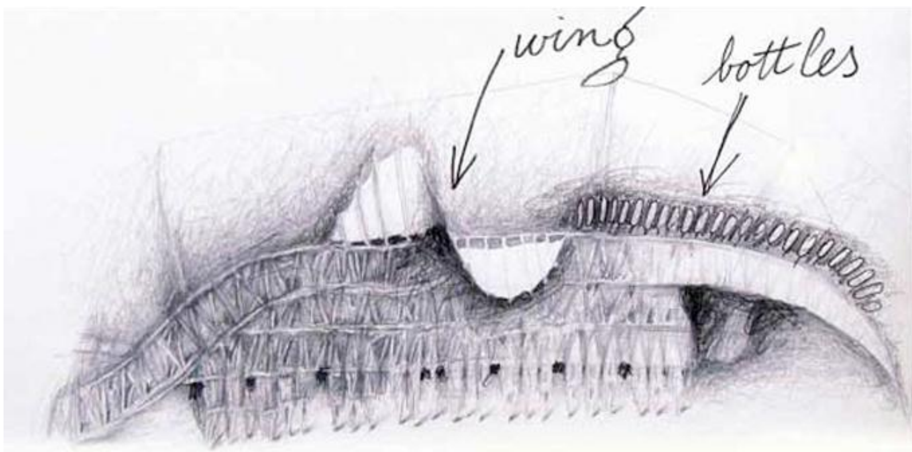


Figure 4: Sinusoidal Sail

The advantages of the sinusoidal sail are as follows:

- The levers of the sail provide torque as well as shaft rotation.
- A gear train is not required, which reduces the overall weight of the mechanism.
- The sail motion is more similar to objects in nature adding to the biomimicry concept of the strandbeest

The disadvantages of the sinusoidal sail are as follows:

- The information for constructing such a sail is not readily available suggesting that it is not very efficient or well engineered.
- The timing of the levers and drive shaft could prove difficult and would be hard to demonstrate in a class environment.

Overall, this concept design is essentially a copy of Theo Jansen's design and would not allow us to explore our own creativity and engineering knowledge, which is why we recommend rejecting this idea.

7.4 Aluminum Klann Linkage with Gear Train Windmill

This concept design uses a leg linkage design that is drastically different than the Theo Jansen design. It also uses a windmill and a gear train to extract wind power since shaft rotation is required to power this type of linkage. Aluminum was chosen due to its lightweight properties since the center of mass will be varying substantially. This design will only have four legs since that is all that is required to replace a wheel. The advantages and disadvantage of using a windmill are the same as described above, but the Klann linkage comes with a heavy set of disadvantages.

7.4.1 Klann Linkage

Figure 5 shows the construction and motion of the Klann linkage.

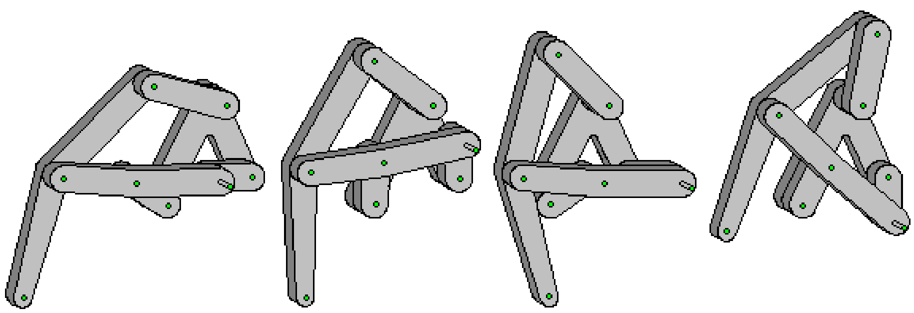


Figure 5: Klann Linkage

The advantages of the Klann linkage are as follows:

- Only six linkages are required for each leg meaning a lower weight and lower cost.
- The decreased number of joints needed means less friction.

The disadvantages of the Klann linkage are as follows:

- The stepping motion causes high variation of height in the center of mass, which means that a lot of the power input is wasted on moving the device up and down.
- There is an obvious location of equilibrium when both legs are touching the ground meaning that the input toque required would vary drastically.

Overall, the Klann linkage is too jerky in its motion to be powered by wind and would likely not move at all under low wind speed conditions. For this reason we highly recommend rejecting this concept design.

8. Feasibility

We will rely on wind to power the structure via a windmill. The maximum power available to the propellers of the windmill is the mass flow rate of air through the propeller times the total kinetic energy of the wind. With average wind speeds of 14.9 m/s (CWEEDS, 2013), this maximum power is 1,985 W/m^2 of blade sweep area. Because the blades cannot extract all the kinetic energy from the air, this value is lowered to 1176 W/m^2 according to the Betz's law. Assuming a blade diameter of 300 mm, the available power to the structure is then 83 W. Please see the calculations in appendix A.

The Jansen linkage mechanism requires 120° of crank rotation per step of a leg member, therefore a minimum of two legs will be on the ground at any given time. With a total of six leg linkages proposed for the structure, four of which will be on the ground at any given time, the structure is allowed a stable foundation. Each leg member will employ 11 links, which will require eight joints with eight bearings. Using the VXB 1.5 x 5 x 2 miniature ball bearings with a coefficient of friction of 0.005, total friction factor is 0.24 and total friction losses will be 282 W/m^2 and for a blade of 300 mm diameter, losses will be 20 W. This value is expected due to the low efficiency of the linkages as opposed to wheels. The mechanical efficiency is calculated as $\eta = 75\%$. Therefore there will be sufficient power from the windmill to drive the structure. Please see the calculations in appendix A.

A gear reduction will be required to lower the speed of the structure and increase the torque to the leg link cranks. The final speed of the structure has not been determined however, a reduction can easily be obtained by using a small gear on the shaft and a large gear which will drive each of the six linkages with an offset shaft. This will require a total of three small gears and six large ones. The gears may be rapid prototyped to reduce the cost or higher quality gears may need to be sourced. Lego education machined gears are approximately $60.00 per pair.

Currently the cost of one random length lumber futures contract on the Chicago Mercantile Exchange for the month of November 2013 is $366.50 at 260 m^3 spec. The cost of an aluminum futures contract on the Chicago Mercantile Exchange for the month of November 2013 is $1,812 per 1,000 kg. On an equal comparison by 1,000 kg mass, the cost of aluminum is 1,000 times more than that of wood however, given the small amount needed for this project, the cost difference between aluminum and wood may be in the order of ten to one respectively.

9. Testing and Verification

To test the legs, a Lego model of a front and back Jansen leg linkage was made. Using Theo Jansen's magic numbers, the linkage functioned the way that was predicted. The next stage is to connect at least two more pairs together to ensure the drive shaft will run smoothly and be unobstructed by the rotating linkages. This will be tested with more Lego pieces. Once the general design of the structure is decided upon, analysis of the forces on the members will be completed using SolidWorks. When the body is analyzed, the model should be built to size using the desired materials. The way the links are attached must be as frictionless as possible at this stage, allowing them to move easily.

Choosing the correct windmill is important to make sure it will capture enough wind to overcome the forces resisting movement. A wind propeller may be then attached to the drive shaft and tested using a device such as a hair dryer. If this does not work, a push sail (relies on friction from the feet to propel forward) may have to be introduced. At which stage, materials with higher friction coefficients may have to be used at the base of the feet. Once movement of 10 meters is achieved, the project will be completed.

10. Required Engineering Expertise

Technical Area	Team Member Responsible	Level of Expertise
Force analysis- A complete static analysis of the mechanism to determine the forces acting on the body	Jonathan	Intermediate
Material selection- Finding materials with good strength to weight ratios that can support the forces found in the force analysis but are light enough to promote movement	Nico, Rachel	High
Dynamics of machines- determining how the mechanism moves, the optimal joint lengths, and the minimal resistance	Nico	Intermediate
Environmental- Made with renewable/recyclable resources and powered by clean energy	All	High
Energy analysis- Determining the theoretical amount of energy needed to move the mechanism, and sourcing the right size wind turbine	Terry	High
Machining- Creating the desired parts from the selected materials	All	Low

11. Resources and References

11.1 Facilities

The facilities used to complete this project are the machine shop and the wind tunnel at Dalhousie's Sexton campus as well as the Halifax commons for full scale testing. The machine shop is already available since our group has completed the safety tour requirement with Angus MacPherson. To gain access to the wind tunnel we will contact Mark MacDonald and Albert Murphy to find out what requirements are needed to use the wind tunnel and complete these requirements. The Halifax commons is open to the public so it is already available.

11.2 Additional Advisors

Other individuals to contact for project advice will be Reg Peters, Dr. Lukas Swan, and Emanuel Jannasch. Reg Peters and Emanuel Jannash can be contacted for wood construction advice and Jannash can also have helpful input regarding the architecture of the Strandbeest. Dr. Lukas Swan can be contacted for wind power advice, which will put the Strandbeest in motion.

11.3 Funds

The funds needed to fund this project will come from the Mechanical Engineering Department after applying and local businesses that are willing to donate materials. If enough funding is not available then we will look to salvaging recyclable materials.

Appendix A

Windmill

Power available to propeller

$$\frac{1}{2} \rho A V^3 \quad \text{where } \rho = 1.2\ kg/m^3$$
$$V = 14.9\ m/s\ *$$

* V of 14.9 m/s obtained from CWEEDS @ Sable Island 5 m elevation.

$$\therefore P_{avi} = \frac{1}{2} \cdot 1.2\ kg/m^3 \cdot (14.9\ m/s)^3$$
$$= 1985\ W/m^2 \text{ of sweep area.}$$

Power which can be extracted by windmill

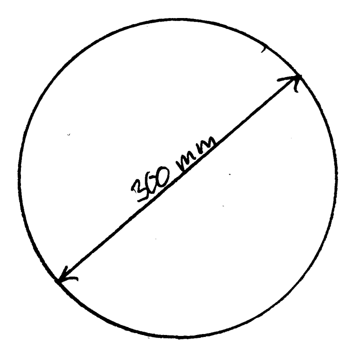
$$\frac{8}{27} \rho A V^3 \quad \text{According to Betz's law}$$

$$\therefore P_{ext} = \frac{1}{2} \cdot \frac{16}{27} \cdot 1.2\ kg/m^3 \cdot (14.9\ m/s)^3$$
$$= 1176\ w/m^2 \text{ of sweep area}$$

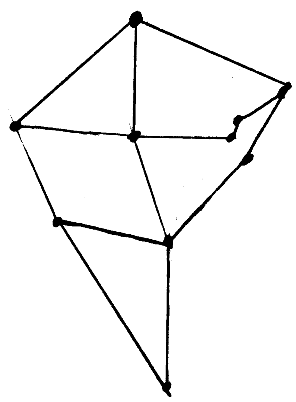
Assuming blades of 300 mm DIA

$$\text{sweep area} = \frac{\pi \cdot \left(\frac{300}{1000} m\right)^2}{4}$$
$$= 0.071\ m^2$$

$$P_{ext} = 1176\ w/m^2 \cdot 0.071\ m^2$$
$$= 83\ W$$



Jansen Linkages



11 links
1 crank
8 bearings

Use VXB 1.5 x 5 x 2 ball bearings

Coefficient of friction = 0.005

$\therefore$ 8 bearings per leg linkage x 6 proposed legs x 0.005
= 0.24 total friction factor

Power from windmill = 1176 W/m^2 sweep area

losses = 1176 W/m^2 · 0.24
= 282 W/m^2

For 300 mm DIA blade, loss =
282 W/m^2 · 0.071 m^2
= 20 W

$$\eta = 1 - \frac{20}{83} = 75\%$$

which is expected from a structure with so many links