Designing and Prototyping of Multi-Crop Solar Powered Harvester

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Abstract—The demands on the grains have been being increased radically in Ethiopia. The existing ways of harvesting grains are not differed from the ancient methods. In order to satisfy the needs our ancestors have been being applied their full money, power and times which leads financial and physical weakness and health problems especially on their backbones. No one was hearing and trying to minimize and eradicate this problem. Hence, a simple to operate and cheap in cost harvester is designed and prototyped which is driven by solar power. The machine harvest grains that have grass physical nature such as wheat, barley, Teff, rice even the grass itself for animal feed. The design and prototype were achieved by following a method of reviewing literatures, collecting data, synthesizing and analyzing the mechanism and structure at a preliminary and detail design stage (using manual and CATIA), making drawings, manufacturing a prototype and testing. The prototype of solar grain harvester has one hp DC motor, 2.4 m^2 solar panel, four-wheel vehicle and cutter assembly. It can harvest 600 mm width of grain at a speed of 500 mm/s i.e., it can harvest 0.108 ha/hr. or 18.73 times more than a single person can do. Therefore, small-scale solar grain harvester will become preferable means of harvester because it is none pollutant and freely available.

keywords—solar grain harvester, basic structure of cutting Mechanism, geometry synthesis and analysis, preliminary and detail design, and Design and Prototype of Harvester,

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1 Introduction

THE mechanization of agriculture not only reduces the overall cost of production but also increases the total agricultural yield. Through mechanized farming, many countries in the world are reaching the upper limits of their cultivable land. The increasing use of agricultural machinery, equipment and fertilizers coupled with better irrigation facilities, together revolutionizes the agricultural sector [17].

It is obvious that different types and levels of harvesting tools and machines are applicable in different countries. However, the current harvesting systems are not different from the ancient styles in Ethiopia. This is due to the low-level economy of the farmer, the awareness of the people and the high taxation system of the government. Due to this reason, the farmers have been being forced to use the traditional and the time and power consuming way of harvesting. The harvesting times, of the grains, have been being elongated for months to cover small pieces of lands. This has adverse effect both on the farms and on the country productivity. The farmers have been killing more time that maximizes the cost of production and they will not think for further value-added processes and more production systems. In addition, the amount of seeds collected will be reduced since it falls into the ground and eaten by animals. This leads to an abrupt time-to time increasing on the price of the grains and the demand will not be satisfied. Beside this, the country will not prepare the grains on time both for the people and for foreign countries, which makes the country uncompetitive and lags behind others in supplying the foods. Since the pressures on demand of the grains are increasing drastically, it will be difficult to supply the future needs. Therefore, a simple and cheap system should be implemented which can fill the gap between the traditional and high-level modern ways of harvesting.

The main aim of this research is to design a harvester operated by solar energy and to manufacture the prototype locally using our manpower and workshop. Specifically, the mechanism that transfers input power to output will be designed and the necessary parameters of the source of power will be analyzed. Hence, the frames, motors, connecting mechanisms, cutters, collectors, couplings, joints, and solar panels will be synthesized and analyzed.

The harvester has very great role to maximize the harvesting rate of grains such as wheat, barley, Teff, rice, grass, etc. It collects more grains than a person can do. Since the time required to harvest grains reduced, the farmers will gain additional time in order to have further farming time. That means they can farm more than once per year. The productivity will be increased because the grains will be harvested at the critical stages. In addition, there will be a chance for the producers to add values on their seeds. The burden on the workers reduced which will increase their life span.

2 Research Gap

The previous harvesting systems are either manual or mechanical. The mechanical harvesters are operated using fuel energy. Fuel energy is efficient in driving the system however, it is expensive and pollutant. To overcome these a solar powered harvester is proposed. Since the efficiency of solar power is low, it is necessary to think over the mechanism of existing harvesters. The current harvesters have a mechanism that has sliding cutter bar. It is obvious

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that sliding friction is higher than rolling friction. So that by changing the sliding to rolling cutter bar it is possible to minimize the energy needed to overcome frictional resistance. Therefore, an efficient solar harvester can be achieved using cutter bar that reciprocates on roller support.

3 Preliminary Design

The harvester is driven by using solar power. Hence, it should have solar panel, battery, motor, power transmission between motor shaft and cutter bar. There is always movement during harvesting, i.e., the harvester should have at least two wheels. One of the basic activities in this research is synthesizing the mechanisms between the motor and cutter. In addition, there is analysis of solar panel size, motor capacity, and structure development and strength analysis. The latter provide strength and make the system together by supporting and driving the cutting mechanisms. Therefore, the mechanism synthesis should be done first.

The cutting mechanism always moves in straight line in reciprocating motion. The reciprocation of the cutter can be done by using either slider crank mechanism or eccentric cam and follower.

Among the above alternatives, eccentric cam and follower mechanisms was selected using appropriate design and manufacturing criteria like possibility to design and manufacture the system using the current available knowledge and technologies, ease of operation, structure simplicity, easy to implement, efficiency, wear rate and Compactness by applying weightage method.

3.1 Basic Structure of Cutting Mechanism

The basic structure of the cutting and conveying mechanisms are shown in **figure**. The cutter reciprocates using positive return eccentric cam and follower mechanism. This type of cam does not require a spring to return the follower.

The harvester composed of power system, driving system, guide system, vehicle system, cutter system and conveyor system. Its means tree is shown in table 1.

Table 1
Functional Analysis or Means Tree of Solar Harvester

Harvester					
Power System	Driving System	Cutter System	Conveyor system	Guide System	Vehicle System
Solar panel	DC motor	Cutter bar	Pulley	Crop lifter	Tire
Battery	Coupling	Guide lip	Roller	Divider	Handle
Charge control	Gear Box	Cutter	Belt	Star Wheel	Damper
Supports & frames	Supports & frames	Supports & frames	Supports & frames	Supports & frames	Supports & frames
Joints	Joints	Joints	Lugs	Joints	Steering
			Joints		Joints

4 Detail design

4.1 Working Principles

A DC motor drives the system. The power is supplied into the DC Motor either from DC batteries or direct solar panels. As the DC motor starts, the power is transmitted to intermediate shaft through the belt pulley mechanism see Fig. 1. This power is again transmitted to the camshaft through bevel gear assembly. When camshaft rotates, the positive return follower reciprocates back and forth using eccentric cam see Fig. 2. At the same time, the cutter bar reciprocates back and forth together with follower since the attachment is rigid. When the cutter bar reciprocates, it cuts the grain. At the same time, the camshaft drives the lugged conveyor system through the pulley in order to collect the grains to one side.

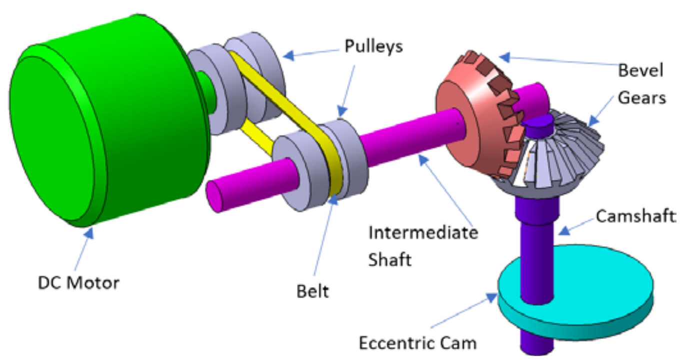

Fig. 1 Power Transmission System

4.2 Geometry Synthesis and analysis

The basic geometrical synthesis and analysis carried for the speed of DC motor, speed of pulley on the DC motor shaft, speed of camshaft, length of cam nose, stroke length of the follower, speed of lugged conveyor, pitch of lugs and pitch of star wheels.

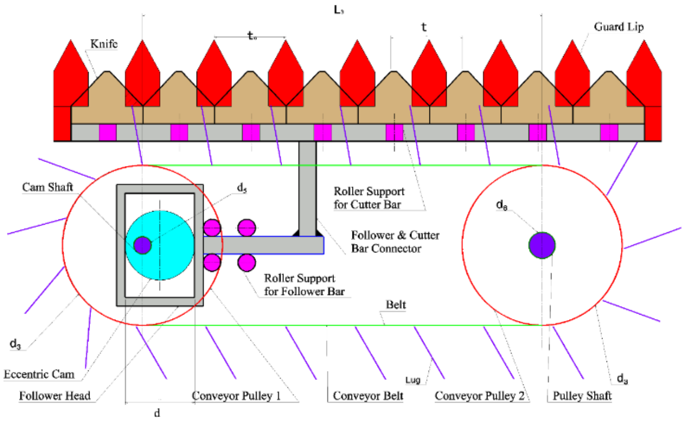

Fig. 2 Basic Structure of Cutting and Conveying Mechanism

The velocity ratio of the motor and intermediate shafts Fig. 1 is;

$$\frac{\omega_1}{\omega_2} = \frac{d_2}{d_1} \quad --\rightarrow \omega_1 = \frac{d_2}{d_1}\omega_2 \tag{1}$$

The velocity ratio of the intermediate and cam shafts Fig. 1 is;

$$\frac{\omega_3}{\omega_2} = \frac{d_7}{d_4} \quad --\rightarrow \omega_3 = \frac{d_7}{d_4}\omega_2 \tag{2}$$

Where ω_3 is the angular speed of the camshaft rad/s, ω_2 is the angular speed of the intermediate shaft in rad/s, ω_1 is the angular speed of the motor shaft in rad/s, d_1 is diameter of pulley on the motor shaft, d_2 is diameter of pulley on the intermediate shaft, d_3 is diameter of the conveyor pulley, d_4 is pitch diameter of bevel gear on the intermediate shaft, d_7 is pitch diameter of bevel gear on camshaft, d is diameter of eccentric cam, d_5 is diameter of camshaft and d_6 is diameter of idler conveyor pulley shaft. In addition, based on the mechanism of the harvester the driver and driven pulley for the conveyor (d_3 and d_6) and camshaft (d_5) have the same rotational speed (ω_4).

The velocity of the nose of the cam (V_c) in m/s is defined as follows

$$V_c = \omega_3 L_2 \tag{3}$$

Where L_2 is the largest distance of the cam from its center of rotation to the nose

The velocity of the lugged conveyor and pulley belt (V_b) Fig. 2 in m/s defined as follows;

$$V_b = \omega_3 \frac{d_3}{2} \tag{4}$$

The power transmitted from the pulley of the motor shaft (P_1) to the intermediate shaft is the product of tangential net force (F_1) and velocity (V_1) of the pulley;

$$P_1 = V_1 \times F_1 = \omega_1 \frac{d_1}{2} \times F_1 = \omega_1 \times T_1 \tag{5}$$

The amount of tangential velocity and force of belt on the motor shaft and intermediate shaft pulley is the same i.e., $V_1=V_2$; $F_1=F_2$. This implies that the ideal output power of the motor shaft is equals to the input power of the intermediate shaft. The torque in the intermediate shaft (T_2) becomes

$$T_2 = \frac{d_2}{2} \times F_2 = \frac{d_4}{2} \times F'_2 \tag{6}$$

The amount of tangential velocity and force of bevel gear on the intermediate shaft and camshaft is the same ($V'_2=V_3$; $F'_2=F_3$). This implies that the ideal output power of the intermediate shaft is equals to the input power of the camshaft. The torque in the camshaft (T_3) mathematically defined as follows;

$$T_3 = \frac{d_7}{2} \times F_3 = T_4 + T_5 = L_2 \times F_4 + \frac{d_3}{2} \times F_5 \tag{7}$$

The torque in the camshaft (T_3) is shared by the cam and conveyor pulley 1 i.e., the sum of the torque in the cam (T_4) and the conveyor pulley 1 (T_5) is equals to the torque in the camshaft (T_3).

Where F_1 is tangential force at the motor shaft pulley; F_2 is the tangential force at the intermediate shaft pulley; F'_2 is the tangential force at the intermediate shaft bevel gear pitch diameter, F_3 is the tangential force at the camshaft bevel gear pitch diameter, F_4 is the tangential force at the nose of cam and F_5 is the tangential force at the conveyor pulley. The tangential force F_4 is perpendicular to the line between cam rotational center and the contact point of the cam and follower. The component of the force F_4 transferred into the cutter bar is always parallel to the path of motion of the cutter bar. It can be derived from the free body diagram of the cam and follower as follows in Fig. 3.

The component of force that pushes and pulls the cutter bar is

$$F_{cb} = F_4 \sin\theta \tag{8}$$

Where F_{cb} is the applied force on the cutter bar by the cam and θ is the angle between the cam and the line of motion of the cutter bar.

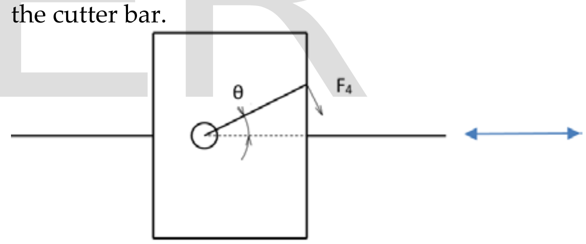

Fig. 3 Schematic Diagram of Cam and Follower

The equations that relate the follower displacement, velocity and acceleration to the cam rotation angle θ is simple hormonic motion [Shigley & Uicker, 1988]:

$$\begin{cases} S_f = \frac{1}{2}H\left(1 - \cos\left(\frac{\pi\theta}{\beta}\right)\right) \\ V_f = \frac{1}{2}\frac{H\pi\omega_4}{\beta}\left(\sin\frac{\pi\theta}{\beta}\right) \\ a_f = \frac{1}{2}H\left(\frac{\pi\omega_4}{\beta}\right)^2 \cos\left(\frac{\pi\theta}{\beta}\right) \end{cases} \tag{9}$$

4.3 Physical and mechanical properties of crops

The Physical and mechanical properties of crops are studied by different researchers. The studies have been carried in different countries, different values of moisture contents and different species of grains. The results show that their values differ in different magnitudes of shearing strength and cross-sectional area. It is advisable to consider the worst things in order to make the harvester universal i.e., applicable

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throughout the world. This means that the capacity of the harvester can be analyzed by using maximum values of shearing strength and cross-sectional area which are taken from different literatures. Hence, the machine can harvest efficiently all types of grains in all countries.

The shearing strength and cross-sectional area of wheat is the highest value among barley and rice. So that the geometry, force and strength analysis should be based on wheat which 36.365 N shearing force.

Table 2
Physical and Mechanical Properties of Crops

Straw	Wheat	Barley	Rice
Minimum cross-sectional area A mm²	2.32	na	na
Maximum cross-sectional area A mm²	3.087	5.377	4.055
Minimum shearing strength τ MPa	4.91	3.90	1.429
Maximum shearing strength τ MPa	11.78	6.18	1.629
Maximum shearing force F N	36.365	33.23	6.606

Note: na is stands for not available

$$\tau = \frac{F}{A} - - - \rightarrow F = \tau A \quad (10)$$

$$= 11.78 * 3.087\ N = 36.365\ N$$

Where τ is shear strength, F shear cutting force and A cross sectional area for a single straw

A number of knives cut the grain at a time. The total force requirement can be determined by multiplying the previous force with the numbers of knives n.

$$F_{cb} = nF = \frac{L_{cb}}{t} F \quad (11)$$

Where L_{cb} is the length of the cutter bar

4.4 Modeling of force on cutter bar assembly

The magnitude of total force (F_T) required to move the cutter bar assembly depend on the grain cutting force (F_{ca}), frictional resistance (F_f) and inertial force (F_i) of a linear motion of cutter bar assembly.

$$F_T = F_{ca} + F_f + F_i = F_{ca} + N_{ca} \times \mu + m_{ca} \times a_{ca}$$

$$= F_{ca} + N_{ca} \times \mu + m_{ca} \times \frac{1}{2} H \left(\frac{\pi\omega_4}{\beta}\right)^2 cos\left(\frac{\pi\theta}{\beta}\right) \quad (12)$$

Where N_{ca} is normal force on the cutter bar assembly i.e., weight of cutter bar assembly, μ is coefficient of rolling friction, m_{ca} is mass of cutter bar assembly, g is gravitational acceleration and a_{ca} is acceleration of cutter bar assembly

5 Results

Table 3
Result from Geometry and Force Analysis

Parameter	Value
Speed of the motor shaft ω_1	1800 RPM
Motor power P_1	2HP
Motor Torque T_1	7.915 Nm
Forward speed of machine V_m	0.5 m/s
Minimum speed of knife V_k	0.7 m/s
Cam raise & return stroke angle β	180°
stroke of the knife for reaper H	76.2 mm
Spacing of guard lip t_o	76 mm
Spacing of knives t	76.2 mm
Angular velocity of camshaft ω_3	88 rpm
Ratio of ω_1 and ω_3	20.464
Diameter of pulley on motor shaft d_1	40 mm
Diameter of pulley on intermediate shaft d_2	180 mm
Two solar panels	200 W each
Minimum Voltage required	36 V
Input torque into camshaft T_3	162.065 Nm
Input force into camshaft	1790.769 N
Numbers of knives n	8
Length of cutter bar L_{cb}	600 mm
Pitch diameter of bevel gears D_p	40 & 180 mm
Diameter of conveyor pulleys	289 mm
Conveyor Pulley velocity V_b	1.33 m/s
Pitch of lug P	125.5 mm
Angular speed of lugged belt ω_4	41.82 rpm
Number of lugs N_l	15
Diameter of star wheel D_s	200 mm
Numbers of arms on star wheel N_s	5

5.1 Testing Result

The harvester was tested on shop in two ways. The first was a test of the harvester after completing the assembly in order to check its functionality. The second was conducted first by feeding a single straw and then a row of straws. The harvester cut nicely the straws in both a single and row of straws.

Shop (After Assembly) Test: The shop test was carried out by using solar panel and Solar Battery separately. There are two solar panel and Solar Battery as a source of power available in order to drive the harvester. The experiment was carried six times. These are using single battery, two batteries in series, two batteries in parallel, single solar panel, two solar panel in series and two solar panel in parallel. The testing of the harvest was carried out on October 31, 2018 at 3:15 PM in Adama Science and Technology University.

Test Equipment: Two solar batteries, two solar panels, charge controller, Infrared Tachometer, multi meter and harvester machine. The capacities of a single battery and solar panel are 200 Ah and 200 Watt respectively.

Table 4
Voltage Recorded during the Test

Power source	1 Battery	2 Series Batteries	2 Parallel Batteries	1 Solar Panel	2 series Solar Panel	2 parallel Solar Panel
Measured Voltage V	13.01	25.77	13.01	39.7	79.6	39.7

Table 5
Measured RPM Values of Shafts

S. No.	Shafts	Speed in RPM					
		1 Battery	2 Series Batteries	2 Parallel Batteries	1 Solar Panel	2 series Solar Panel	2 parallel Solar Panel
1	Motor output shaft	0	64	0	138	347.18	267
2	Intermediate Shaft	0	59	0	136	223.52	171.9
3	Cam shaft	0	56	0	129	176	135.4
4	Conveyor shaft	0	47	0	49.9	75.12	57.8

The power requirement of the harvester becomes clear. The harvester initiates rotation when the voltage supplied into the DC Motor becomes greater than 24 V, which is attained by using two batteries in series, single solar panel, two solar panels in series and two solar panel in parallel. A minimum of 36 voltage is required to harvest the grains. However, the weight of two batteries is 130 Kg, which is not feasible due to its high weight. Even if the cutter works by using single solar panel, it is not recommended to use it as sole source of power because the harvester may not be energetic to cut at full feeding condition. Hence, two solar panel either in series or in parallel can be used to drive the harvester.

5.2 Capacity of Solar Harvester

The theoretical capacity of the solar harvester (Q) is estimated by considering maximum cutting width (w) 0.6 m and machine forward speed (V_m) of 0.5 m/s. Hence, it becomes;

$$Q = w * V_m \tag{13}$$

$$= 0.6 m x 0.5 \frac{m}{s} = \frac{0.3m^2}{s} = 0.108 \frac{ha}{hr}$$

This shows that 0.108 hectare can be harvested with one hour or 9.26 hours are required to harvest a hectare of grain using the new solar harvester which 18.73 times faster than manual harvester.

6 Conclusion

The small-scale solar powered harvester has been prototyped successfully. The prototype incorporates power generation system, cutting system and vehicle system. The power is collected from direct sunray using solar panels 200 watt each. This power is transferred to the cutting system using Dc Motor with 1 Hp power rate. The grains are harvested and conveyed into one side using the cutting system. The whole assembly is transported using the vehicle using human hand force.

The harvester is effective by using solar panels instead of batteries. It can harvest 0.108 ha/hr. or 18.73 times more than a single person can do by using two solar panels. Hence, it is confidential to conclude that a small-scale solar harvest is feasible as none pollutant means of harvesting grains.

7 Recommendation

The effectiveness of solar grain harvester is promising. Hence, it is recommended to manufacture and supply to the users by improving the following components. These are on the

- mass balancing of the rotating parts i.e., to minimize
- vibrations especially the shape and size of the cam; fits and tolerances of the cutting system i.e., shape, size and connections of follower, follower bar, cutters, cutter bar, guard lip, guard lip bar;
- optimization of the structure in order to reduce the weight and decide best center of center of gravity.

The harvester can also be used to collect grasses for animal feed.

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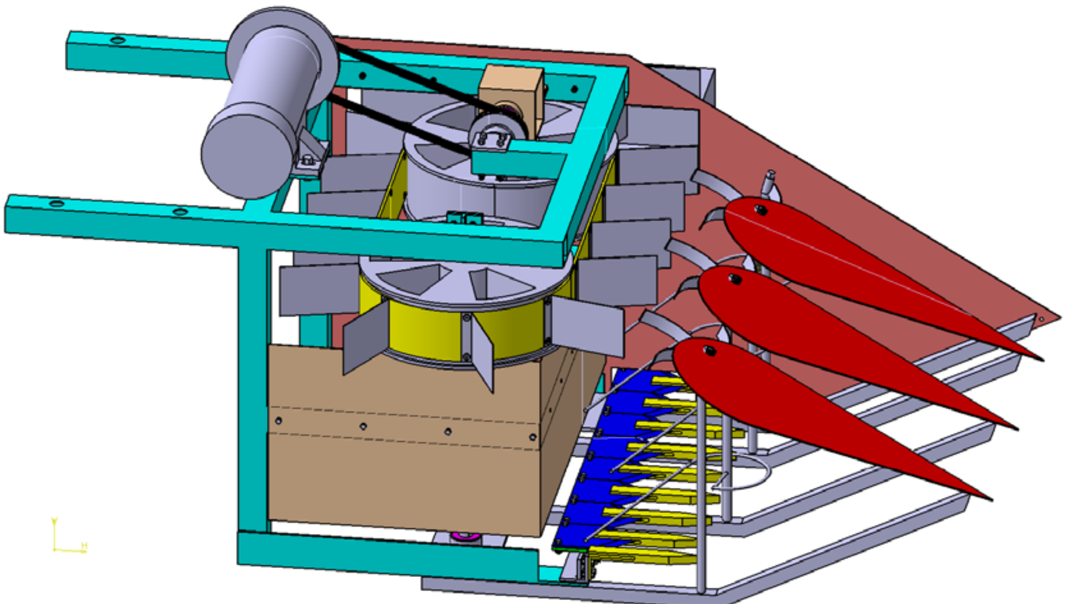
Appendix

Appendix A Isometric Drawing of Cutter and Conveyor System Assembly



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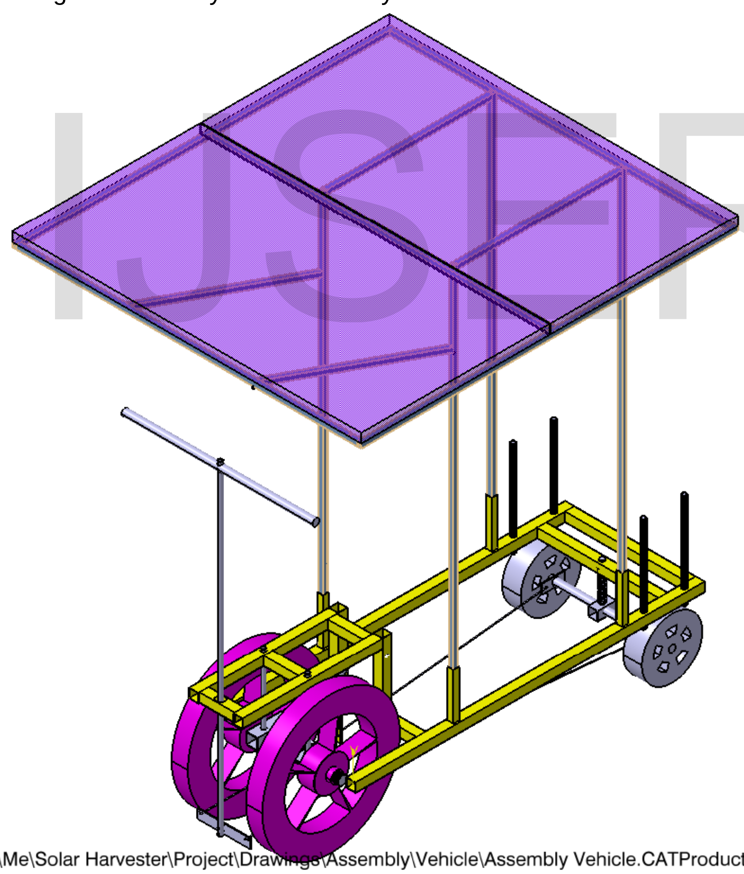
Appendix B Isometric Drawing of Vehicle System Assembly



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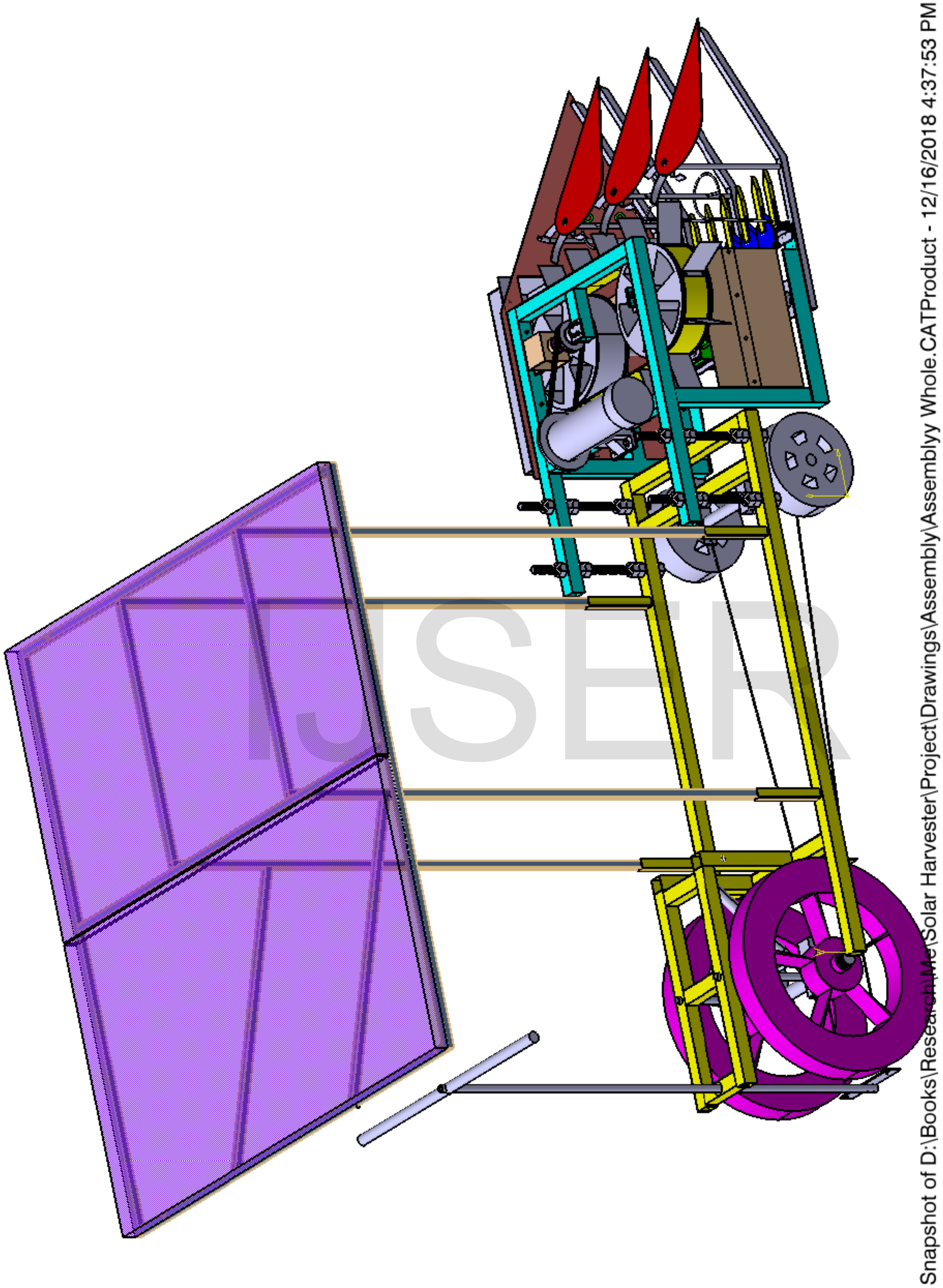
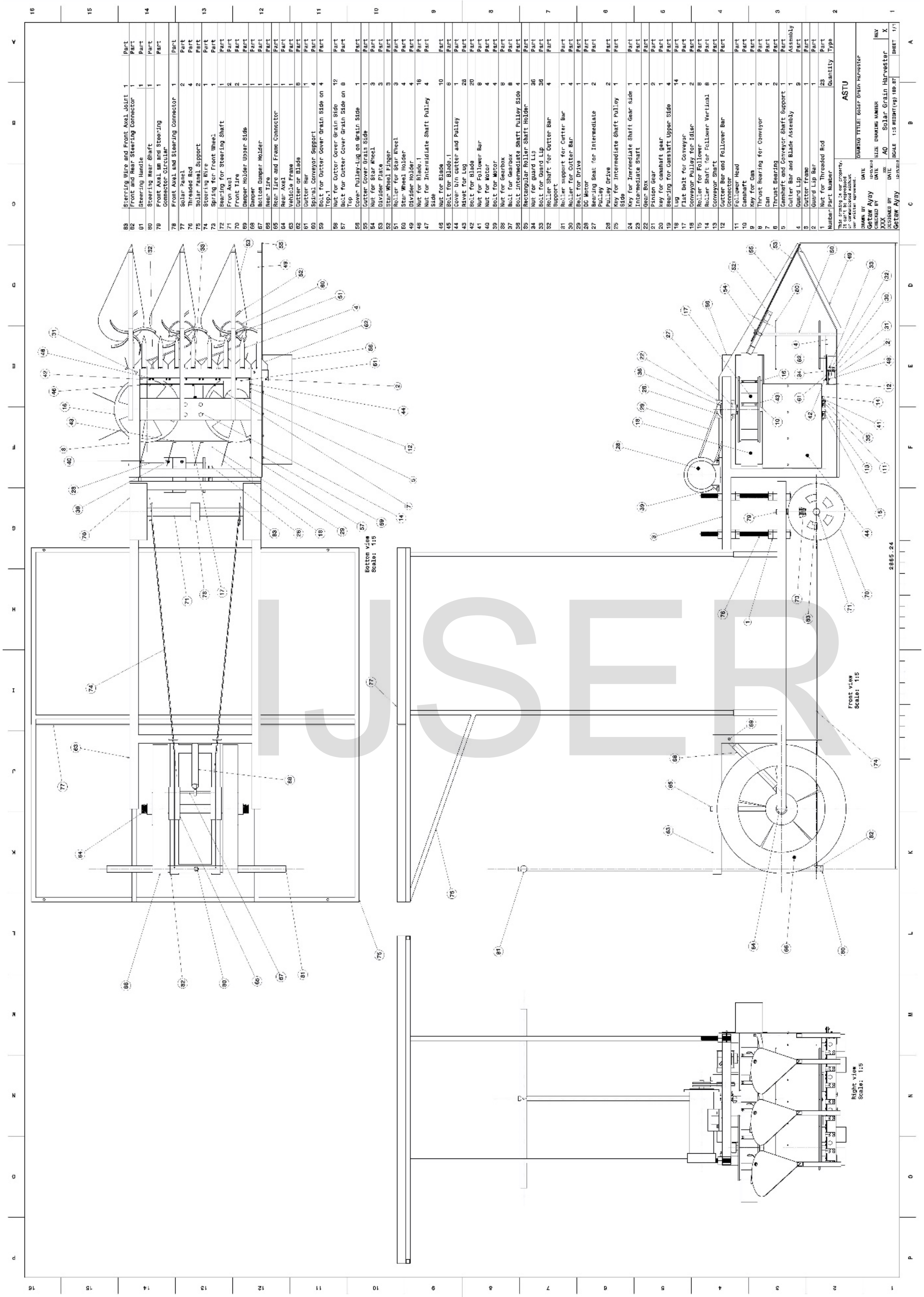
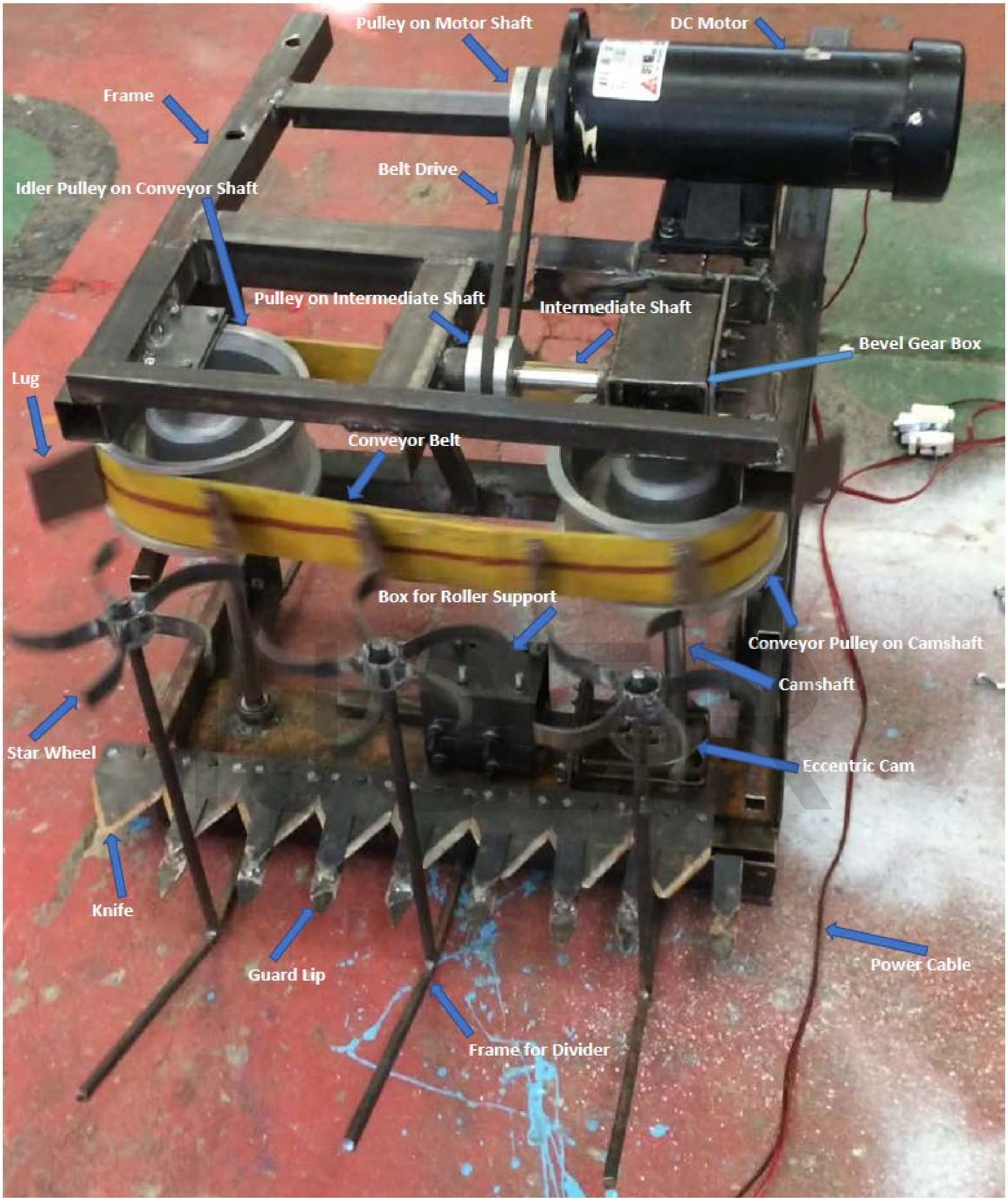


Appendix C Isometric Drawing of Harvester Assembly



Appendix D Multiview Drawing of Harvester Assembly

Appendix E Photo of Cutter and Conveyor System Assembly under Manufacturing



Appendix F Photo of Harvester During Field Test