European Journal of Applied Sciences – Vol. 13, No. 02
Publication Date: April 25, 2025
DOI:10.14738/aivp.1302.17590.
Khan, L. A., Khan, M. K., Kaleem, M. M., Rehman, M., Nasir, W., & Liaquat, H. (2025). Design and Kinematic Analysis of Mechanized Rice Transplanting Mechanism. European Journal of Applied Sciences, Vol - 13(02). 41-58.

Design and Kinematic Analysis of Mechanized Rice Transplanting Mechanism

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ABSTRACT

Precise pick and place point of rice transplanting arm is necessary for the efficient production of rice. Literature shows that inaccurate picking and placing points reduces the rice production efficiency by almost 20-30%. This study is made to obtain the path of rice transplanting arm using linkage, determined the path mathematically and designed cam and follower to simulate it. Pump type rice transplanting arms have the problem of links size adjustment, if link lengths are not selected properly, the points of interest are disturbed, hence lowering the efficiency. A detailed kinematic analysis of link lengths, position of coupler points and verification via Grashoff conditions is made in this research, the results of different link lengths with their effect on path of transplanting arm is done, and the best of them is selected and further analyzed. Finally, the pump type transplanting arm is designed, simulated, and tested for different crank angles, position, velocity and acceleration analysis is done. Results from mathematical model and simulation are compared. Two arms-based rice transplanters have been designed, and a prototype is made and tested. The results are close to design parameters.

Keywords: Rice transplanting arm, Grashoff conditions, kinematic analysis, crank angle, mathematical modeling.

INTRODUCTION

Agriculture is an important source of foreign exchange for export for Pakistan which accounts almost 18.9% of Pakistan's GDP and about 42.3% labor force is dependent on it. According to US department of agriculture, Pakistan harvested a record rice crop of 8.9 million tons in financial year 2021-22[1]. Rice is the third-largest export of Pakistan as in 2019 by $834 million [2]. It is reported that three fourths of rice is cultivated by traditional puddled transplanting methods. In this method, rice nursery is raised and then its seedlings are transplanted into a flooded field. The rice transplanter which was manually operated was developed to transplant the mat type rice paddies. It can transplant in two or more rows at a time. The objective of this machine is to meet the requirements of medium farmers whose investments are limited but they have large lands to work with short time and minimum resources.

The need for a small, cheap, labor-saving transplanting mechanism is obvious in the rice growing areas of Asia. Several transplanting mechanisms are available in Asia, but not in Pakistan, the conventional labor method is being applied. The design of rice transplanting mechanism requires special attention in calculations and dimensions of picking and placing point of a paddy as well as movement of mechanism. The picking point requires a specific height from the field, called clearance, which must be considered in design so that machine maintains a constant forward speed, The convincing factors duly motivate researchers and engineers towards the most promising and viable solution for mechanical rice transplanter. Chang-Jun determines that the quality, efficiency and reliability of the transplantation process is highly dependent on the "transplantation mechanism" [3] The calculations of mechanism and its dimensioning depends upon several factors including field, depth of plantation, plantation speed, and type of paddy etc. All these factors are considered and analyzed for determining the required link lengths, transplanting arm dimensions and smooth movement of mechanism.

Rice Production Stages in Lowland Fields in Pakistan

Rice growing have several important stages which is summarized in Figure 1 showing the sequence of growing rice in Pakistan.

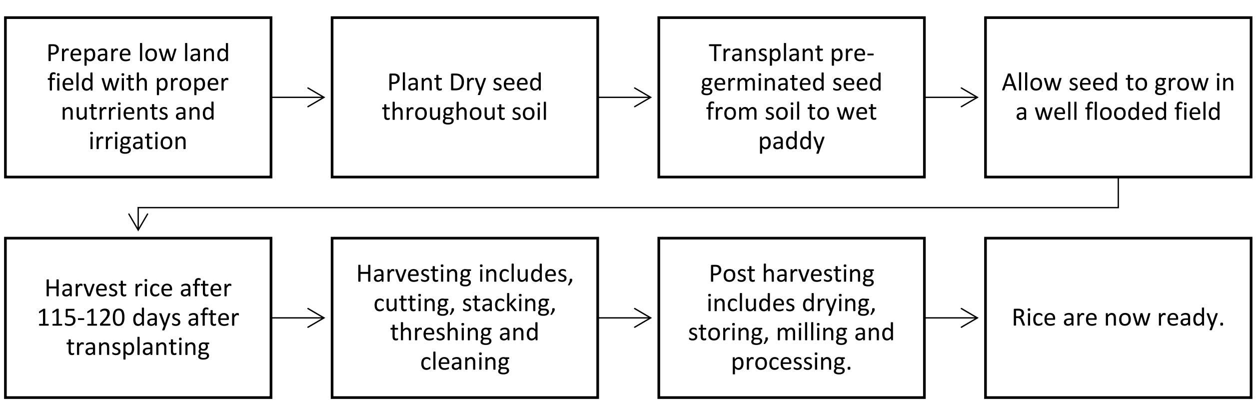

Figure 1: Sequence of Rice growing in Pakistan

Manual Rice Transplantation:

Manual transplanting can be done by the following procedures [4]:

1. Straight Row: Rice is transplanted according to a uniform pattern. In this method, the operator can achieve optimum spacing between plants.
2. Random: Seeds are scattered randomly and a particular spacing cannot be achieved. In this method, the hill spacing is roughly 10 to 25 cm.

The process of manual transplantation consists of the following steps [5].

1. Seedlings are prepared in a modified mat nursery.
2. The seedlings ready for transplantation at 15-20 days after sowing (DAS) are transported to the fields.
3. These seedlings are immediately transplanted in a properly levelled, puddled field after being removed from nursery (as delay can cause damage to seedlings).
4. Seedlings are transplanted in groups of 2-3 per hill at shallow depth and specific spacing.

Drawbacks of Manual Rice Transplantation:

Following are the few drawbacks of manual seedlings transplantation [6]:

1. Heath risks for labors such as back pain because of stooped posture or skin damage due to fields filled with corrosive chemicals.
2. Laborious and exasperating process (up to 30 person- per days per ha).
3. Excruciatingly time-consuming process (250-300 man-hours/ha).
4. The lower density of plants (50000-8000 plants/acres).
5. It is challenging to get the desired spacing with random transplanting and labor on contract.
6. Hard to get adequate labor to plant paddies in time at peak period of rice transplanting.

There is a chance of seedlings getting too old before desired rainfall in rained areas.

Inter-paddy Spacing During Transplantation:

Optimum plant spacing plays a vital role in increasing grain yield. For tall and leafy varieties, the following spacing is optimum.

Table 1: Soil spacing dimensions.

Season	Soil type	Spacing/cm
Dry	Poor Fertility	25×25
	Rich Fertility	30×30
Wet	Poor fertility	30×30
	Rich Fertility	35×35

However, for the dwarf varieties, which are not affected by photoperiods, a spacing of 20×20 cm is recommended for all seasons. For soils with low fertility 20×10 cm spacing should be used [7].

Age of Paddy and Depth Required in Transplantation:

Young seedlings are transplanted: age usually 14 days old when they have only two leaves and a shallow depth of about 1-2 cm is used for transplanting.

Mechanical Transplantation of Paddies/Seedlings:

In this process, specially raised rice seedlings, mat type nursery having polyethene sheet, are transplanted at desired depth and spacing with the help of a machine called rice transplanter. Rice transplanters have seedling boxes/trays to hold the seedlings ready for transplanting. Seedlings are grown in a thin soil of about 30 by 60 cm trays, or they are grown at a larger area and then cut into mats that are fitted in these trays. These seedlings are then picked up one at a time by a picking mechanism and sowed in-ground at a specified depth.

LITERATURE REVIEW

Rice crops, being an important food and export item, calls for research in rice cultivation while bringing into modern technologies and machinery so that the output can be optimal. The research in the domain of rice, an essential eatable item in the entire world, plantation and production is perceptibly critical for the advancement of the equipment plus techniques, which improves the yield, hence profit for the farmers, especially in emerging Asian countries [8]. The transplantation of rice is significantly more efficacious than "direct seeding," "drilling" and "broadcasting" because transplantation provides enhanced weed control, uniformityof plantation and ripening, better irrigation control, high paddies density, requires field for comparatively lesser time and results in 10 to 25% greater yield than other methods [9]. Murumkar and Dongarwar define "manual transplantation" as a painstaking and expensive mean of yielding rice crop while analyzing that it requires 250-300 man-hours/ha, which become approximately the one-fourth of the total needed labor [10]. It has also been affirmed by Ibrahim that laborers are prone to serious health issues due to prolonged exposure of corrosive chemical, scorching heat and extensive stooped posture [11]. Kumbhar writes that owing to the shorter optimum span available for transplantation, skilled workers are scarce in peak times during transplantation season. If the transplantation is postponed for one month, shrinks the production by 25%, whereas two months delay leads to a 75% reduction; hence, the time of transplantation is crucial [12]. At present, mechanized rice seedling picking is categorized into three main categories, these are clamping type, top-out and finally pneumatic type. The clamping type consists of a mechanism which separate the seedlings from paddy tray by clamping stem of the seedling [13] [14] [15] .The top out mechanism works on the action of rod called top rod, which tops the seedling from back of plate to complete its action [16]. The pneumatic mechanism relies on the force of air, so that the seedlings blow out of the paddies try. Japan produced the top out type transplanters, in the last of nineteenth century, which included the following operations: pushing, conveying and planting, but the mechanism was complex mechanism with low efficiency. Zhang et al. [17] developed a top-out rice seedling transplanter, which used a guide tube to push out the seedlings from the tray and planted them into the paddy field and made a theoretical model of the drop movement of the seedling in the air and the guide tube which consists of a sliding movement. Song et al. [18] performed experimental analysis on tensile properties and pulling performance of seedlings and concluded that the tensile force which is the force of breaking of the seedling is much greater than the required force for pulling the seedling out of tray. On this basis, the 2ZPY-H530 rice seedling transplanter was developed.

METHODOLOGY AND DESIGN

In a mechanical transplanting machine, the arm follows a desired path of motion. A planar four-bar linkage with all revolute pairs are chosen, because of its simplicity, such mechanisms which works on this principle are easy to manufacture and maintain. Crank is used for input motion so that a continuous and rotary motion is achieved, while the output motion follows the path of interest to meet the requirements of transplanting machine specified below. The mechanism must have one degree of freedom and consists of a coupler point where the transplanting finger is attached. Different components of a coupler are shown in Figure-2.

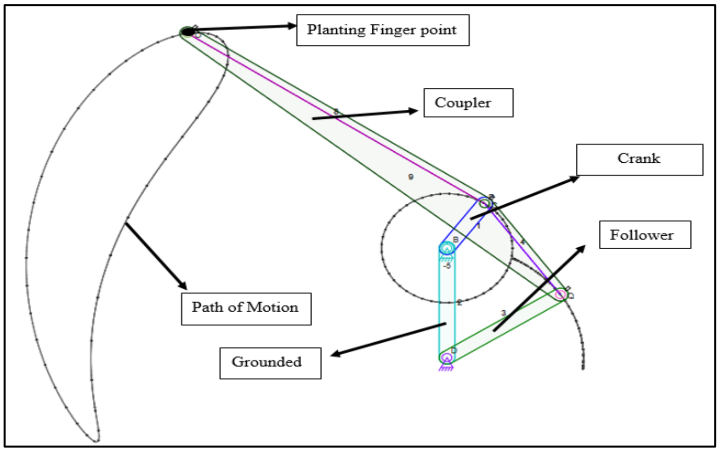

Figure 2: 4 bar mechanism (basic) with coupler link extension (Image: Linkage Software)

Linkages Parameters for Design

Important parameters for Links are given below.

1. Crank length, L1.
2. Coupler length, L2.
3. Follower length, L3.
4. Fixed link length, which is grounded, L4.
5. Length of coupler extension, LF.
6. Angle of coupler extension, β.

The above mentioned parameters are mentioned in Figure-3.

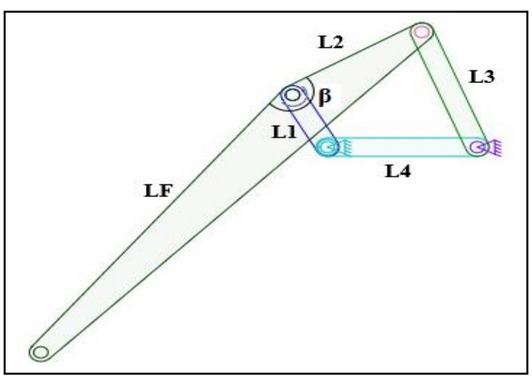

Figure 3: Linkages Parameters for Design

The design is based on the dimensions of four links, the orientation of fixed link, the angle of coupler extension and its length. Thus, these must be decided to design the mechanism. Since the above-mentioned important dimensions can’t be synthesized directly, thus a hit and trial method were applied and the output path is examined, the suitable path (given in results section) for transplanting is achieved after 19 trials and the dimension for that particular trial is selected for further analysis. Linkage software was used for the trials purpose. The dimensions were varied, and the transplanting finger path of motion was calculated analytically and displayed. Finally, the couplers motion was achieved and tested for its motion without any interference as per requirement.

Recommended Dimensions

The motions possible from a four-bar linkage will depend on both the Grashoff condition and the mechanism inversion chosen. The graphical synthesis of a four-bar mechanism was done, and the suitable dimensions were selected. At the end the Grashoff condition for complete revolution of crank was checked [19]. The path followed by the picking point depends on the length of the links and the angle of the fork. The links shown in Figure-3 satisfy Grashoff's conditions. According to which the mechanism can work properly only if equation (1) is satisfied, that is:

$$Ls + L_1 \leq Ly + Lx \quad (1)$$

$$30+62 < 60+61$$

$$92 < 121$$

Where,

Ls = Shortest Link, L_l = Longest Link, Lx and Ly = Remaining Links

The dimensions used are taken initially on trials basis whose result with graphical representation is given in results section. The 3rd trail linkage gives the desired motion and obtained to satisfy the required mechanism inversion, Grashof condition, no toggle position, desired planting depth, assumed coupler path (i.e. Crunode type path or curve) with possible link dimensions. Thus, the specified link dimensions and ground link orientation will be used to perform the other required analysis. The best trajectory obtained by using Linkage is shown in figure 4.

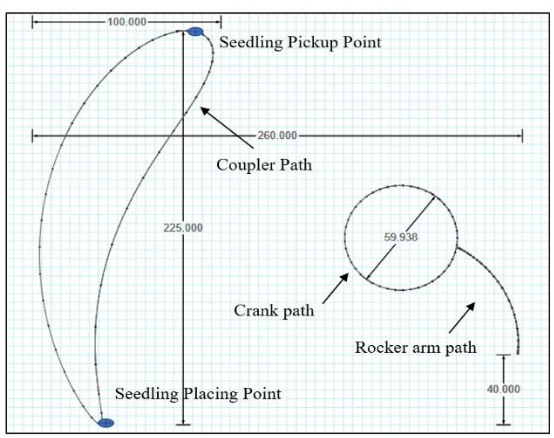

Figure 4: Trajectory of all Linkages in planting Mechanism

Kinematic Analysis of Linkages:

To obtain the desired results from the Rice transplanting arm mechanism, it is necessary to design the mechanism according to designing standards, for this purpose, the kinematic analysis of the linkage mechanism is given below.

Referring to figure 3, the modified 4-bar mechanism with coupler point K at BC link is introduced, where the Link-BC is acting as the transplanting arm, and coupler point K as the transplanting finger. The modified 4-bar mechanism is shown in Figure 5.

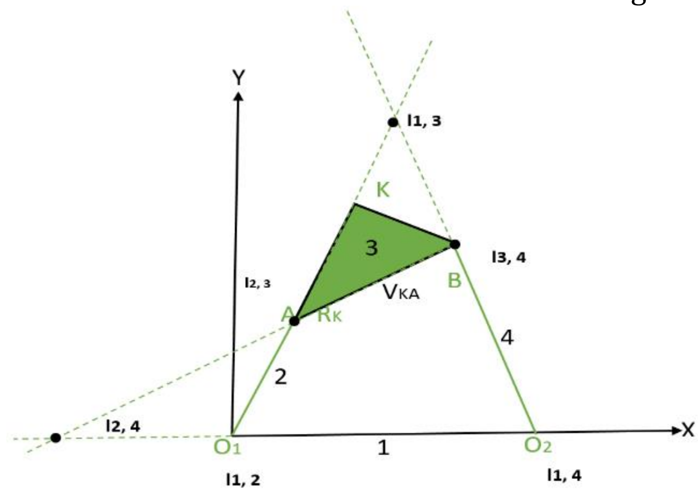

Figure 5: Four bar mechanism

The Instantaneous centers of velocity are indicated by

$$I_{(1,2)}\ I_{(2,4)}\ ,\ I_{(2,3)}\ ,\ I_{(3,4)}\ ,\ I_{(1,4)} \text{ and } I_{(1,3)}.$$

Links nomenclature is as follows:

- Link 01: Ground
- Link 02: Crank (Input)
- Link 03: Coupler (Output in our case)
- Link 04: Follower

Position Analysis:

The Input is angular displacement θ_2 and desired position of coupler point K is derived from the position of link-03.

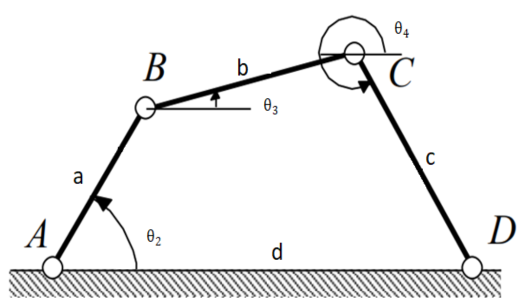

Figure 6: Four bar mechanism

From Figure-6 the coordinates of point A:

$$\mathrm{A_x} = a\mathrm{Cos}\theta_2 \; and \; \mathrm{A_y} = a\mathrm{Sin}\theta_2 \tag{2}$$

Coordinates of point B, as circle with centered at A

$$\text{At A: } (b)^2 = (\mathrm{A_x} - \mathrm{B_x})^2 + (\mathrm{A_y} - \mathrm{B_y})^2 \tag{3}$$

And for link c, as circle centered at O_2;

$$(c)^2 = (\mathrm{d} - \mathrm{B_x})^2 + (\mathrm{B_y})^2 \tag{4}$$

Subtract eq. 4 from eq. 3

$$(b)^2 - (c)^2 = (\mathrm{d} - \mathrm{B_x})^2 + (\mathrm{B_y})^2 - (\mathrm{d} - \mathrm{B_x})^2 - (\mathrm{B_y})^2$$

After solving.

$$(b)^2 - (c)^2 = (\mathrm{a})^2 - 2\mathrm{B_x}(\mathrm{A_x} - d) - 2\mathrm{A_y}\mathrm{B_y} - (\mathrm{d})^2$$
$$(\mathrm{A_x}^2 + \mathrm{B_y}^2) = \mathrm{a}^2 \tag{5}$$

Now

$$\mathrm{B_x} = \frac{a^2 - b^2 + c^2 - d^2 - 2\mathrm{A_y}\mathrm{B_y}}{2(\mathrm{A_x} - d)}$$

$$\mathrm{B_x} = \frac{a^2 - b^2 + c^2 - d^2}{2(\mathrm{A_x} - d)} - \frac{\mathrm{A_y}\mathrm{B_y}}{(\mathrm{A_x} - d)} \tag{6}$$

Putt eq. 6 in eq. 4

$$(c)^2 = [\mathrm{d} - (\frac{a^2 - b^2 + c^2 - d^2}{2(\mathrm{A_x} - d)} - \frac{\mathrm{A_y}\mathrm{B_y}}{(\mathrm{A_x} - d)})]^2 + (\mathrm{B_y})^2$$

Solving this we will get a quadratic equation.

$$(\mathrm{B_y})^2 \left[\frac{\mathrm{A_y}^2}{(\mathrm{A_x} - d)^2} + 1\right] - \mathrm{B_y}\frac{2(d-s)\mathrm{A_y}}{(\mathrm{A_x} - d)}(d - s)^2 - c^2 = 0 \tag{7}$$

Let:

$$\mathrm{P} = \left[\frac{\mathrm{A_y}^2}{(\mathrm{A_x} - d)^2} + 1\right], \mathrm{Q} = \left[\frac{2(d-s)\mathrm{A_y}}{(\mathrm{A_x} - d)}\right] \text{ and } R = (d - s)^2 - c^2$$

The Quadratic equation for B_y is:

$$\mathrm{P}(\mathrm{B_y})^2 + \mathrm{QB_y} + R$$

Which can be solved by quadratic formula

$$\mathrm{B_y} = \frac{-Q \pm \sqrt{Q^2 - 4PR}}{2P} \quad (8)$$

And,

$$s = \frac{a^2 - b^2 + c^2 - d^2}{2(\mathrm{A_x} - d)}$$

Position Angles

$$\theta_3 = tan^{-1}\left[\frac{\mathrm{B_y} - \mathrm{A_y}}{(\mathrm{B_x} - \mathrm{A_x})}\right] \quad (9)$$

$$\theta_4 = tan^{-1}\left[\frac{\mathrm{B_y}}{(\mathrm{B_x} - d)}\right] \quad (10)$$

Consider coupler link AB, as shown in figure 7:

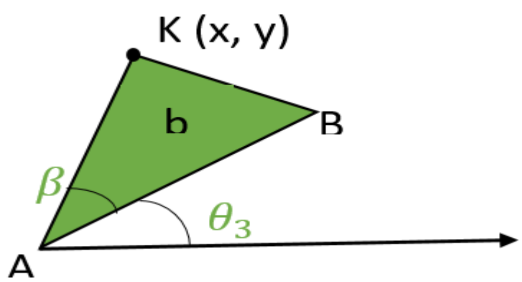

Figure 7: The coupler Link AB with coupler point K

Position Coordinates of coupler point **K (x, y)**:

$$x = acos\theta_2 + (AK)cos(\beta + \theta_3) \quad (11)$$

$$y = asin\theta_2 + (AK)sin(\beta + \theta_3) \quad (12)$$

From synthesis of link lengths, the following link lengths are selected.

Table 2: Desired Dimensions of Links

Link. No.	Link representation	Link Role	Value
01	A	Ground	30mm
02	B	Crank	60mm
03	C	Coupler	62mm
04	d AK	Follower Coupler point length	60mm 165mm
Coupler angle	β	--	162°

Velocity Analysis

The velocity vectors are shown in Figure-8.

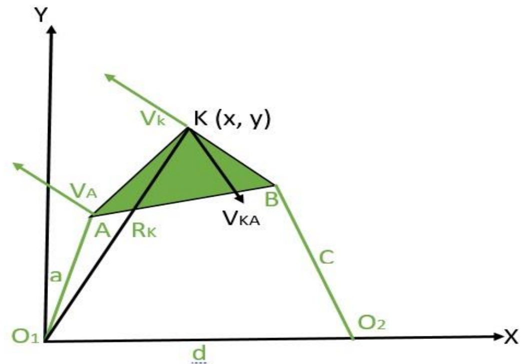

Figure 8: The Velocity vectors and Position vector of coupler point K

From Figure-9, the position vector R_k is given as:

$$\mathbf{R_k} = a[jcos\theta_2 + sin\theta_2] + p[j\cos(\theta_3 + \beta) + sin(\theta_3 + \beta)] \quad (13)$$

Differentiating the position vector equation with respect to time gives:

$$V_k = a\omega_2[jcos\theta_2 - sin\theta_2] + p\omega_3[j\cos(\theta_3 + \beta) - sin(\theta_3 + \beta)] \quad (14)$$

Where: ω_2 Is Input angular velocity and

$$\omega_3 = \frac{a\ \omega_2}{(b)} \cdot \frac{sin(\theta_4 - \theta_2)}{sin(\theta_3 - \theta_4)} \quad (15)$$

Acceleration Analysis

The acceleration vector of coupler point, which is the point of interest is shown in Figure-9 graphically.

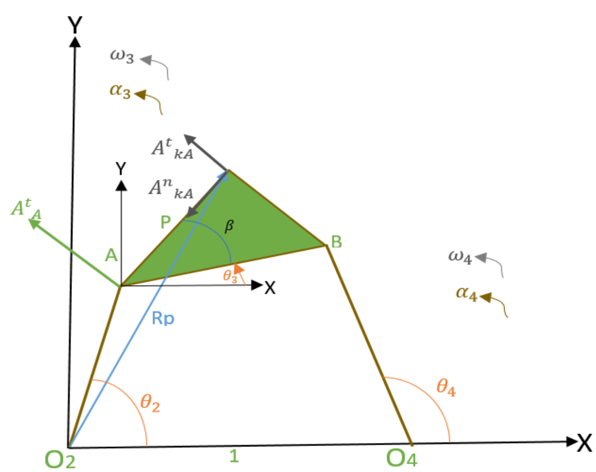

Figure 9: The Acceleration vectors and Position vector of coupler point K

Differentiating the velocity equation with respect to time gives the acceleration of coupler point K.

$$\boldsymbol{A_k} = -\omega_2{}^2 a[jcos\theta_2 + sin\theta_2] + i a\alpha_2[jcos\theta_2 + sin\theta_2] + i\alpha_3 p[jcos(\theta_3 + \beta) + sin(\theta_3 + \beta)] - (\omega_3{}^2)P[jcos(\theta_3 + \beta) + sin(\theta_3 + \beta)] \quad (16)$$

Where:

$$\alpha_3 = \frac{CD-AF}{AE-BD} \text{ and } \alpha_4 = \frac{CE-BF}{AE-BD}$$

Where:

- A = c $sin\theta_4$ B = b $sin\theta_3$
- C = $a\alpha_2\ sin\theta_2 + \omega_2{}^2 a\ cos\theta_2 + b\omega_3{}^2 cos\theta_3 - c\omega_4{}^2 \cos\theta_4$
- D = c $\cos\theta_4$ E = b $cos\theta_3$
- F = $a\alpha_2\ cos\theta_2 - \omega_2{}^2 a\ sin\theta_2 - b\omega_3{}^2 \sin\theta_3 + c\omega_4{}^2 \sin\theta_4$

Where:

$$\omega_4 = \frac{a\ \omega_2}{(c)} \cdot \frac{sin(\theta_2-\theta_3)}{sin(\theta_4-\theta_3)} \quad (17)$$

The acceleration of point K at given input angular velocity can be found easily using 16.

CAD Model

3D Computer Aided Design model of transplanting arm is designed as per calculations after various trials. SolidWorks software is used for design modeling.

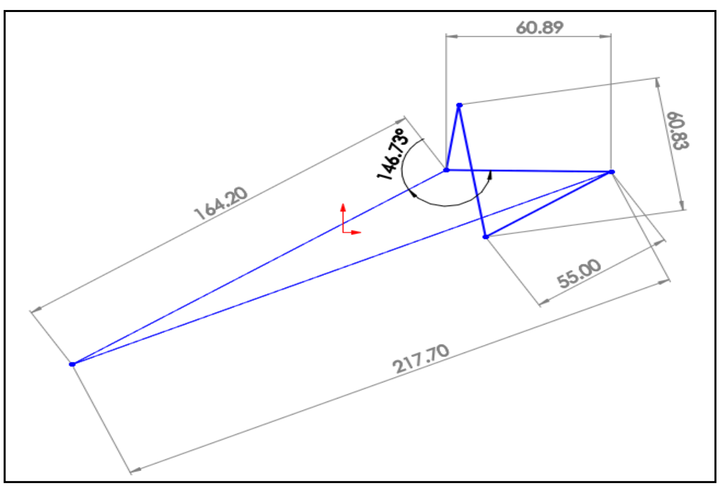

Figure 10: 2D links Drawing on Solid works

From Figure-10, a planting mechanism was designed which pick up the seedlings and transfer them to the soil with a pushing rod mechanism which pull itself back when picking up the seedling and push downward at the time of placing seedling in soil as per desired depth. The fingers must return to original position after action, during the return motion, fingers must avoid any interference with the already planted seedlings. Also, the arm must pass without any disturbance with the seedling tray to prevent any damage to the tray and seedlings it contains. The picking point must be located at a specific height from the field for smooth motion of arm, and tray movements. The point of picking must be located at a proper height from the field level so that the seedling tray can have proper clearance from the field level. The CAD model views of coupler are shown in Figure-11.

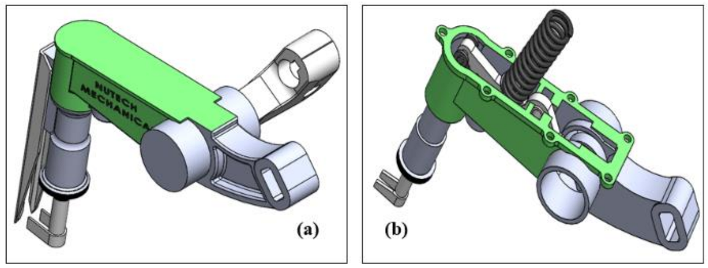

Figure 11: (a) 3D Design Model and (b) Internal view of Transplanting Arm

Exploded view of Internal Mechanism of Transplanting arm is shown in Figure-12. This shows, the different components of a coupler arm like, body, cam, follower, compressional spring etc. Figure-13 shows the top, front and section views of the transplanting arm.

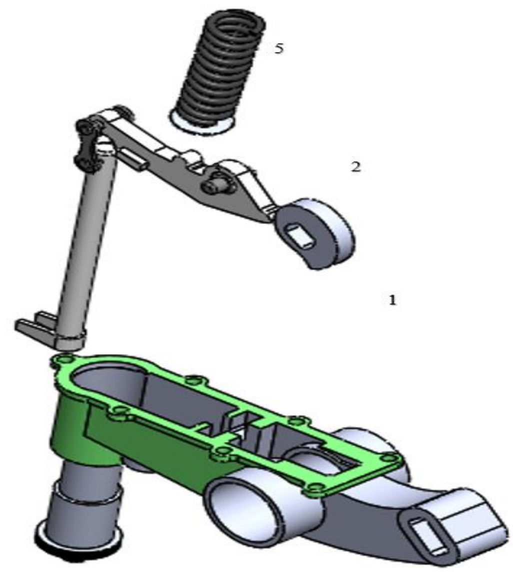

Figure 12: Exploded view. of transplanting arm

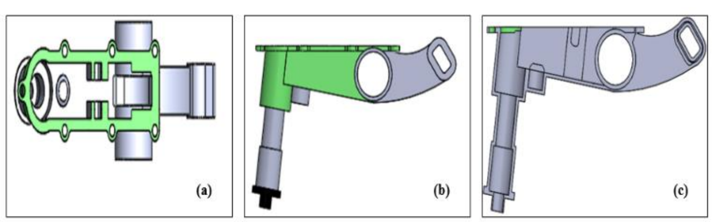

Figure 13: Top, Front & Section view of Transplanting arm

Cam and Follower

Cam and follower Design is one of the challenging part of mechanism, it requires special attention, and the design dimensioning of cam from center of rotation of input shaft to different points on cam profile is shown in Figure 14 with different views of designed cam.

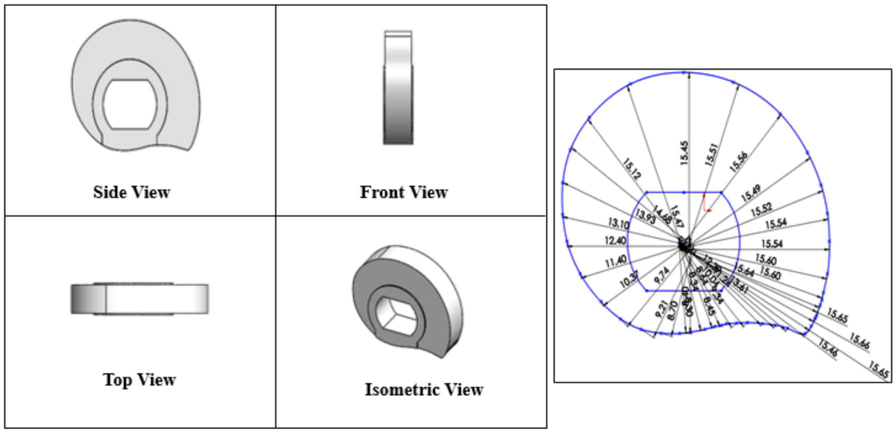

Figure 14: Side, Front, Top & Isometric View of Cam with Cam Dimensions

The follower is the necessary and complex part for a given mechanism. The follower designed for rice transplanting arm mechanism with dimensions and views is shown in Figure 15.

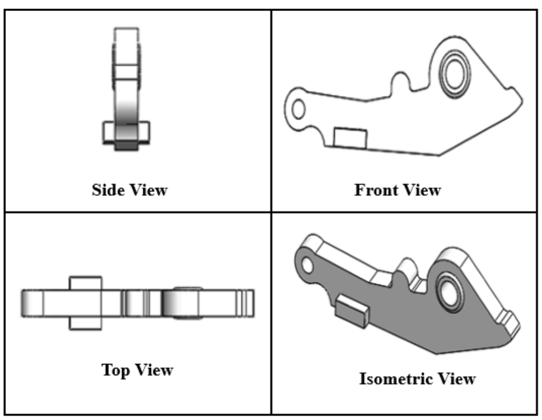

Figure 15: Follower views and Dimensions

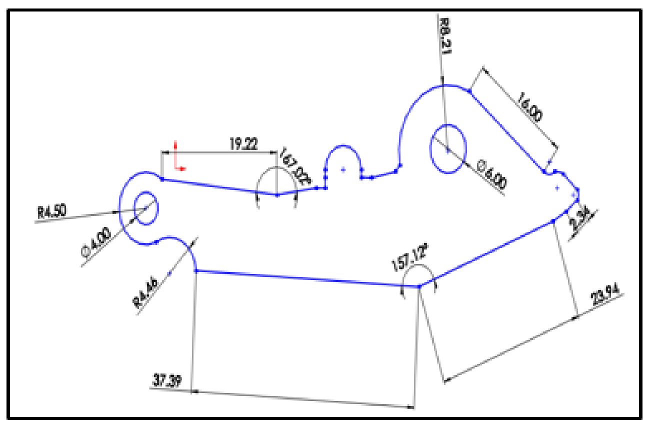

Figure 16: Follower view with dimensions

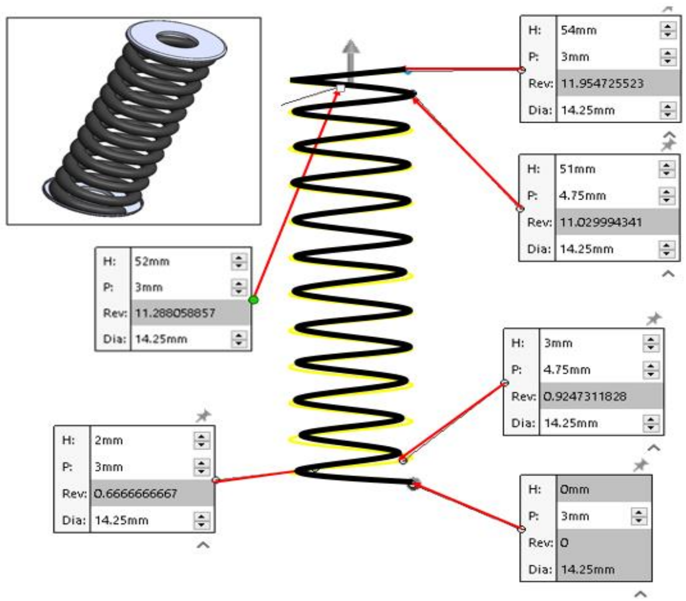

Figure 17: Spring Dimensions, characteristics with 3D view

RESULTS AND DISCUSSION

The link dimensions which satisfy all the necessary conditions for a transplanting arm to work properly are selected as given in Table-3. The curve obtained from different trials are shown, the final curve which is in accordance with that of analytical points is recommended for selection of dimensions.

Table 3: Link lengths with results

Trial No.	Link Dimension (mm)					B	Result
	L_1	L_2	L_3	L_4	LF	(deg)	
1	25	90	46	40	164	155	Not Recommended
2	15	60	90	114	170	145	Not Recommended
3	30	60	62	60	165	162	Recommended
4	30	60	90	220	164	162	Not Recommended

The results mentioned in Table-3 are analyzed graphically to obtain the desired coupler curve.

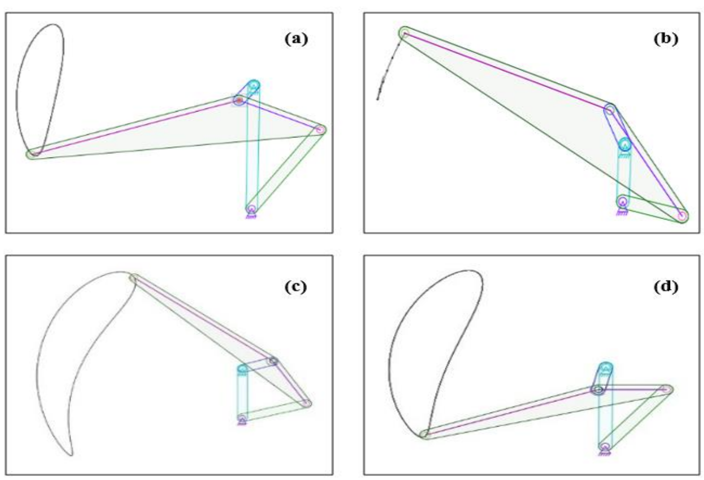

Figure 18: Graphical Representation of links with coupler curves

The results obtained from mathematical modeling and kinematic analysis for position and velocity of coupler point K at different input crank angles are tabulated in Table-4. The curve (path of coupler point) obtained from these points is shown in Figure 18, with comparison to the path obtained by linkage.

Table 4: Position coordinates of coupler point with input crank angle.

Input θ_2	P	Q	R	s	B_x	B_y	θ_3	θ_4	Output K (x,y)
0	1	0	-3480.46	40.93	40.93	58.99	1.38	-1.25	(-74.1, -191.5)
15	1.062	-10.21	-3427.21	39.58	55.053	61.80	1.12	-1.49	(-121.79, -149.68)
30	1.194	-21.07	-3272.66	36.09	63.39	61.90	0.89	1.51	(-155.96, -105.08)
45	1.299	-30.99	-3040.86	31.66	65.43	61.76	0.74	1.48	(-177.13, -69.245)
50	1.318	-33.685	-2953.57	30.16	65.04	61.79	0.70	1.48	(-182.4, -59.76)
60	1.333	-37.77	-2773.98	27.28	63.04	61.92	0.64	1.52	(-191.36, -44.286)
75	1.307	-40.48	-2512.4	23.50	57.88	61.96	0.58	-1.53	(-202.45, -28.734)
90	1.25	-39.53	-2281.12	20.46	51.14	61.365	0.55	-1.42	(-211.96, -20.953)
105	1.182	-35.81	-2090.2	18.12	43.70	59.81	0.53	-1.30	(-220.23, -19.811)
120	1.12	-30.22	-1940.71	16.37	36.20	57.25	0.54	-1.17	(-227.05, -24.586)
135	1.068	-23.44	-1829.85	15.12	29.17	53.79	0.57	-1.05	(-231.89, -34.793)
150	1.03	-15.9516	-1753.89	14.28	22.95	49.71	0.62	-0.93	(-234.0, -50.01)
165	1.007	-8.063	-1709.67	13.8	17.76	45.38	0.67	-0.82	(-232.72, -69.760)
180	1	-3.78E-15	-1695.16	13.64	13.64	41.17	0.75	-0.72	(-227.04, -93.269)
195	1.007	8.063	-1709.67	13.80	10.53888	37.38	0.85	-0.64	(-216.21, -119.409)
210	1.030	15.95	-1753.89	14.28	8.309549	34.23	0.96	-0.58	(-199.75, -146.635)
225	1.068	23.44	-1829.85	15.12	6.802832	31.84	1.08	-0.53	(-177.59, -173.098)
240	1.12	30.22	-1940.71	16.37	5.889038	30.26	1.21	-0.50	(-150.33, -196.887)
255	1.182	35.81	-2090.2	18.12	5.489549	29.53	1.34	-0.49	(-119.26, -216.30)
270	1.25	39.53	-2281.12	20.46	5.597502	29.73	1.47	-0.50	(-86.414, -230.14)
285	1.307	40.48	-2512.4	23.50	6.309063	31.00	-1.54	-0.52	(70.080, 179.925)
300	1.33	37.77	-2773.98	27.28	7.891826	33.59	-1.45	-0.57	(57.328, 187.870)
315	1.299	30.99	-3040.86	31.66	10.93237	37.89	-1.39	-0.65	(52.057, 194.593)
330	1.194	21.07	-3272.66	36.09	16.5821	44.25	-1.41	-0.79	(60.037, 200.323)
345	1.062	10.21	-3427.21	39.58	26.52306	52.18	-1.52	-1.0	(87.80, 202.148)
360	1	9.34E-15	-3480.46	40.93	40.93	58.99	1.38	-1.25	(-74.0, -191.58)

The curves obtained from analytical solution and design parameters (linkages) are compared and shown in Figure 19.

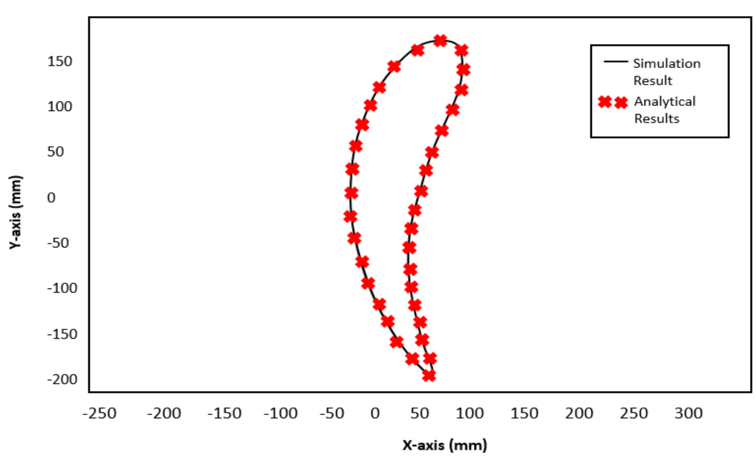

Figure 19: Path comparison of Analytical and simulation model

Both curves are overlapping hence verifying the mathematical modeling and kinematic analysis of the mechanism. The results at different crank angles up to 360° of rotation show a complete rotation of crank. Hence cam design, mathematical modeling, kinematic analysis, link lengths, are verified. The mathematical model is solved using MATLAB code.

Table 5: Linear and angular velocity with input crank velocity.

Input ω_2 (rad/sec)	ω_3 (rad/sec)	V_k (mm/s)
2	-1.22	61.22
4	-2.43	122.41
6	-3.64	183.66
8	-4.86	244.87

The Velocity analysis shows that the linear velocity of the coupler point (point of interest) as well as rotational velocity increases as the input velocity from crank increases. Hence, moving a machine at higher linear velocity will cause the mechanism to move faster and maintain the required paddy distance, which is an important requirement of rice transplantation. This behavior is shown graphically in Figure-20.

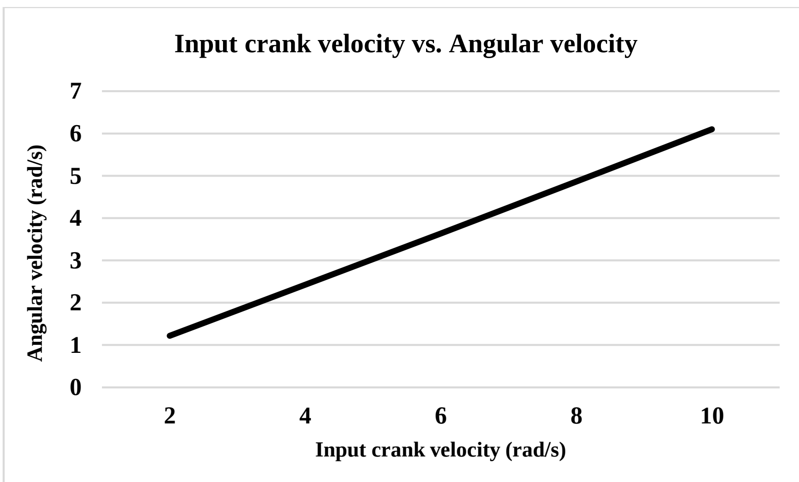

Figure 20: Crank velocity (input) vs. output linear velocity

CONCLUSION

Proper dimensioning of link length and coupler point is an important factor in obtaining precise results for rice transplanting machines. A minor change in link lengths significantly disturbs the pick and place point of rice seedling, hence disturbing the machine efficiency, Linkage software is used to determine the path of coupler point or point of interest on rice transplanting arm. The desired path is obtained by changing the link lengths and by adjusting the joint angles properly. Kinematic analysis of links is done to obtain mathematical relations for coupler point and input crank angle. Position, velocity and acceleration analysis are then proceeded. MATLAB code is used to solve the mathematical relations for crank angles 0 to 360° and the position coordinates of coupler point(s) on XY-plane. The two curves obtained, one from mathematical solution and other from linkage are compared and hence, both models are verified. A mechanism consisting of Cam and Follower is then designed to generate the same curve or path at output for input crank angle over a complete revolution. Other necessary components for transplanting arm including spring and housing are also designed hence completing the CAD modeling of transplanting arm. Finally, a complete prototype is made and tested.

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