Design of a five-bar duckbill-type mechanism for sorghum transplanting

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Abstract

Sorghum seedling transplanting is an essential agricultural activity in Sub-Saharan Africa. However, conventional manual transplanting of sorghum is a time-consuming, labour-intensive, costly activity with a low transplanting rate, uneven plant distribution, and low degree of accuracy. In order to realize rapid and precise sorghum seedlings transplanting, a duckbill-type mechanism has been designed. This mechanism is a five-bar linkage consisting of two crankshafts, two connecting rods, and a duckbill-shaped planter to improve the quality of transplanting operations. The study includes kinematic and synthesis analysis through MATLAB software, parts design, and motion analysis using SolidWorks software. After synthesis analysis using a genetic algorithm, the optimal length between the two cranks is 300 mm, the length of the upper crankshaft is 106 mm, the length of the connecting rod I is 169 mm, the length of the connecting rod II is 222 mm, and the length of the lower crankshaft is 67 mm. Furthermore, the speed and acceleration analysis show that the seedlings are planted with zero-speed operation to obtain a high perpendicularity qualification. The results show that the proposed planting mechanism meets the agronomic requirements of transplanted sorghum with a good transplanting rate.

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Introduction

Sorghum (*Sorghum bicolor* [L.] Moench) is a cereal domesticated in Africa. It is well adapted to semi-arid tropics because of its hardiness and moderate water requirements. Distributed outside its continent of origin and gradually acclimatised to temperate zones, sorghum also holds a notable place in the agriculture of some emerging and developed countries. With an annual production estimated at 28 million tons', sorghum is the third cereal crop in Africa after maize and rice (FAO, 2021). Although, in semi-arid regions, climatic conditions limit the potential for higher-yielding crops such as maize, farmers have no option but to rely on medium-yielding yet stress-resistant crops that can grow even under a harsh agroecology, such as sorghum (Tsusaka *et al.,* 2013).

African farmers of semi-arid tropics developed original cropping systems based on transplanted sorghum (Chantereau *et al.,* 2013). This sorghum has the advantage of completing its growth cycle, in the dry season, until harvest without additional fertiliser and water (Basga *et al.,* 2018). Farmers, with the support of research centres, find the necessary agronomic requirements every growing season (Oumarou *et al.,* 2017; Mundia *et al.*, 2019). However, they remain limited by the relatively short transplanting period and labour shortage. The labour shortage during the growing season causes delays in transplanting operations leading to seedling mortality and possibly loss of production. Consequently, these regions continuously experience serious food insecurities.

Sorghum is transplanted manually using locally designed hand tools like sharp stakes (Mathieu, 2002). Transplanting techniques have not evolved over time. In Cameroon, the standard technique consists of digging a hole, supplying water to the hole, and inserting seedlings into the hole (Nenwala *et al*., 2022). Khadatkar *et al.* (2018) reported that manual transplanting required about 40% of total time and 184 person-hours/ha for cultivation and also often resulted a non-uniform spatial distribution of crops. In addition, the work is of great drudgery and laborious as the operation is performed in a bending and squatting posture. Mechanising the transplanting process can solve this problem and help increase sorghum production.

Many researchers have developed different mechanisms for seedling transplanting. The most prominent are the finger-clip-type, conveyor-type, dibble-type, duct-type, and duckbill-type mechanisms (Khadatkar *et al.*, 2018; Ji *et al.*, 2020; Zhang *et al.*, 2020; Iqbal *et al.*, 2021; Hongzhen *et al.*, 2022). The duckbill-type planting mechanism is particularly eye-catching. In particular, with the upright vertical position of the plant after transplanting, less mechanical damage to the seedling, constant planting depth, and high positioning accuracy due to their inherent rigidity. This mechanism also has growing applications in robotics, positioning systems, measurement devices, and so on (Sang *et al.*, 2018; Cervantes-Culebro *et al.*, 2021).

With its applicability in planting on dry lands and under mulch, the duckbill-type planting device can be very useful for sorghum transplanting. However, the sizing of the mechanism depends on the desired culture. Thus, this mechanism has been proposed for tomato transplanting, peppers, onions, melons, and Chinese medicinal plants (Shao *et al.*, 2019; Sun *et al.*, 2019; Jin *et al.*, 2020, Hongzhen *et al.*, 2022, Liu *et al.*, 2022). In the design of a transplanting device, requirements such as the target crop row spacing, planting depth, and travel speed should be considered, and dynamic and kinematic analysis should be conducted to verify the design. From the literature review, it is becoming apparent that the proposed mechanisms do not meet the agronomic requirements of sorghum transplantation.

Jioadi *et al*. (2016) analysed a transplanting device planting trajectory, velocity, and acceleration using a visual basic programming platform. Sun *et al.* (2019) analysed the planting trajectory of a five-bar linkage-type transplanting device by kinematic simulation using MATLAB. In most studies related to transplanters' design, a theoretical analysis is conducted first, and then a field or real-life experiment is conducted to verify the design. The initial design on a theoretical basis is very important to improve the completeness of the product and save development time. Regarding design parameter optimisation, genetic algorithms have been used in various fields, including structural optimisation due to their good performance, ease of use, and relatively short computation time (Jiang *et al.*, 2014; Liu *et al.*, 2022). This study aims to develop a machine for rapidly transplanting sorghum while respecting 'agronomics' requirements.

Materials and Methods

Requirements for the design of the planting mechanism

Figure 1 shows the path followed by the duckbill planter during transplanting operations. Looking into the previous works on the duckbill planter (Shao *et al.*, 2019; Jin *et al.,* 2020) and works on the transplanted sorghum (Mathieu, 2002; Chantereau *et al.,* 2013), the planting mechanism must meet the following agronomic requirements: i) the transplanting rate should be in the order of 60 to 80 plants/min; ii) the transplanting interval should be between 800 and 1200 mm; iii) the average planting depth should be 200 mm; iv) the angle between the transplanted seedling and the vertical direction of the centre of the transplanting hole should be less than 10 degrees; v) when the duckbill receives the seedling at the highest point of its trajectory (point a), its speed must be zero; vi) when the duckbill releases the seedling into the ground (point c), its speed and acceleration must be zero.

Structure and working principle of the planting mechanism

As shown in Figure 2A, the duckbill planter mechanism mainly comprises a fixed plate, sprocket, cranks, connecting rods, duckbill planter, and connector. The two crankshafts are set in motion by a chain transmission system.

As the original parts, the cranks AB and OD rotate clockwise at the same speed around point A and point O, respectively (Figure 2B). The crankshafts actuate the connecting rod BC and the connecting rod CD to drive the duckbill EG to move according to the predetermined trajectory. The duckbill is attached to the rod CE and has a cup hopper EF to pick the seedling. When the duckbill moves to the trajectory's highest point (point a), the seedling is picked up. When the mechanism brings the seedling to the ground level (point b), a cam-connector system controls the opening of the duckbill. At the lowest point of its trajectory (point c), the duckbill releases the seedling into the ground. When the planting mechanism moves away from the seedling, the duckbill closes (point d), and the work cycle begins again.

Kinematic analysis of the mechanism

A kinematic analysis allows the mechanism's dimensions and angles to be determined per agronomic requirements. The origin of the axes chosen is point O (as shown in Figure 2B). The mechanism has two degrees of freedom. L_1, L_2, L_3, L_4, L_5, L_6, L_7, and L_8 identify the lengths of links. The angles between links and the x-axis are θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, and θ_7. The displacement of point A can be expressed using Eq. (1):

$$A\begin{cases} x_A = L_1\cos\theta_1 \\ y_A = L_1\sin\theta_1 \end{cases} \tag{1}$$

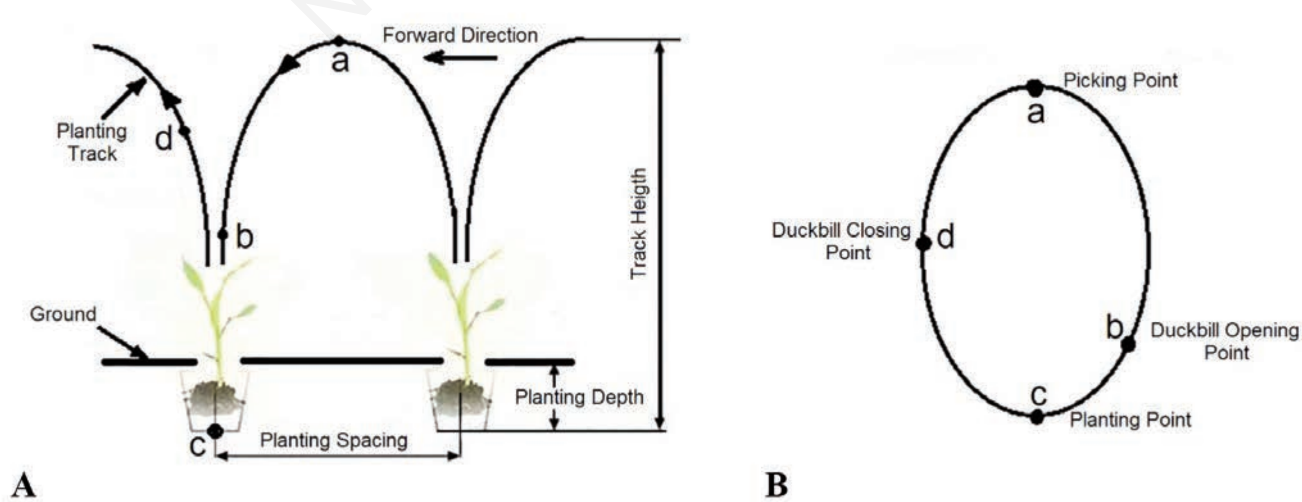


Figure 1. The trajectory of the duckbill-type planter: **A**) dynamic trajectory; **B**) static trajectory.

The displacement of point B is expressed using Eq. (2):

$$B\begin{cases} x_B = x_A + L_2\cos\theta_2 \\ y_B = y_A + L_2\sin\theta_2 \end{cases} \tag{2}$$

The coordinates of point D can be calculated using Eq. (3):

$$D\begin{cases} x_D = L_5\cos\theta_5 \\ y_D = L_5\sin\theta_5 \end{cases} \tag{3}$$

The closed-loop motion of the mechanism is described in Eq. (4):

$$\overrightarrow{OA}+\overrightarrow{AB}+\overrightarrow{BC}=\overrightarrow{OD}+\overrightarrow{DC} \tag{4}$$

From the above equations, the displacement of point C can be expressed in Eq. (5):

$$C\begin{cases} x_C = L_1\cos\theta_1 + L_2\cos\theta_2 + L_3\cos\theta_3 = L_5\cos\theta_5 + L_4\cos\theta_4 \\ y_C = L_1\sin\theta_1 + L_2\sin\theta_2 + L_3\sin\theta_3 = L_5\sin\theta_5 + L_4\sin\theta_4 \end{cases} \tag{5}$$

The known angles are θ_1, θ_2 and θ_5, they allow to find θ_3 and θ_4. The angle θ_3 is obtained using Eq. (6):

$$\theta_3 = 2\arctan\left(\frac{b\pm\sqrt{a^2+b^2-c^2}}{a-c}\right) \tag{6}$$

with,

$$\begin{cases} a = 2L_3L_1\cos\theta_1 + 2L_3L_2\cos\theta_2 - 2L_3L_5\cos\theta_5 \\ b = 2L_3L_1\sin\theta_1 + 2L_3L_2\sin\theta_2 - 2L_3L_5\sin\theta_5 \\ c = L_1^2+L_2^2+L_3^2+L_5^2-L_4^2+2L_1L_5\sin\theta_1\sin\theta_5 - 2L_2L_5\sin\theta_2\sin\theta_5 \\ \quad -2L_1L_2\sin\theta_1\sin\theta_2 + 2L_1L_5\cos\theta_1\cos\theta_5 \\ \quad -2L_2L_5\cos\theta_2\cos\theta_5 - 2L_1L_2\cos\theta_1\cos\theta_2 \end{cases} \tag{7}$$

From Eqs. (5) and (6), the angle θ_4 can be expressed using Eq. (8):

$$\theta_4 = \arcsin\left(\frac{L_1\cos\theta_1 + L_2\cos\theta_2 + L_3\cos\theta_3 - L_5\cos\theta_5}{L_4}\right) \tag{8}$$

The displacement of point E is expressed using Eq. (9):

$$E\begin{cases} x_E = x_D + (L_4+L_6)\cos\theta_4 \\ y_E = y_D + (L_4+L_6)\sin\theta_4 \end{cases} \tag{9}$$

Similarly, the displacement of point G is expressed using Eq. (10):

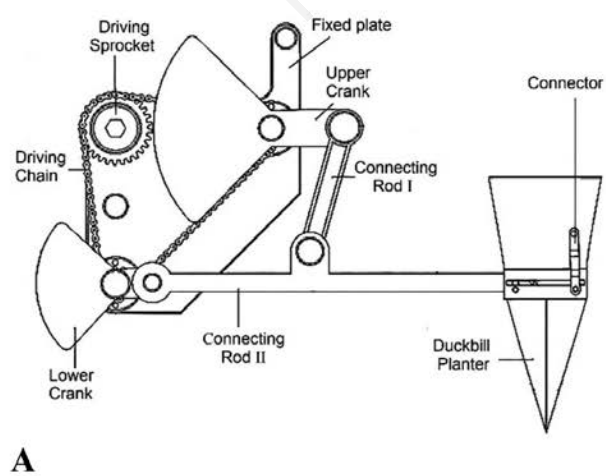
$$G\begin{cases} x_G = x_E + L_8\cos(\pi-\theta_7-\theta_4) \\ y_G = y_E - L_8\sin(\pi-\theta_7-\theta_4) \end{cases} \tag{10}$$

The corresponding velocity and acceleration at each point can be obtained by computing the first and second derivatives of the above position equations with respect to time.

Synthesis of the planting mechanism

The study of the mechanism synthesis corresponds to an optimisation problem. The aim is to determine the parameters of the mechanism capable of generating the desired trajectory (trajectory of the planter tip G). The design parameters (variables) of the mechanism are given by L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, θ_1, θ_2, θ_5, and θ_7.

First, the initial dimensions of the five-bar mechanism are defined. Then, using a program, the mechanism parameters are adjusted by observing the effect of each bar's length on the planter tip's trajectory. This approach is effective when applied to the synthesis of planar mechanisms (Jiaodi *et al.*, 2016; Sun *et al.*, 2021). This step makes it possible to obtain the range of the mechanism's design variables and suggests the ideal trajectory of the planter tip. Subsequently, an optimisation of the parameters is necessary. The quadratic sum of error defines a fitness function for this purpose. It reflects the difference between the desired result and the calculated one. A zero error corresponds to an optimal solution that generates exactly the targeted trajectory, as shown in the work of Jiang *et al*. (2014) and Liu *et al*. (2022).



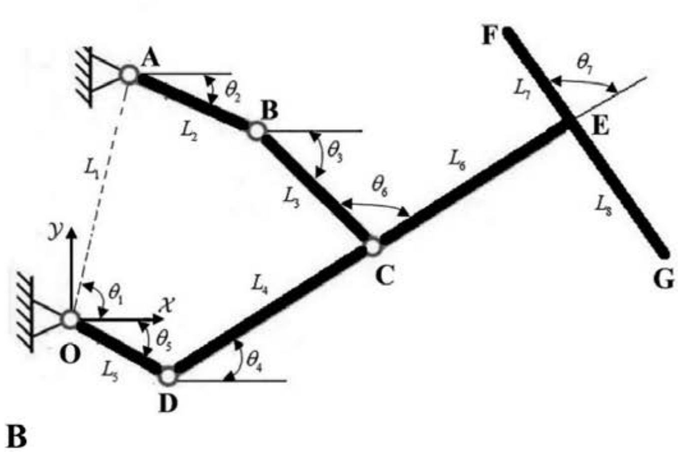


Figure 2. A) Structure; **B**) sketch of the planting mechanism.

The mechanism synthesis problem is translated into an optimisation problem of a fitness function to be minimised. The fitness function is defined as follows:

$$f=\sqrt{\sum_{k=1}^{m}\left[\left(x_{G_2}^{(k)}-x_{G_1}^{(k)}\right)^2+\left(y_{G_2}^{(k)}-y_{G_1}^{(k)}\right)^2\right]} \tag{11}$$

Where $\left(x_{G_1}^{(k)},y_{G_1}^{(k)}\right)$ and $\left(x_{G_2}^{(k)},y_{G_2}^{(k)}\right)$ represent the respective coordinates of the desired and generated position through which the duckbill passes. m is the total of the trajectory points.

The minimum value of the fitness function can be found using the genetic algorithm. Indeed, the genetic algorithm is one of the best methods to solve the multi-objective optimisation problem of a mechanism (Connor 1996). The flowchart of the genetic algorithm is shown in Figure 3. These algorithms are inspired by the workings of natural evolution, notably Darwin's selection and Mendel's rule of procreation.

Step 1. Create the initial population

When creating an initial population, the parameter values are created randomly with a uniform distribution over the specified range. In this study, we want to optimise variables (L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, θ_1, θ_2, θ_5, θ_7.) The population I of n individuals is:

$$I=\begin{cases} I_1=\left(L_1^1,L_2^1,L_3^1,L_4^1,L_5^1,L_6^1,L_7^1,L_8^1,\theta_1^1,\theta_2^1,\theta_5^1,\theta_7^1\right)\\ I_2=\left(L_1^2,L_2^2,L_3^2,L_4^2,L_5^2,L_6^2,L_7^2,L_8^2,\theta_1^2,\theta_2^2,\theta_5^2,\theta_7^2\right)\\ I_3=\left(L_1^3,L_2^3,L_3^3,L_4^3,L_5^3,L_6^3,L_7^3,L_8^3,\theta_1^3,\theta_2^3,\theta_5^3,\theta_7^3\right)\\ \\ I_n=\left(L_1^n,L_2^n,L_3^n,L_4^n,L_5^n,L_6^n,L_7^n,L_8^n,\theta_1^n,\theta_2^n,\theta_5^n,\theta_7^n\right)\end{cases} \tag{12}$$

Once the initial population has been created, the first step in the selection must be carried out (Table 1).

Step 2. Evaluation

The fitness function contains information about the individual's skilfulness. Evaluation of solution quality is usually based on fitness function, which always returns the real value for each possible solution. The lower the value, the better the potential solution. The other termination condition is when the maximum number of generations is reached.

Step 3. Selection

Once the performance of the initial population has been evaluated, it is necessary to classify the individuals and associate them with a probability of reproduction (Davis *et al.*, 1991). A stochastic remainder selection procedure by Goldberg (1989) is used to determine the selection frequency of each individual. We obtain a set of individuals who have survived the selection and represent the best solutions.

Step 4. Crossover

The next step is to select pairs of individuals that will interbreed to form offspring. Each pair of individuals is chosen randomly from the selection set. If there is a crossover, the Wright (1991) technique is used to create offspring. The process is the same for creating the other two individuals. Once the offspring are created, we again have a population of n individuals who perform better on average than the previous generation.

Step 5. Mutation

First, we check if there is a mutation according to the mutation probability; in work done here, we use a non-uniform mutation of Michalewicz (1992). The process of selection, reproduction, and mutation is then repeated. Each time these three operations are performed, it constitutes a generation. This is continued until the maximum number of generations is reached or until the performance of the best individual is smaller than a previously specified minimum error.

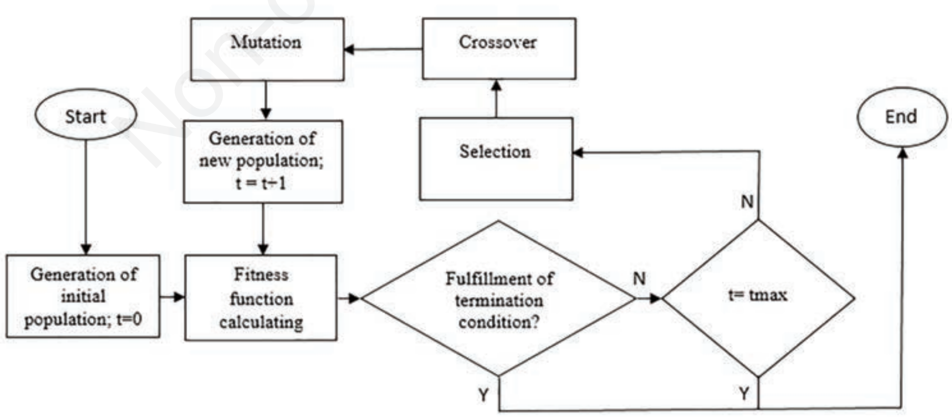


Figure 3. The flow chart of global search based on genetic algorithm.

Table 1. Range of the design variables.

I	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	θ_1	θ_2	θ_5	θ_7
I_{min}	200	50	100	150	50	250	150	100	0	–180	–180	0
I_{max}	350	200	250	300	200	400	300	250	180	180	180	180

Results and Discussion

The proposed approach has been implemented in MATLAB. First, using Eqs. 1 to 10, the theoretical planting trajectory according to the main link lengths could be obtained. Then, the genetic algorithm was used to optimize the link lengths for the planting trajectory. Furthermore, a computer aided design (CAD) model is obtained in SolidWorks.

The planting trajectories of some parameter combinations are illustrated in Figures 4 to 8. These trajectories have varying buckle widths, spans, vertical elongations, and inclinations to the vertical axis. It is to be expected that the wider the cross buckle, the greater the disturbance (hole width, dislocations) of the planter tip on the soil. The buckle's elongation influences the planting depth, *i.e.*, the more the buckle elongates vertically downwards; the deeper the hole is in the soil. The inclination is the difference in angle between the trajectory of the tip and the vertical direction of the centre of the transplanting hole. The greater the inclination of the path, the more the seedling is tilted; this can cause the seedling to break after transplanting.

Figure 4 shows the relationship between the length L_1 and the trajectory of the duckbill tip G, when L_2=100 mm, L_3=170 mm, L_4=220 mm, L_5=75 mm. This diagram shows that when L_1 increase, the buckle formed by the trajectory of the tip changes to a U-shape. This negatively affects the making-hole and can damage the planting mechanism.

Figure 5 shows the relationship between the length L_2 of the upper crank AB and the trajectory of the tip G, when L_1=300 mm, L_3=170 mm, L_4=220 mm, L_5=75 mm. This figure shows that as L_2 increases, the width of the buckle formed by the trajectory of the tip G decreases, and its vertical elongation increases. In addition, the angle between the vertical axis and the direction of the trajectory increases. The results show that as the length of the crank AB increases, the hole becomes more profound. However, as L_2 increases, the seedling is tilted towards the ground.

Figure 6 shows the relationship between the length L_3 of the connecting rod BC and the trajectory of the tip G, when L_1=300 mm, L_2=100 mm, L_4=220 mm, and L_5=75 mm. This diagram shows that the trajectory of tip G does not change significantly with the increase of the length L_3, but there is a slight variation in the span of the trajectory. This means that the length of the connecting rod BC determines the relative position of the hole formed by the tip G, but it does not affect the hole size and the seedling's inclination. Thus, by changing the length of the BC rod, the upper and lower positions of the hole can be adjusted to accommodate different shapes of the ridge.

Figure 7 shows the relationship between the length L_4 of the connecting rod CD and the trajectory of the tip G when L_1=300

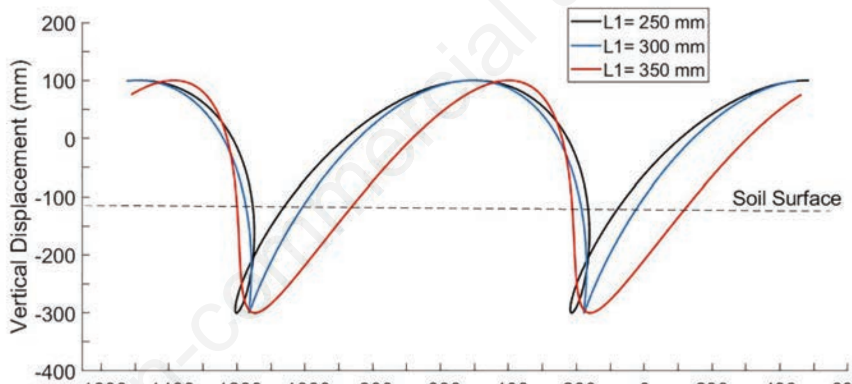


Figure 4. Relationship between L_1 and the trajectory of tip G.

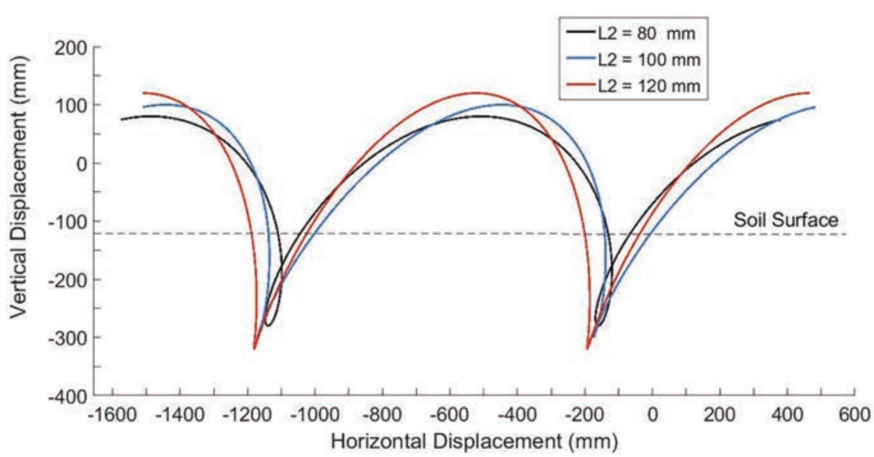


Figure 5. Relationship between L_2 and the trajectory of tip the *G*.

mm, L_2=100 mm, L_3=170 mm, and L_5=75 mm. As L_4 increases, the cross buckles decrease, and the vertical elongations shorten. This means that as the length of the rod CD increases, the disturbance of the planting duckbill tip on the ground is reduced, and damage around the hole is minimal. In addition, the hole becomes shallower as the elongation becomes shorter.

Figure 8 shows the relationship between the length L_5 of the lower crank OD and the trajectory of tip G when L_1=300 mm, L_2=100 mm, L_3=170 mm, and L_4=220 mm. This figure shows that as L_5 increases, the width of the buckles formed by the trajectory of tip G increases. In addition, the angle between the vertical axis and the trajectory direction narrow. The results show that as the length of the crank OD increases, the seedling, after transplanting, tends to a straight vertical position. However, as L_5 increases, the width of the hole after transplanting is larger.

Detailed analysis of Figures 4 to 8 shows that the length OA

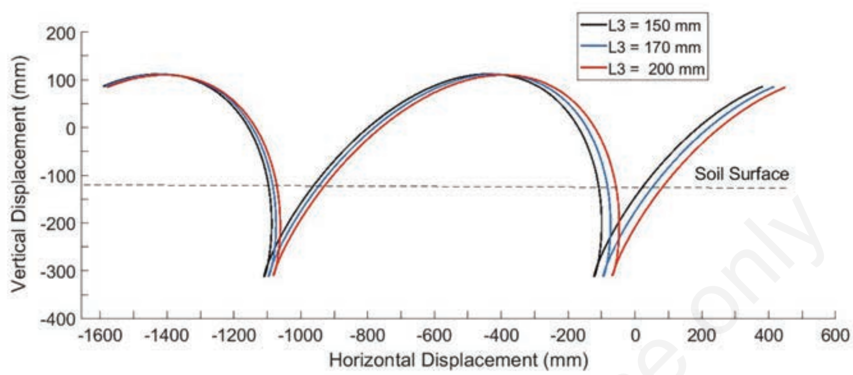


Figure 6. Relationship between L_3 and the trajectory of tip the *G*.

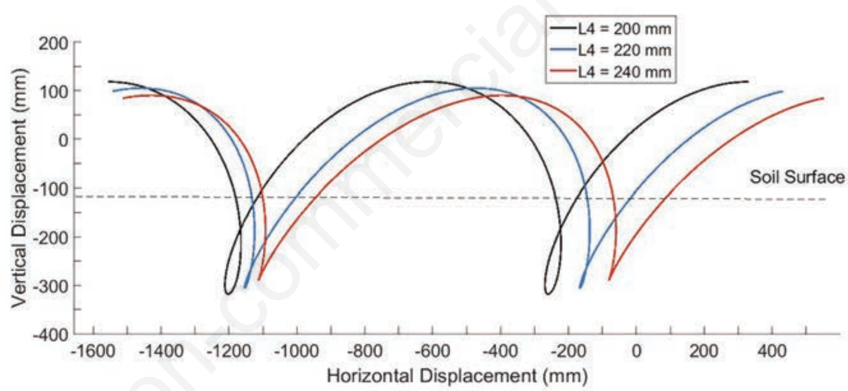


Figure 7. Relationship between L_4 and the trajectory of tip the *G*.

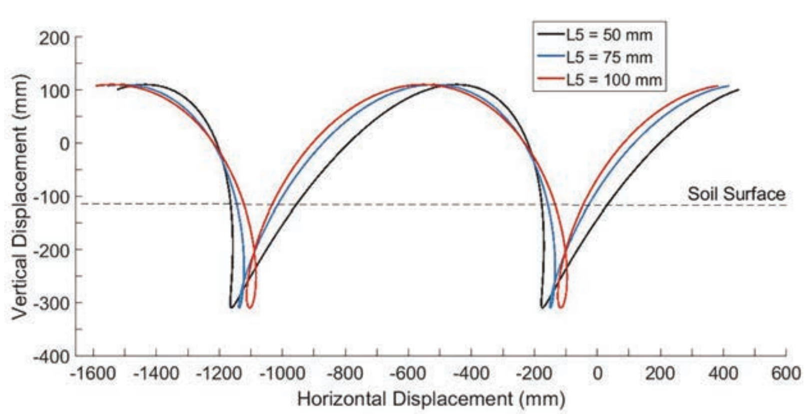


Figure 8. Relationship between L_5 and the trajectory of tip the *G*.

between the cranks mainly affects the width of the hole. A change in the length AB is mainly related to the vertical displacement of the planting point. The length of the connecting rod BC primarily determines the relative position of the formed hole and the position of the ridge for proper seedling reception. As the CD rod lengthens, the hole becomes narrower and shallower. A change in the crank OD mainly affects the inclination of seedlings.

On the other hand, maximum and minimum X coordinate values were –104.18 mm and –1221.33 mm, respectively, and the maximum and minimum Y coordinate values were 106.67 mm and –351.90 mm, respectively. Thus, the maximum width of the trajectory (maximum X coordinate, minimum X coordinate) was 1117.15 mm, and the maximum height of the trajectory (maximum Y coordinate, minimum Y coordinate) was 458.57 mm. Based on these observations and from previous work on this transplanting mechanism (Shao *et al*., 2019; Jin *et al*., 2020), we could define the range of the design variables and the theoretical trajectory of the transplanting tip.

In order to further improve the search performance of the parameters of the mechanism, the genetic algorithm has been implemented under MATLAB software. In this paper, the parameter configuration of the genetic algorithm is shown in Table 2. In addition, Figure 9 presents the evolution of the fitness function during the execution of the algorithm.

The execution of the algorithm ends after 20 generations, with the best fitness values of 1.03×10^{-2} mm. The algorithm generates the optimal combination of transplanting mechanism as follows: L_1=300.38 mm, L_2=106.20 mm, L_3=168.98 mm, L_4=221.63 mm, L_5=66.74 mm, L_6=305.02 mm, L_7=280.24 mm, L_8=170,18 mm, θ_1=45°, θ_2=89.41°, θ_5=44.70°, θ_7=90°. The trajectory of the planting tip G for this combination of parameters is shown in Figure 10.

It can be seen from Figure 10 that the planting depth is 192 mm. The inclination of the trajectory is 4.4° with respect to the vertical axis, which allows a seedling planting angle of 85.6° in the ground. The plant spacing is 989 mm. The proposed combination can allow seedling transplanting while meeting agronomic requirements, essential for better growth and yield of sorghum seedlings. The parameters obtained in MATLAB software are used in SolidWorks for a complete design of the transplanting mechanism, as shown in Figure 11. The stationary trajectory of the planting duckbill tip for the obtained parameter combination is shown in Figure 12. It can be seen from Figure 12 that the static track of the planting duckbill tip is nearly upright to the ground, which is consistent with the kinematic analysis. Furthermore, velocity and acceleration analyses of the mechanism are performed in SolidWorks software. When the mechanism is driven at a rotational speed of 78 rpm, the graphs of Figure 13 are obtained. The transplanter forward velocity is equal and opposite to the horizontal velocity of the maximum down point of its trajectory because, at this point, the duckbill releases the seedling into the soil. Figure 13A shows that the duckbill's maximum horizontal speed at the seedling release point is –642 mm/s. Thus, the corresponding forward speed of the transplanter is 642 mm/s, for a rotational speed of 78 rpm.

When the duckbill receives the seedling (point a) from the feeding mechanism, its vertical velocity is zero, as shown in Figure 13C, and its horizontal acceleration is close to zero, as shown in Figure 13B. Point b is the opening point of the duckbill; its speed and acceleration are reduced. When the seedling is released in the soil (point c), the duckbill's vertical speed and horizontal acceleration remain zero, as shown in Figure 13C and B. Finally, point d is the duckbill's closing point; its speed increases and its acceleration is drastically reduced. These results are close to the observations

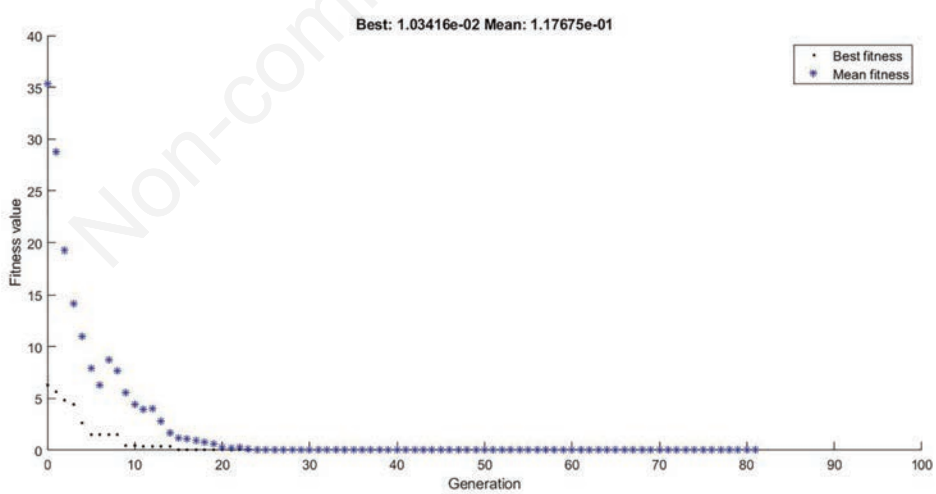


Figure 9. Fitness value chart of the genetic algorithm.

Table 2. Parameter setting of the genetic algorithm.

Population size	Number of generations	Crossover probability	Mutation probability
50	100	0.7	0.05

made by Shao *et al*. (2019) and Jin *et al*. (2020).

At every 0.769-s interval, transplanting at constant horizontal velocity occurs, and at every 0.769-s interval, a seedling is successfully collected by the mechanism, as shown in Figure 13A. Thus, seedling collection and transplanting occur every 0.769 s. It appears that the transplanting rate is 78 seedlings/min when the mechanism is driven at a rotational speed of 78 rpm. These values comply with the aforementioned agronomic requirements.

Conclusions

In this study, a duckbill-type planter has been designed to automatically transplant sorghum seedlings. The design process is conducted through kinematic, synthesis, velocity, and acceleration analysis methods. First, using a genetic algorithm, the optimal dimensions of the planting mechanism were determined to meet the requirements of receiving, positioning, and planting seedlings.

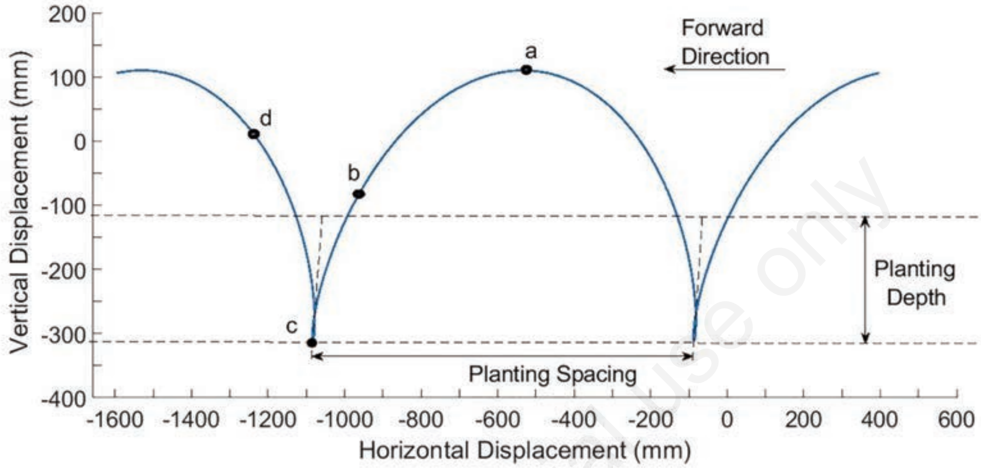


Figure 10. The trajectory of the proposed planting mechanism.

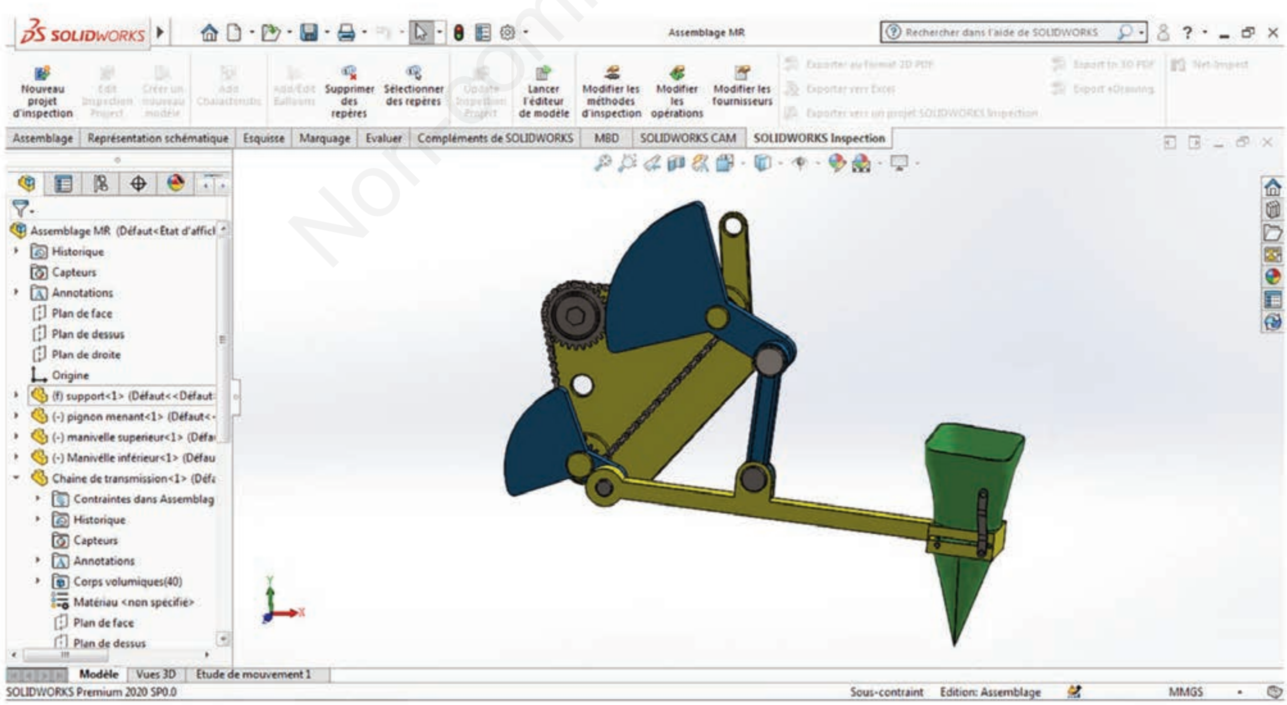


Figure 11. Planting mechanism model in SolidWorks.

Then, the speed and acceleration of the mechanism were analysed. The results show that the proposed mechanism can transplant sorghum seedlings with 85.6° upright planting qualification, a seedling spacing of 989 mm when the transplanter displacement velocity is 642 mm/s. The actual operability and dynamic properties, such as force and stress exerted in the link structure, will be studied in future research.

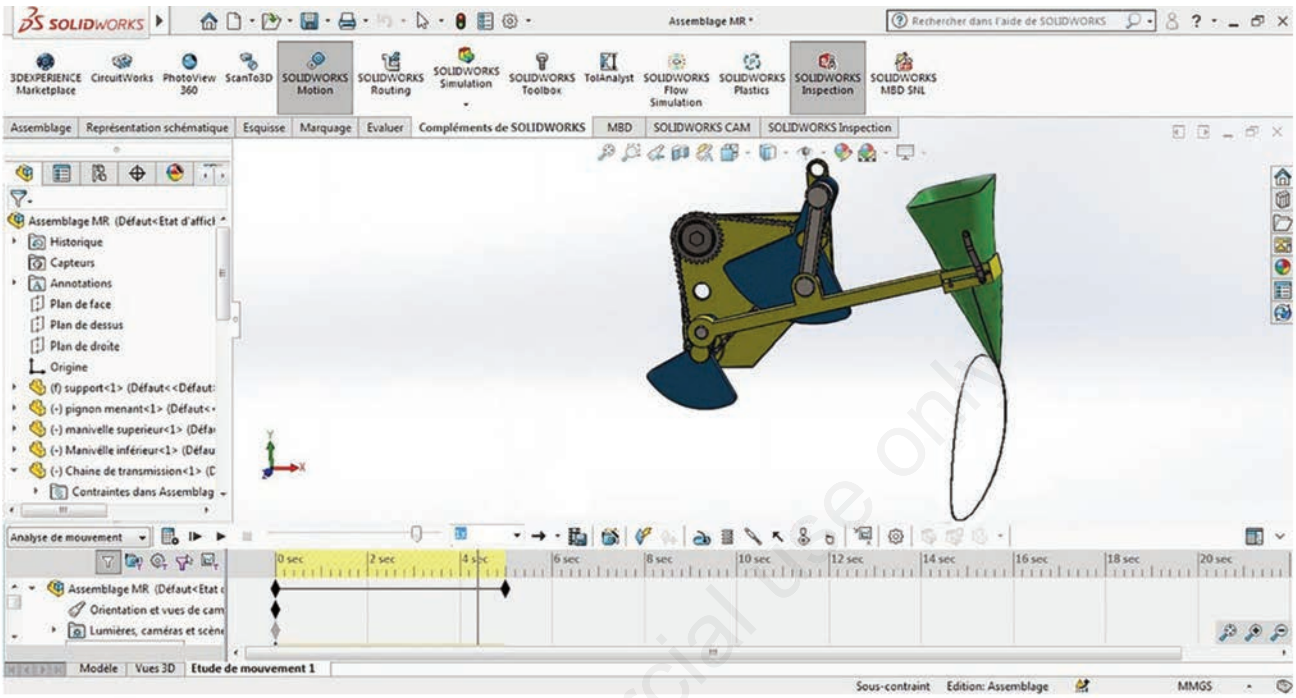


Figure 12. The static trajectory of the duckbill planter in SolidWorks.

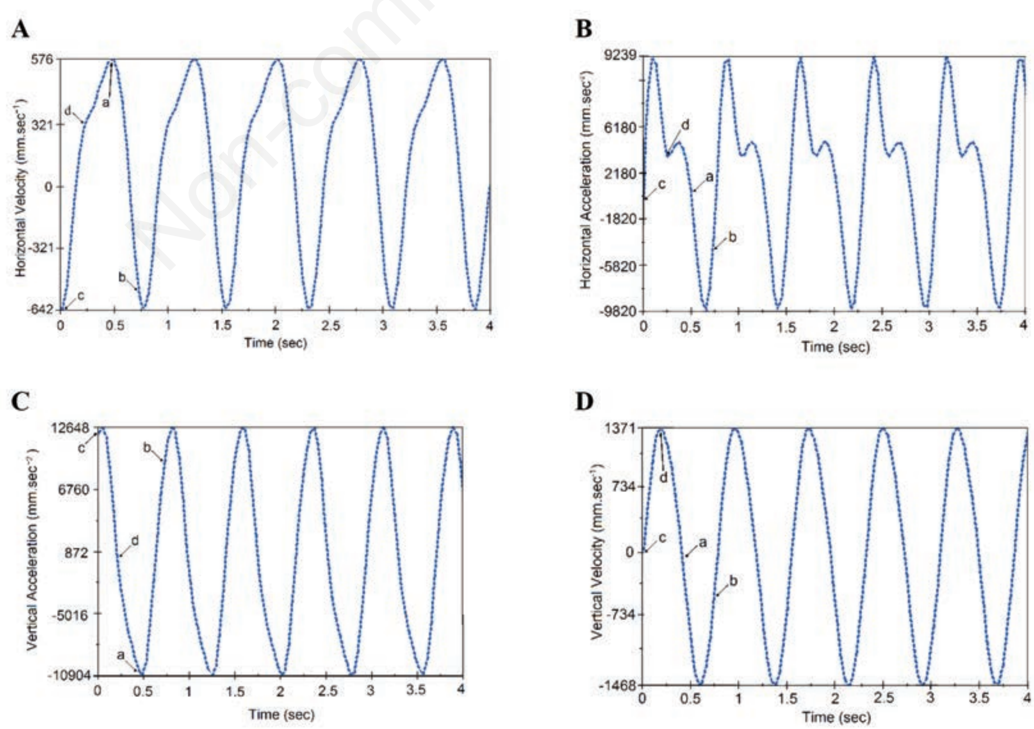


Figure 13. A) Horizontal velocity; B) horizontal acceleration; C) vertical velocity; D) vertical acceleration of the duckbill tip planter at 78 rpm.

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